Modular circular economy in energy infrastructures:
The case of Small Modular Reactors

Benito Mignacca

Submitted in accordance with the requirements for the degree of

Doctor of Philosophy

The University of Leeds

School of Civil Engineering

May 2021

Academic Supervisors:

Professor Giorgio Locatelli

Dr Konstantinos Velis

Professor Nigel Smith

The candidate confirms that the work submitted is his own, except where work which has formed part of jointly authored publications. The contribution of the other authors in the jointly authored publications included in this work has been explicitly indicated below. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others.

This thesis is following the "Protocol for the format and presentation of an alternative style of doctoral thesis including published material" by the Faculty of Engineering of the University of Leeds.

Acknowledgements

First and foremost, I am extremely grateful to my supervisor, Professor Giorgio Locatelli, for his invaluable advice, continuous support, and patience during my PhD. His immense knowledge and great experience have encouraged me in my academic research and daily life. I would also like to thank Dr Diletta Invernizzi and Dr Tristano Sainati for their kind help and support from the first day of my PhD. Finally, I would like to express my gratitude to Engineering and Physical Sciences Research Council for sponsoring this PhD and to the Major Project Association for providing further support.

Abstract

Policymakers, practitioners, and academics increasingly discuss modularisation and Circular Economy (CE) in the energy sector. However, these topics are usually discussed individually, failing to recognise their interdependency. Recognising interdependency is crucial because modularisation can become a key enabler of CE. This PhD research addresses this gap in knowledge. Traditional stick-built infrastructures have a lifecycle often predetermined by components very difficult or expensive to replace. Modular energy infrastructures could be made reconfigurable and extend their lifecycle by decoupling the life of the infrastructures from their modules. Modules can be designed in a way that, when a module reaches its end of life, it could be exchanged, extending the life of the infrastructure. Moreover, when the infrastructure needs to be retired, modules still functioning could be used in another infrastructure. Shifting the attention from component to module level can facilitate CE initiatives. Leveraging this intuition, this research investigated the link between modularisation and CE, focusing on the case of Small Modular Reactors (SMRs), which the literature considers a key modular technology in the next 10-20 years. This research contributes to both theory and practice. Regarding the contribution to theory, the link between modularisation and CE has been theoretically conceptualised by introducing the Modular CE, which is the key novelty of this PhD research. The Modular CE has been compared to traditional modularisation by leveraging a systematic review and a case study. Regarding the contribution to practice, this research focused on the reuse initiative, identifying and examining enabling factors and barriers for the Modular CE by interviewing 24 experts in the nuclear and oil and gas sector. Furthermore, this research identified and ranked the most relevant elements hindering and favouring Modular CE in the case of SMRs by conducting a questionnaire survey involving 97 SMR experts. Finally, this research paves the way to future research opportunities, such as investigating the Modular CE in other infrastructures (e.g. wind farm) and the quantitative evaluation of the economic and environmental implications of Modular CE initiatives.

Table of content

List of publications and candidate's contribution

This section lists the 9 publications included in this thesis and the related candidate's contribution, clustering them into the ones in the main body of the thesis (i.e. section B) and the ones in the appendix (i.e. section D). The publications in the main body of the thesis satisfy the requirements for the University of Leeds doctoral thesis's alternative style. The ones in the appendix also contributed to the progress of this PhD research, and they further demonstrate the quality of the candidate's scientific work.

Publications in the main body of the thesis

I. Mignacca, B., Locatelli, G., 2020. *Economics and finance of Small Modular Reactors: A systematic review and research agenda*. Renewable and Sustainable Energy Reviews, Vol. 118 - **Scopus indexed journal, Impact Factor: 12.11**. **Among the most downloaded articles of the journal at the time of writing (May 2021).**

As the first author of Publication I, the candidate critically and systematically reviewed the scientific and industrial literature about the economics and finance of Small Modular Reactors (SMRs), focusing on the implications of modularisation and modularity. The candidate was also responsible for preparing the first draft of the paper and managing the review process. Professor Giorgio Locatelli provided valuable support and comments in the early stages of this research and during the review process. The candidate's contribution to Publication I was approximately 85%.

II. Mignacca, B., Locatelli, G., Velenturf, A., 2020. *Modularisation as enabler of circular economy in energy infrastructure*. Energy Policy, Vol. 139 - **Scopus indexed journal, Impact Factor: 5.042, ABS 2**.

As the first author of Publication II, the candidate was responsible for planning the research design, critically reviewing the literature, collecting and analysing primary data (by series of communications including one in-depth interview with a senior project manager) and secondary data (from company reports and websites). The candidate was also responsible for preparing the first draft of the paper and managing the review process. Professor Giorgio Locatelli provided valuable support and comments, particularly in the early phases of this research. Dr Anne Velenturf, involved after the first review, was responsible for section 5.1 and provided valuable comments on the paper. The candidate's contribution to Publication II was approximately 80%.

III. Mignacca, B., Locatelli, G., 2021. *Modular circular economy in energy infrastructure projects: Enabling factors and barriers*. Journal of Management in Engineering (accepted, to be scheduled for an issue) - **Scopus indexed journal, Impact Factor: 3.928, ABS 2.**

As the first author of Publication III, the candidate was responsible for planning the research design, collecting and analysing data from 23 semi-structured interviews. The candidate was also responsible for writing the first draft of the paper and managing the review process. Professor Giorgio Locatelli provided valuable comments during the research and concerning the first draft of the paper. The candidate's contribution to Publication III was approximately 95%.

IV. Mignacca, B., Locatelli, G., Sainati, T., 2020. *Deeds not words: Barriers and remedies for Small Modular nuclear Reactors*. Energy, Vol. 206 - **Scopus indexed journal, Impact Factor: 6.082, ABS 3.**

As the first author of Publication IV, the candidate was responsible for planning the research design, collecting and analysing data from a survey involving 97 SMR experts. The candidate was also responsible for writing the first draft of the paper and managing the review process. Professor Giorgio Locatelli and Dr Tristano Sainati provided valuable comments concerning the research design and the first draft of the paper. The candidate's contribution to Publication IV was approximately 85%.

Publications in the appendix of the thesis

V. Mignacca, B., Locatelli, G., Alaassar, M., Invernizzi, D.C., 2018. *We never built small modular reactors (SMRs), but what do we know about modularisation in construction?* The proceedings of the 26th International Conference on Nuclear Engineering, London - **Scopus indexed proceedings**.

As the first author of Publication V, the candidate was responsible for further analysing the data collected and elaborated by Mr Alaassar for his MSc dissertation, including further literature, writing the first draft of the paper, managing the review process and presenting the paper at the 26th International Conference on Nuclear Engineering in London. Professor Giorgio Locatelli supervised Mr Alaassar during his dissertation and provided feedback on the first draft of the paper. Dr Invernizzi also provided valuable comments and feedback on the first draft. The candidate's contribution to Publication V was approximately 35%.

VI. Mignacca, B., Alawneh, A.H., Locatelli, G., 2019. *Transportation of small modular reactor modules: What do the experts say?* The proceedings of the 27th International Conference on Nuclear Engineering, Ibaraki (Japan) - **Scopus indexed proceedings**.

As the first author of Publication VI, the candidate was responsible for further analysing the data collected and elaborated by Mr Alawneh for his MSc dissertation, including further literature, writing the first draft of the paper, managing the review process and presenting the paper at the 27th International Conference on Nuclear Engineering in Ibaraki (Japan). Professor Giorgio Locatelli supervised Mr Alaassar during his dissertation and provided feedback on the first draft of the paper. The candidate's contribution to Publication VI was approximately 35%.

VII. Locatelli, G., Mignacca, B., 2020. *Small Modular Nuclear Reactors*. Book chapter in Future Energy: Improved, Sustainable and Clean Options for Our Planet, pp. 151-169, **Scopus indexed chapter**.

As the second author of Publication VII, the candidate was responsible for drafting several sections of the book chapter, also providing comments and feedback on the first draft. The candidate's contribution to Publication VII was approximately 40%.

VIII. Mignacca, B., Locatelli, G., 2020. *Economics and finance of Molten Salt Reactors*. Progress in Nuclear Energy – **Scopus indexed journal, Impact Factor 1.508. The most downloaded article of the journal at the time of writing (May 2021).**

As the first author of Publication VIII, the candidate critically and systematically analysed scientific and industrial literature, defined the most relevant gaps in knowledge, elaborated on the data collected, and provided future research opportunities. The candidate was responsible for writing the first draft of the paper and managing the review process. Professor Giorgio Locatelli provided valuable comments on the first draft of the paper and during the review process. The candidate's contribution to Publication VIII was approximately 90%.

IX. Locatelli, G., Sainati, T., Mignacca, B., 2021. *Developing UK strategy for nuclear SMRs*. Brief 6, Policy Leeds, University of Leeds.

As the third author of Publication IX, the candidate was responsible for writing two sections. These two sections are based on the findings of Publication I and IV. Furthermore, the candidate provided comments and feedback on the policy brief. The candidate's contribution to Publication IX was approximately 30%.

Current status of the publications

The current status of the four publications in the main body of the thesis is as follows:

- Publication I – published
- Publication II – published
- Publication III – accepted
- Publication IV – published

The current status of the publications in the appendix of this thesis is as follows:

- Publication V – published
- Publication VI – published
- Publication VII – published
- Publication VII – published
- Publication IX – published

Structure of this thesis

This thesis is structured in four main parts:

- PART A presents the research background, the gap in knowledge, the research aim, the research objectives and their link to the publications in the main body of the thesis, and explains the research design and philosophy;
- PART B consists of publications I, II, III, and IV. Each of them addresses one of the research objectives introduced in Part A;
- PART C presents the discussion and conclusion, highlighting the contribution to knowledge in terms of theory and practice to theory and practice. Moreover, PART C suggests future research opportunities and presents other activities related to this PhD research;
- PART D consists of publications V, VI, VII, VIII, and IX. These are supplementary publications relevant for the progress of this research, also demonstrating the scientific maturity of the candidate.

A. Introduction

A.1 Research background

Policymakers, practitioners and academics are increasingly discussing the transition from traditional stick-built construction to modularisation in order to reduce time and cost and of energy infrastructures (Choi et al., 2019, 2016; Lloyd et al., 2021; O'Connor et al., 2014) and the transition from a linear economy to Circular Economy (CE) to reduce their environmental impact (Lapko et al., 2019; Purnell, 2019; Schiller et al., 2017; Vondra et al., 2019). However, these topics were discussed separately before the candidate's publications, as highlighted in the following sections.

A.1.1 Modularisation in energy infrastructures

Modularisation is the "*process of converting the design and construction of a monolithic or stick-built plant to facilitate factory fabrication of modules for shipment and installation in the field as complete assemblies*" (GIF/EMWG, 2007) (Page 24). Modularisation and modularity are often used interchangeably in both scientific and industrial literature, although having different meanings. Figure 1 clarifies the difference between modularisation and modularity and compares them with traditional stick-built construction and pure standardisation.

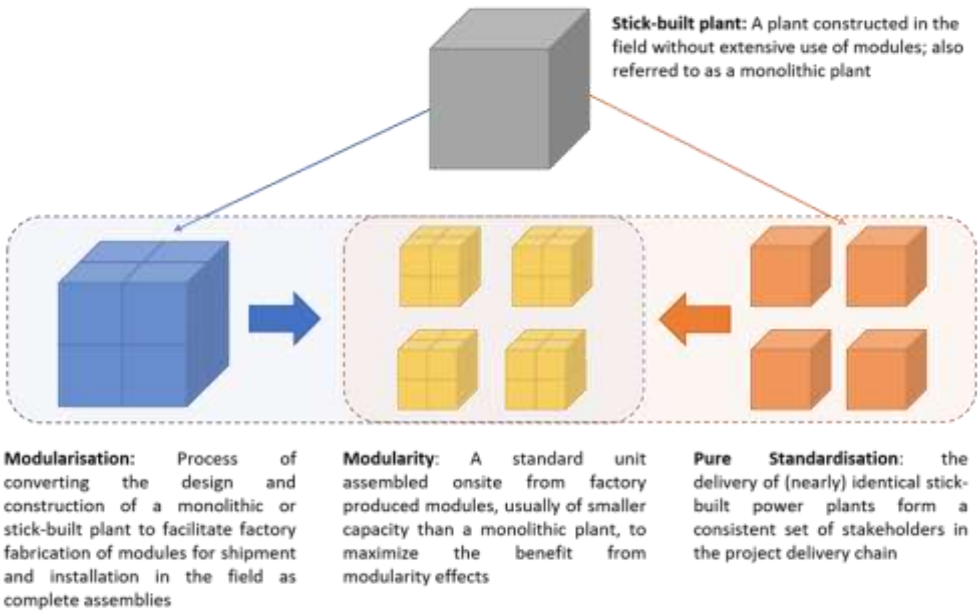


Figure 1: Meaning of stick-built plant, modularisation, modularity, and pure standardisation – Extracted from (Mignacca et al., 2020)

Most of the literature concerning modularisation in energy infrastructures deals with working in a better-controlled environment leading to quality improvement, construction schedule and cost reduction (Choi et al., 2019, 2016; Ikpe et al., 2015; Maronati et al., 2017; O'Connor et al., 2015, 2014). Modularisation is also essential to build infrastructures in remote areas characterised by logistic or environmental challenges (Auverny-Bennetot et al., 2019). Modularisation can bring further benefits (e.g., further cost and schedule reduction) if coupled with standardisation. (O'Connor et al., 2015) stressed this point, highlighting two approaches to integrate design standardisation with modularisation: "Modular Standardised Plant", i.e. standardisation of plant design and modularisation of the design to obtain standard modular plants; and "Standard Modules", i.e. modularisation of the design and standardisation of some modules. The standardisation of modular plants coupled with a substantial decrease in size (with respect to the stick-built counterpart) leads to modularity, as shown in Figure 1. Modularisation also presents challenges, such as a higher project management effort (Carelli and Ingersoll, 2014), a higher cost for transportation activities and transportation challenges in general (Lloyd et al., 2021), uncertainties in off-site logistics (Yang et al., 2021), and the supply-chain start-up cost can be high (UxC Consulting, 2013).

A.1.2 Circular economy in energy infrastructures

There are many definitions of CE, as reviewed by (Kirchherr et al., 2017). This research adopts Preston and Lehne's (2017) definition: "*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*" (Page 4). In other words, CE is concerned with maintaining resources at their highest value possible through CE initiatives such as repair, reuse and recycle (Ellen MacArthur Foundation, 2020; Minunno et al., 2020; Rausch et al., 2020; Velenturf and Purnell, 2021).

The literature about CE in energy infrastructures can be categorised into three domains (Mignacca and Locatelli, 2021):

1) Raw material (e.g. steel)

The majority of the literature regarding CE in energy infrastructures deals with raw materials (Busch et al., 2014; Christmann, 2018; Dong et al., 2019; Heath et al., 2020; Krausmann et al., 2017; Lapko et al., 2019; Ng et al., 2016; Reuter et al., 2015; Roelich et al., 2014; Schiller et al., 2017). For instance, (Busch et al., 2014) stressed the importance of monitoring the critical materials (i.e. materials at risk of supply disruption, such as rare earth elements, cobalt, and lithium) embedded in infrastructures, thereby enabling opportunity for material recovering and reusing. The authors presented a stocks and flows model to evaluate CE initiatives quantitatively. (Lapko et al., 2019) identified enabling factors (e.g. legislation support for waste reduction and collection of end-of-life products) and bottleneck conditions (e.g. lack of appropriate recycling technology and instability of market for recycled materials) for the implementation of a closed-loop supply chain for critical raw materials in the case of photovoltaic panels and wind turbine technologies. (Christmann, 2018; Dong et al., 2019; Ng et al., 2016; Reuter et al., 2015) discussed the importance of sustainable management of metals (such as lead and zinc and their minor elements) and minerals both in terms of higher reusing and recycling.

2) System (infrastructure as a whole)

The system domain focuses on CE initiatives by considering the infrastructure as a unit of analysis. This literature deals with topics such as using infrastructure waste as feedstock for other infrastructures or products. A much-discussed topic is represented by the opportunity to reclaim energy from waste and, more generally, resources from waste (Fuldauer et al., 2019; Liguori and Faraco, 2016; Purnell, 2019; Venkata Mohan et al., 2016; Vondra et al., 2019). For instance, (Velenturf et al., 2019) reported a series of technologies under development that can recover organic and inorganic fractions from waste, such as "*biorefineries that incorporate microbially-mediated metal recovery approaches to produce new catalysts from liquid wastes, for the production of liquid and gaseous fuels in addition to generating electricity from bio-hydrogen via fuel cell catalysts*" (Page 967). Another key topic in this area is cogeneration, i.e., generating two different valuable products from a single primary energy source, saving a significant amount of energy (Locatelli et al., 2018, 2017).

3) Module (e.g. pump) and component (e.g. valve)

The distinction between module and component is complex (Brusoni and Prencipe, 2001). For instance, a pump can be considered both a module (including components such as bearings) and a component (as part of a reactor pressure vessel). In general, modules and components are functional units and are treated as such in this PhD research. The literature in this domain is scarce and mostly highlights the need for reusing components rather than providing solutions. According to (Invernizzi et al., 2020), policymakers need to act proactively in developing policies favouring CE solutions (e.g., reusing components) for future energy infrastructures to tackle the challenges associated with decommissioning megaprojects. (Jensen et al., 2020) highlighted this need in the case of low carbon infrastructures, focusing on offshore wind. The aforementioned model of (Busch et al., 2014) also includes components with their own stocks and flow dynamics to evaluate the potential for reuse quantitatively. Before this PhD research, the focus of this domain was at the component level, neglecting the link between modularisation and CE, as discussed in the next section.

A.1.3 The gap in knowledge and its relevance

As aforementioned, policymakers, practitioners and academics are increasingly discussing modularisation and CE in energy infrastructures. However, before the candidate's research, these topics were discussed individually, failing to recognise their interdependency. Before this research, there was no literature investigating the link between modularisation and CE in energy infrastructures, as shown in Publication II. Recognising the interdependency between modularisation and CE is crucial because modularisation can become a key enabler of CE and dramatically change energy infrastructures' lifecycle. Traditional stick-built energy infrastructures have a lifecycle often predetermined by components that are difficult or very expensive to replace.

The key idea of this research (developed and tested in two different domains, i.e. nuclear and oil and gas) is that modular infrastructures could be made reconfigurable and extend/adapt their lifecycle by decoupling the life of the infrastructure from their modules. Modules can be designed in a way that, when a module reaches its end of life, it could be exchanged, extending the life of the infrastructure. Furthermore, when the infrastructure needs to be retired, modules that are still functioning could be used in another infrastructure. In this way, the residual lifetime of certain modules with a longer life is not "wasted". The transition from a focus at the component level to a focus at the module level can facilitate the implementation of CE initiatives.

The need for implementing CE initiatives in energy infrastructures is remarkable. For instance, in the nuclear industry, there are 444 operational reactors in the world, 192 reactors in permanent shutdown, 50 under construction and only 17 had been completely decommissioned, which means that there will be the need to deal with the lifecycle of at least other 669 nuclear reactors (IAEA, 2021). However, nuclear plants are not the only energy infrastructures. The total global wind power installed is 540 GWe, the vast majority installed in the last 10 years (GWEC, 2019). Considering an operating life of about 25 years (Ghenai, 2012), in a decade or two, and the absence of CE initiatives, there will be decommissioning megaprojects in the wind power sector (Purnell et al., 2018). Moreover, according to (Infrastructure Outlook, 2020), the budget to be invested in energy infrastructures until 2040 is $28 Trillion; therefore, more and more energy infrastructures will be built, and new thinking about their lifecycle will be needed.

These numbers clarify the importance of managing energy infrastructure lifecycles, including extending the lifetime of the infrastructures and their modules.

A.2 Research aim and research objectives

From the considerations in the previous section (A.1), the author derived the aim of this research.

The aim of this research is to investigate the link between modularisation and circular economy in energy infrastructures.

The research domain is the nuclear sector, particularly SMRs. SMRs are considered a key modular technology for the next 10-20 years (HM Government, 2020; Lloyd et al., 2021; Locatelli et al., 2015; NuScale, 2018; Wrigley et al., 2021). The oil and gas sector has also been considered, where modularisation has been practised for the last 40 years (Bjørnstad, 2009).

To achieve the aforementioned aim, the candidate developed four objectives:

I. Identify advantages, disadvantages, and economic implications of modularisation over SMR lifecycle. This objective has been achieved through the research presented in Publication I.

II. Explore the link between modularisation and CE in energy infrastructures. This objective has been achieved through the research presented in Publication II.

III. Identify and examine the factors enabling and hindering the link between modularisation and CE in energy infrastructures. This objective has been achieved through the research presented in Publication III.

IV. Identify and rank the elements hindering and favouring the link between modularisation and CE in SMRs. This objective has been achieved through the research presented in Publication IV.

A.3 Research design and philosophy

Research designs are tailored according to the research questions and/or research objectives. This PhD research includes the four primary research objectives presented in section A.2, and a series of research questions and research objectives related to the four primary research objectives. The detailed designs to answer each research question or research objective are detailed described in each of the publications in section B. This section describes the overall research philosophy. The book "Research Methods for Business Students" (Saunders et al., 2015) is the main reference.

A.3.1 Philosophical assumptions

During every stage of the research, several philosophical assumptions are made, determining the researcher's position about the development of knowledge. (Saunders et al., 2015) highlight three main philosophical assumptions:

1) Ontological, i.e. the researcher's view about the nature of reality;
2) Epistemological, i.e. what the researcher evaluates as acceptable and valid knowledge;
3) Axiological, i.e. the role of values and ethics in the research process.

Management research philosophies are scattered between two extremes: objectivism and subjectivism.

Ontologically, objectivism incorporates realism, which considers social entities existing independently of our perception, believing there is only one true social reality. Conversely, subjectivism embraces nominalism (extreme form) and social constructionism (less extreme form). The first considers the social phenomena are created by the researchers and other social actors, believing that everyone perceives reality differently. The second considers the reality constructed through social interaction, creating partially shared meanings.

Epistemologically, objectivists study the social world through observable and measurable facts. Conversely, subjectivists are interested in different opinions to account for different social realities.

Axiologically, objectivists consider their research free of values, believing that the contrary determines bias in their findings. Conversely, subjectivists consider their research value-bound (Saunders et al., 2015).

A.3.2 Research philosophy

There are five major research philosophies (Saunders et al., 2015):

1) Positivism, i.e. the researcher assumes one true reality and considers acceptable knowledge only measurable and observable facts. A positivist uses theory to develop hypotheses and claims to be external to the process of data collection.

2) Critical realism, i.e. the researcher assumes reality as external and independent, considering what he experiences as the manifestation of the things and not the actual things. A critical realist embraces epistemological relativism as an approach to knowledge, considering knowledge as a product of its time and the social facts as agreed by people rather than existing independently.

3) Interpretivism, i.e. the researcher assumes different social realities, determined by different people and situations, aiming to create a new understanding of the social world and context. An interpretivist focuses on participants' lived experiences (phenomenologist), cultural artefacts (hermeneuticist), or social interactions (symbolic interactionist).

4) Postmodernism, i.e. the researcher rejects the realist ontology of things, emphasising that any order is provisional. A postmodernist assumes that dominant ideologies guide truth and knowledge.

5) Pragmatism, i.e. the researcher assumes reality as the practical consequence of ideas. A pragmatist strives to reconcile objectivism and subjectivism by considering concepts, hypotheses, findings, and theories in terms of their roles as tools of thought and action and their consequences in specific contexts. This research philosophy considers the research questions as the most relevant determinant for the research design.

In this PhD research, the pragmatism philosophy has been adopted for three reasons:

1) For a pragmatist, the research starts with a problem to address. This research starts with a problem, which is the need to improve energy infrastructure lifecycle, as also explained in section A.1.

2) For a pragmatist, the research aims to provide practical solutions informing future practice. This research project aims to investigate the link between modularisation and CE in energy infrastructures, providing guidelines to academics and practitioners about enabling factors and barriers for harnessing such link.

3) A pragmatist strives to reconcile objectivism and subjectivism. This research needs to reconcile the experts' perspectives involved in the research (requiring a more subjectivist view) with the collection of other secondary data (e.g. reports about implications of modularisation) requiring a more objectivist view.

Regarding the data collection and analysis, both primary and secondary data have been collected and analysed. Each publication in section B describes in detail the process of data collection and analysis.

B. Publications

B.1 Publication I

Mignacca, B., Locatelli, G., 2020. Economics and finance of Small Modular Reactors: A systematic review and research agenda. Renewable and Sustainable Energy Reviews, Vol. 118 - **Scopus indexed journal, Impact Factor: 12.11**. **Among the most downloaded articles of the journal at the time of writing (May 2021).**

Renewable and Sustainable Energy Reviews 118 (2020) 109519

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: http://www.elsevier.com/locate/rser

Economics and finance of Small Modular Reactors: A systematic review and research agenda

B. Mignacca, G. Locatelli*

School of Civil Engineering, University of Leeds, LS2 9JT, United Kingdom

ARTICLE INFO

Keywords:
Small modular reactor
SMR
Economics
Finance
Modularisation
Modularity

ABSTRACT

The interest toward Small Modular nuclear Reactors (SMRs) is growing, and the economic competitiveness of SMRs versus large reactors is a key topic. Leveraging a systematic literature review, this paper firstly provides an overview of "*what we know*" and "*what we do not know*" about the economics and finance of SMRs. Secondly, the paper develops a research agenda. Several documents discuss the economics of SMRs, highlighting how the size is not the only factor to consider in the comparison; remarkably, other factors (co-siting economies, modularisation, modularity, construction time, etc.) are relevant. The vast majority of the literature focuses on economic and financial performance indicators (e.g. Levelized Cost of Electricity, Net Present Value, and Internal Rate of Return) and SMR capital cost. Remarkably, very few documents deal with operating and decommissioning costs or take a programme (and its financing) rather than a "single project/plant/site" perspective. Furthermore, there is a gap in knowledge about the cost-benefit analysis of the "modular construction" and SMR decommissioning.

1. Introduction

The International Atomic Energy Agency [1] defines Small Modular Reactors (SMRs) as *"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"* (Page 1). [2] provides a summary of the innovative features of SMRs and describes SMRs as *"reactor designs that are deliberately small, i.e. designs that do not scale to large sizes but rather capitalize on their smallness to achieve specific performance characteristics"*. Several SMR designs, detailed in Refs. [1,3–5], are currently at different stages of development. SMR designs relate to virtually all the main reactor categories: water-cooled reactors, high-temperature gas-cooled reactor, liquid-metal, sodium and gas-cooled reactors with fast neutron spectrum, and molten salt reactors [1,4]. The interest in SMRs is growing mainly because of the SMR unique characteristics (in primis size and modular construction) and different applications (electrical, heat, hydrogen production, seawater desalination) [1].

Several documents consider the size as one of the main SMR disadvantages [6–9] in the evaluation of SMR competitiveness with respect to Large Reactors (LRs) because of the loss of the economy of scale. However, the size is not the only factor to consider in the evaluation of SMR competitiveness versus LRs. SMRs present unique benefits mostly determined by modularisation and modularity. Modularisation (factory fabrication of modules, transportation and installation on-site [10]) allows working in a better-controlled environment [8,11,12], standardisation and design simplification [13,14], reduction of the construction time [15]. Modularity (a plant built by the assembly of nearly identical reactors of smaller capacity [16]) allows the co-siting economies [7,12,17,18], cogeneration for the load following of Nuclear Power Plants (NPPs) [19], higher and faster learning, and better adaptability [20].

Once all the aforementioned factors are considered, it is possible to evaluate the SMR economic and financial competitiveness properly. Economic and financial issues represent key barriers for SMR development (as well as LRs) and are of the main reasons because no one "truly modular" SMR has been built so far. Since this paper deals with economics and financial aspects of SMRs, it is worth to clarify these concepts right at the start. Economics is a social science concerned with the study of management of goods and services, comprising production, consumption, and the elements affecting them [21,22]. Usually, economic models do not consider the payment of taxes, remuneration of debt or equity, or debt amortisation. The Levelised Cost of Electricity (LCOE) is a common metric used in economic studies in the energy sector.

On the other hand, finance is concerned with managing funds by taking account of time, financial resources and the risk involved. The

* Corresponding author.
E-mail address: g.locatelli@leeds.ac.uk (G. Locatelli).

https://doi.org/10.1016/j.rser.2019.109519
Received 8 July 2019; Received in revised form 27 September 2019; Accepted 22 October 2019
Available online 1 November 2019

List of abbreviations

ASEE	International Conference on Advances in Energy Systems and Environmental Engineering
BCC	Base construction cost
BIM	Building Information Modelling
CAD	Computer-aided design
CC	Capital cost
EFWG	Energy Finance Working Group
EY	Ernst & Young
FOAK	First-of-a-kind
GIF/EMWG	Generation IV International Forum/Economics Modeling Working Group
IAEA	International Atomic Energy Agency
ICAPP	International Congress on Advances in Nuclear Power Plants
ICONE	International Conference on Nuclear Engineering
ICST	International Conference on Science and Technology
IDC	Interest During Construction
IRR	Internal Rate of Return
LCOE	Levelised Cost of Electricity
LR	Large Reactor
LUEC	Levelised Unit of Electricity
LW	Light Water
MIT	Massachusetts Institute of Technology
NEA	Nuclear Energy Agency
NNL	Nuclear National Laboratory
NOAK	nth-of-a-kind
NPP	Nuclear Power Plant
NPV	Net Present Value
O&M	Operation and Maintenance
OECD	Organisation for Economic Co-operation and Development
OVC	Overnight cost
PP	Payback Period
PWR	Pressurised Water Reactor
SLR	Systematic Literature Review
SMR	Small Modular Reactor
SMR20XX	ASME Small Modular Reactors Symposium 20XX
UK	United Kingdom
USA	United States of America
WACC	Weighted Average Cost of Capital
WNA	World Nuclear Association

aim is to balance risk and profitability. In the energy sector, a financial model is concerned with the analysis of cash flows for both debt and equity holder, establishing a remuneration of the capital according to different risk attitudes. Financial models consider additional stakeholders since financial models deal with the payment of taxes and/or subsidies (so are relevant for a government), raising debt (so relevant for debt providers such as banks and export credit agencies), and equity (so relevant for project developers) [21,22]. Payback Period (PP), Net Present Value (NPV), and Internal Rate of Return (IRR) are metrics commonly used in financial studies.

Economics and finance are two sides of the same coin, and the appraisal of a certain technology needs to consider both. Consequently, both economic and financial studies are reviewed in this paper.

The amount of documents published about SMR economics and finance so far is relatively large, the information is disorganised, and most of the quantitative studies do not follow a standardised approach, making a proper comparison in most of the cases impossible. This paper aims to provide, through a Systematic Literature Review (SLR), an overview of *what we know* and *what we do not know* about the economics and finance of "land-based" Small "Modular" Reactors. Therefore, studies about "Small Reactors" or "Floating Small Modular Reactors" are excluded. Instead of a traditional narrative review, an SLR has been performed to provide a holistic perspective and allow repeatability. The research objective is "to identify the state-of-the-art about economics and finance of land-based SMRs and the most relevant gap in knowledge".

The rest of the paper is structured as follows: section 2 presents the methodology used to conduct the SLR; section 3 summarises "*what we know*" and "*what we do not know*" about SMR economics and finance, suggesting a research agenda; section 4 concludes the paper.

2. Methodology

This paper provides an SLR combining the methodologies detailed in Refs. [23,24]. The selection process of the documents includes two sections. Section A deals with documents extracted from the scientific search engine Scopus, and section B deals with reports published by key stakeholders (e.g. International Atomic Energy Agency).

Section A has three main stages. The first stage is the identification of relevant keywords related to the research objective. Several discussions with experts and several iterations led to this list:

- SMRs: "*small modular reactor*", "*small medium reactor*".
- Economics and finance: "*economic*", "*economy*", "*cost*", "*finance*", "*financing*".
- Construction: "*construction*", "*modularisation*", "*modularization*", "*modularity*", "*fabrication*", "*prefabrication*", "*factory*".
- O&M: "*operation*", "*operating*", "*maintenance*", "*O&M*".
- Decommissioning: "*decommissioning*", "*end of life*", "*shut down*", "*removal*", "*site restoration*", "*dismantling*".

SMR fuel cost is a relatively small percentage of the total cost [19,25], and given the same technology, it is not differentiable between large and small reactors. Therefore, studies about the fuel cost are excluded from the analysis.

In the second stage, strings with the Boolean operator "AND"/"OR" are introduced in Scopus:

1) "*small modular reactor*" OR "*small medium reactor*" AND "*economic*" OR "economy" OR "*cost*" OR "*finance*" OR "*financing*" (search date: 11/01/2019).
2) "*small modular reactor*" OR "*small medium reactor*" AND "*modularization*" OR "*modularisation*" OR "*modularity*" OR "*construction*" OR "*fabrication*" OR "*prefabrication*" OR "*factory*" (search date: January 10, 2019).
3) "*small modular reactor*" OR "*small medium reactor*" AND "*operation*" OR "*operating*" OR "*O&M*" OR "*maintenance*" (search date: 14/01/2019);
4) "*small modular reactor*" OR "*small medium reactor*" AND "*decommissioning*" OR "*end of life*" OR "*shut down*" OR "*removal*" OR "*site restoration*" OR "*dismantling*" (search date: January 10, 2019).

Scopus was chosen because of the scientific merit of the indexed literature. A timeframe was not selected a priori because all the documents have been published after 2004 (therefore it is 2004–2019). The selection step used the aforementioned strings (applied to title, abstract or keywords) and retrieved 763 documents (excluding 14 non-English documents).

The third stage is the filtering characterised by the following two steps:

1) A careful reading of the title and abstract of each document to filter out documents not related to the research objective or duplication.

After the first step, 640 documents were removed leaving 123 documents.

2) A careful reading of the introduction and conclusion of the 123 documents retrieved after the first step to filter out documents not related to the research objective. After the second step, 58 documents were removed, leaving 65 documents.

The distribution of the final retrieved documents is:

- SMR Economics and finance: 46 documents;
- SMR Construction: 14 documents;
- SMR O&M: 3 documents;
- SMR Decommissioning: 2 documents.

Considering the overlap of the documents (i.e. some documents are related to more than one search string), the total number of documents to be analysed is 52 (see the list in Appendix 1). Fig. 1 summarises the selection process for section A.

In the selection process for section B, the documents were searched specifically on the IAEA (International Atomic Energy Agency) and NEA (Nuclear Energy Agency) websites (section: publications) excluding non-serial publications (i.e. lecture notes). IAEA and NEA were selected because they are two leading organisations in the nuclear field and publish high-quality reports. Three keywords related to SMRs were used to search documents: "SMR", "Small" and "Modular" (search date: March 22, 2019).

The distribution of the retrieved documents is:

- "SMR": 5 (4 IAEA documents and 1 NEA document);
- "Small": 136 (129 IAEA documents and 7 NEA documents);
- "Modular": 13 (11 IAEA documents and 2 NEA documents).

The filtering stage has the same two steps of section A. Fig. 2 shows the results.

After the check for duplication, four documents are related to the research objective: [26–28], and [29].

Following discussions with stakeholders, other five documents were added: [30–33], and [34].

Most of the selected documents are published in journals (45.9%), and nine documents (14.75%) are published by organisations/companies/working groups. The remaining ones are conference papers: ICONE[1] (16.39%), ICAPP[2] (13.11%), SMR[3] (4.92%), ASEE[4] (1.64%), ICST[5] (1.64%), and one book (1.64%).

The research objective "to identify the state-of-the-art about economics and finance of land-based SMRs and the most relevant gap in knowledge" determined the choice of information to retrieve from the selected documents. The main themes that emerged from the analysis of the selected documents determined the organisation of the information in the following sections.

3. Economics and finance of SMRs

3.1. *Introduction to the terms used in this paper*

This section provides a brief overview of the terms mainly used in the next sections.

[1] International Conference on Nuclear Engineering.

[2] International Congress on Advances in Nuclear Power Plants.

[3] ASME Small Modular Reactors Symposium.

[4] International Conference on Advances in Energy Systems and Environmental Engineering.

[5] International Conference on Science and Technology.

3.1.1. *Life-cycle costs*

In the nuclear sector, the life-cycle costs (or generation costs) are commonly divided into four groups: capital cost, operation and maintenance costs, fuel cost, and decommissioning cost [9].

3.1.1.1. *Capital cost.* Capital cost is the sum of the "overnight capital cost" and the Interest During Construction (IDC) [35]. [10] defines the "overnight capital cost" as "*the base construction cost plus applicable owner's cost, contingency, and first core costs. It is referred to as an overnight cost in the sense that time value costs (IDC) are not included*" (Page 25). [10] defines the "base construction cost" as "*the most likely plant construction cost based on the direct and indirect costs only*" (Page 19). Examples of owner's cost are land, site works, project management, administration and associated buildings [36]. Capital cost represents the biggest percentage of the life-cycle cost of a nuclear power plant, and typical values are in the region of 50–75% [8].

3.1.1.2. *Operation and maintenance costs.* Operation and maintenance (O&M) costs are the costs needed for the operation and maintenance of an NPP [37]. O&M costs include "*all non-fuel costs, such as costs of plant staffing, consumable operating materials (worn parts) and equipment, repair and interim replacements, purchased services, and nuclear insurance. They also include taxes and fees, decommissioning allowances, and miscellaneous costs*" [10] (Page 33).

3.1.1.3. *Fuel cost.* The fuel cost is the sum of all activities related to the nuclear fuel cycle, from mining the uranium ore to the final high-level waste disposal [38]. Examples of activities related to the nuclear fuel cycle are the enrichment of uranium, manufacture of nuclear fuel, reprocessing of spent fuel, and any related research activities [39].

3.1.1.4. *Decommissioning cost.* The decommissioning cost includes: "*all activities, starting from planning for decommissioning, the transition phase (from shutdown to decommissioning), performing the decontamination and dismantling and management of the resulting waste, up to the final remediation of the site*" [40] (Page 6).

3.1.2. *Indicators of economic and financial performance*

3.1.2.1. *Levelised unit of electricity cost/Levelised Cost of Electricity.* The levelized cost of the electricity for a power plant is usually termed "Levelised Unit Electricity Cost" (LUEC) or "Levelised Cost of Electricity (LCOE)"; it is one of the main indicators for policymakers. This indicator accounts for all the life cycle costs and is expressed in terms of energy currency, typically [$/kWh] [9,41,42].

3.1.2.2. *Net Present Value and Internal Rate of Return.* The most popular indicators to investigate the profitability of investing in a nuclear power plant are the Net Present Value (NPV) and the Internal Rate of Return (IRR) [9]. NPV measures the absolute profitability [$] and uses a discount factor to weight "present cost" versus the "future revenue" [43]. The discount factor depends on the source of financing and for many practical applications can be intended as the Weighted Average Cost of Capital (WACC). A low WACC gives similar weighting to present cost and future revenue (promoting capital-intensive plants, like NPP), while high WACC is weighted more towards the present cost respect to future revenues (promoting low capital cost solutions like gas plants). The IRR is a "specific dimensionless indicator", i.e. the value of WACC that brings the NPV to zero. The greater the IRR, the higher is the profitability of the investment [9,44].

3.2. *What we know*

3.2.1. *Factors to be considered in the evaluation of SMR competitiveness*

This section summarises the key factors in the evaluation of SMR

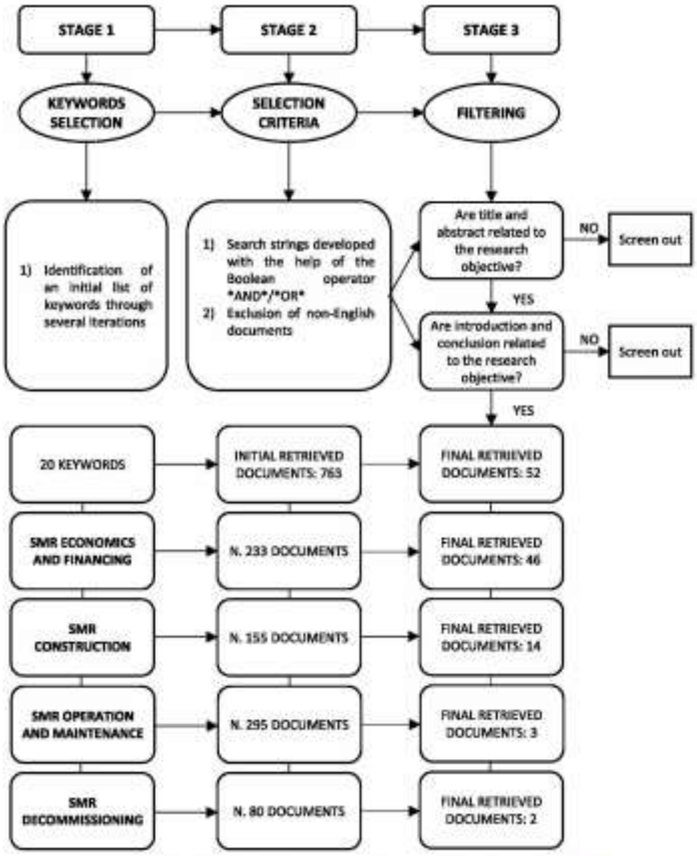


Fig. 1. Section A of the selection process - Framework adapted from Ref. [23].

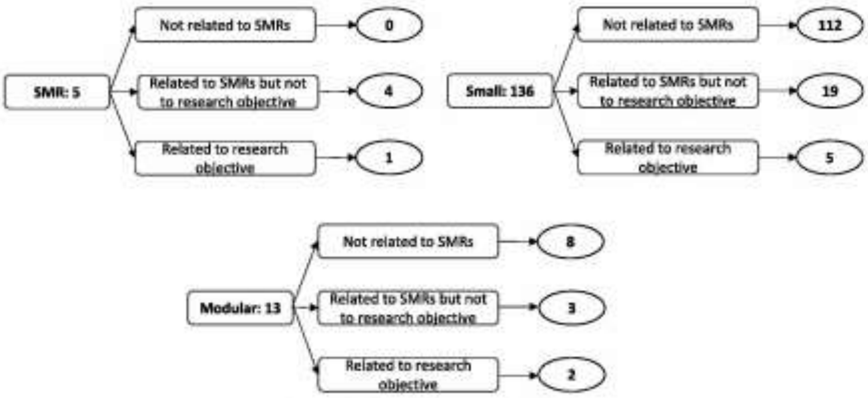


Fig. 2. Results of the filtering stage (Section B).

economic and financial competitiveness, providing qualitative and quantitative information about the impact of these factors.

3.2.1.1. Size. SMR size is frequently considered as a disadvantage for SMRs with respect to LRs [6–9]. Size is related to the "economy of scale" principle. In general, the economy of scale is the cost advantage determined by the spreading of both fixed and variable costs over a larger volume of production [45]. In particular [46], point out how the overnight capital costs and the size (small and large in MWe) of reactors with similar design and characteristics are related:

$$OCC_{small} = OCC_{large} \times \left(Size_{small}/Size_{large}\right)^{n} \quad (1)$$

where n is the scaling factor, and OCC is the Overnight Capital Cost [46]. point out that the cost decreases between 20% and 35% by doubling of the reactor size. Indeed, according to several studies, SMR capital cost is dramatically higher (up to 70%) than the LR one if only the factor size is considered [7,47,48]. The lack of the economy of scale determines higher O&M costs [31,33] and decommissioning cost. Therefore, SMRs might not be seen as competitive with respect to LRs because of an inappropriate interpretation of the economy of scale principle. Indeed, the economy of scale principle cannot be directly applied into the investment analysis of SMRs vs LRs because it relies upon the clause "*other things being equal*", remarkably comparing one small plant with one large plant having the same design [9]. By contrast, SMRs exhibit several unique benefits related to having, for the same power installed, multiple units (fostering learning, co-siting economies, etc.) and different design solutions. These factors, analysed in details in the following sections, can reduce the gap of the economy of scale [7].

3.2.1.2. Modularisation and modularity. One of the main characteristics of SMRs, as their name emphasises, is the "modular construction". It is often called indifferently "modularisation" or "modularity" both in the scientific and industrial literature. However [33], define modularisation as a "*way of simplifying construction by splitting the plant up into packages (modules) which can be factory manufactured, transported to site and assembled in situ, (or close by in an assembly area before being installed)*" (Page 20). On the other hand [49], state: "*the arrangement in which a large capacity power plant is built by assembly of several independent and identical reactors of small capacity is also referred to as "modularity" by GIF (EMWG, 2005)*" (Page 5). This section is based on these two definitions. Fig. 3 further clarifies the definition of modularisation and modularity, also highlighting the meaning of stick-built and pure standardisation.

The key aspects of modularisation are:

- Factory fabrication allows working in a better-controlled environment determining a quality improvement. This allows increasing the quality of the components (reducing mistakes in construction, reworks etc.), reducing construction schedule, reducing maintenance cost because of a reduction of the probability of failure of components, and having a safer construction process [8,11,12]. A great percentage of factory fabrication also improves workers' safety on-site because they handle a smaller number of components [13]. Factory fabrication could determine a cost-saving in labour and construction. By contrast, the supply chain start-up cost is expected to be very high [31].
- Standardisation and design simplification increase efficiency in construction, operation and decommissioning. Standardisation reduces the construction time variability, and the testing and maintenance activities [13,14].
- The expected higher cost of transportation activities is one of the disadvantages of modularisation [8,31,50]. However, for smaller plants like SMRs, modularised components are envisaged to be transported by truck or rail, determining a less vulnerability to delays [13]. Furthermore, modularisation determines an increase in project management effort [8]. Accurate communication between suppliers and contractors is essential to ensure the synchrony of the shipments [8].
- The economic viability is one of the challenges of modularisation and requires research and international collaboration to quantify it [14]. [50] report several examples of cost reduction (an average of 15%) and schedule saving (an average of 37.7%) determined by the

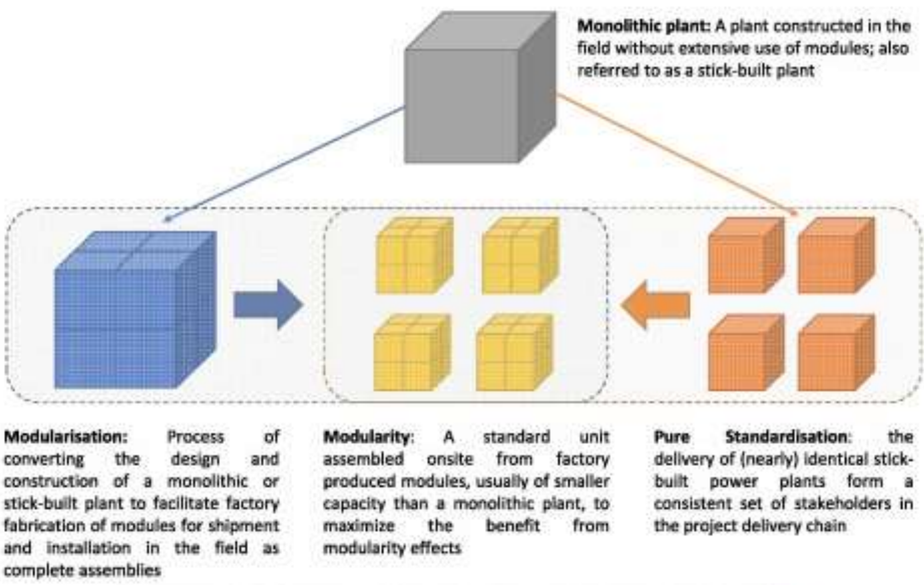


Fig. 3. Meaning of modularisation, modularity, standardisation, stick-built -Text adapted from Ref. [10].

transition from the stick-built construction to modularisation in infrastructure.

- There is a minimum number of SMRs at a certain selling price to recover the cost of setting up a supply chain for modular components. In particular, in the case of 180 MWe SMRs and a factory with $1 billion fixed costs, the selling price and the number of orders should be respectively $1.5 billion and 4 to recover the factory cost [12].
- The impact of modularisation on SMR capital cost depends on the degree of modularisation. [51] evaluate the impact of modularisation on three construction strategies. The analysis shows a capital cost (15% discount rate) saving of 39% for a "complete modularisation", and of 11% for a "lesser degree of modularisation" with respect to the "stick-built" strategy. Furthermore, [11] carry out the same analysis but with a 10% discount rate showing a 29.95% capital cost reduction in the case of "complete modularisation". [52] extend the analysis showing a capital cost reduction of 18% determined by the factory fabrication of the super modules. [53] analyse the impact of modularisation on SMR capital cost, highlighting how a 60% degree of modularisation is necessary to obtain a significant construction cost reduction.
- Modularisation allows performing functional and system-testing activities during the fabrication and assembly stage, determining a higher level of parallelism and, therefore, a shorter time [54].
- Modularisation could reduce construction time. [15] evaluate the impact of the modularisation on the SMR construction time, showing that if the maximum (66%) effective modularisation is applied to the full SMR power plant, the expected SMR construction time could reduce from 5 years to 42–48 months.
- A plant layout simplification and a plant design "ad hoc" is necessary to obtain the expected advantages of modularisation [8]. [55] provide an optimisation model for module layout and allocation within an NPP.
- [56] point out seven steps to follow in a modularisation design process: 1) Assess project applicability; 2) Define built strategy, supply chain, transport and logistic requirements; 3) Define the configurations of the modules breaking down the system and classifying modules; 4) Optimise breakdown of the systems in order to optimise cost and buildability; 5) Definition of the interfaces; 6) Definition of design tools (e.g. CAD, BIM); and 7) Definition of the equipment layout.

The main consequences "strictly" related to modularity translate into several factors to consider in the evaluation of SMR competitiveness with respect to LRs:

3.2.1.3. Incremental capacity addition and the possibility of a gradual shutdown. The incremental capacity addition of SMRs determines a favourable cash flow profile than an LR because the first SMR starts generating revenue while the other SMRs could be still in construction [9]. The incremental capacity addition allows using the revenue generated by this first unit(s) for the reduction of the up-front investment (therefore a lower capital at risk) and the need for loans. Furthermore, the incremental capacity addition allows the investment scalability (considering a relatively constant rate of demand growth) and a reduction of the exposure to external delay events [17,18]. SMRs also present the possibility of a gradual shutdown of some modules which could be applied when electricity price decreases, improving SMR economics [57]. However, this latter aspect is controversial since virtually all the costs of a nuclear power plant are either sunk (e.g. capital cost) or fixed (e.g. salaries), therefore there is little or no saving in reducing the power output.

3.2.1.4. Co-siting economies. Co-siting economies (i.e. having multiple units in the same site) is one of the SMR advantages with respect to LRs. Certain fixed indivisible costs (e.g. licences, insurances, human resources, evacuation plans) can be saved when installing the second and subsequent units [7,12,17,18]. Therefore, the larger the number of NPP co-sited units, the smaller the costs for each unit [58]. The merit of the co-siting economies is confirmed by Ref. [30], which point out an expected capital cost saving per unit of 10–25%.

The sharing of personnel and spare parts across multiple units, and the possibility to share the upgrades on multiple units (e.g. software upgrading) could reduce the operational costs [7,59]. More units at the same site also have an impact on the decommissioning cost, determining a cost saving of 22% in the case of 4 SMRs vs 1 LR [58]. The key point is that also more than one LRs can be built on the same site, but again, considering the same power installed, more SMRs than LRs are built still having greater saving from co-siting economies [18].

3.2.1.5. Cogeneration and load following. SMRs are more suitable for cogeneration than LRs because it is possible to switch some of the SMRs for the cogeneration, and, consequently, SMRs can run at the full nominal power and maximum conversion efficiency [60]. [19,60] provide an overview of the challenges and opportunities related to cogeneration for the load following of NPPs, highlighting how the SMR technologies are particularly suitable for: district heating, desalination, and hydrogen production.

[61] analyse the load following of SMRs by cogeneration of hydrogen, providing an assessment of the technical and economic feasibility with three technologies: Alkaline Water Electrolysis, High-Temperature Steam Electrolysis, and Sulphur-Iodine thermochemical. The first technology is technically feasible, and the investment can be profitable depending on the hydrogen and electricity price (hydrogen price $\geq$0.40 €/Nm^3 and the electricity price relatively low). Regarding the second technology, the coupling with a Light Water Reactor SMR might be challenging because of the different temperature between the steam produced and the cogeneration process requirements. This coupling becomes profitable when the hydrogen price is in the range of 0.30–0.45 €/Nm^3 or above. Regarding the third technology, the coupling with a High-Temperature Gas Reactor SMR is possible, but it is infeasible for the coupling with a Light Water Reactor SMR. This coupling results very profitably as far as the hydrogen price reaches 0.30 €/Nm^3.

[62,63] analyse the coupling of a "NuScale" SMR plant with different desalination technologies, and [25] carry out a real options analysis to demonstrate the economic viability of coupling an SMR (IRIS) plant with a desalination plant. Both analyses show how the coupling is easy and effective. [64] analyse the coupling of six "SMART" reactors with desalination plants in Indonesia. The analysis shows a rate of return of 11% and a Payback Period (PP) of around 14.7 years. Furthermore, [65] evaluate a combination of an off-shore wind farm and an SMR operating as a virtual power plant. A key result of the study is that the combination of a wind farm and SMR in demand-following mode might improve the synchronisation with demand up to 60–70% with respect to the wind-only system.

Next sections summarise other factors to consider in the evaluation of SMR competitiveness: learning, construction time, design, cost uncertainties, adaptability to market conditions, availability, licensing time, capacity factor, and the possibility of nuclear power plant construction.

3.2.1.6. Learning. [33] explains the learning rate is: "*A progressive increase in efficiency and effectiveness can be achieved by building experience and learning how to perform a process and use tools to deliver a product. The learning rate is the cost reduction realised in this way, for every cumulative doubling of production*". Since more SMRs than LRs are built for the same power installed, stronger and faster learning is expected. The expected learning rate of the SMR industry ranges between 5% and 10% (with a proportion of factory fabrication of 45–60%) [33]. This range is consistent with the 8% considered by Ref. [7] in the comparison 4 SMRs vs 1 LR. [32] points out that a 10% cost reduction is achievable for every doubling of volume (with a proportion of factory fabrication of 30%). Learning rate increases through modularisation and factory fabrication, high production rates, standardisation of design, the achievement of best practice by the workforce (both on the same site and in the factory), a consistent delivery chain, in a stable regulatory environment [9,17,33]. As highlighted by Ref. [66], the learning curve generally flattens out after 5–7 units. [6] agree with this view by pointing out that at least 5–7 SMR units are needed to exploit learning from factory fabrication fully.

[9] highlight the difference between "worldwide learning" and "on-site learning". The first is independent of where the units are built, and it is mostly related to the vendor and contractors shared across the various projects, while the construction of successive units at the same site determines the second and it is mostly related to local/national stakeholders. Learning can provide a huge advantage to SMRs. However, the learning factor is "time-dependent", which means that after a certain time, the experience accumulated will not determine relevant construction saving [18]. [67] present a model to assess how the supply chain structure influences the SMR production learning in factories and the consequent capital cost saving.

3.2.1.7. Construction time. SMRs could solve one of the key issues in the nuclear industry: the long construction time. The long construction time is a key issue in the nuclear sector for several reasons. For instance:

- Thousands of workers and the utilisation of expensive equipment (e.g. cranes) determine high fixed costs for each working day [9];
- The postponing of cash in-flow increases the interest to be paid on the debt [9];
- The present value of future cash flow decreases exponentially with time [9];
- Possible scope changes due to changes in legislation (e.g. post-Fukushima accident);
- Price of commodities could increase.

SMRs have an expected shorter construction schedule than LRs [33,68]. The SMR expected schedule is 4/5 years for the FOAK (First-of-a-kind) and 3/4 years for the NOAK (nth-of-a-kind), instead of the six years (or more) for LRs [33,69]. SMR schedule reduction is determined by smaller size, simpler design, increased modularisation, a large fraction of components produced in a factory, serial fabrication of components and standardisation [47,69].

Three key consequences of the schedule reduction are:

1) reduction of the time to market [68];
2) reduction of the interest during construction [70];
3) possibility to match demand growth [9].

[7] estimate a capital cost saving of 6% determined by the shorter construction schedule coupled with the capability of better following the demand, and [30] points out a capital cost saving estimated by SMR vendors of 20% determined by the shorter construction schedule. [15] present a methodology to forecast SMR construction schedule starting from a built LR. Furthermore, SMRs could present a reduction of schedule risks with respect to LRs [12].

3.2.1.8. Design. SMR design could determine a cost-saving with respect to LRs [17]. Design simplification in some SMRs could be achieved through "*broader incorporation of size-specific inherent safety features that would not be possible for large reactors*" [30] (Page 149). The SMR integral (major primary system components inside the reactor vessel eliminating the external piping) and modular approach simplify the plant leading to a reduction of the number and type of components [9]. For instance, the design-related characteristics of the "IRIS" SMR with respect to GEN III + reactor (e.g. elimination of the pressuriser, steam generator pressure vessels, high-pressure injection emergency core cooling system) might determine a 17% capital cost saving [7]. Furthermore, designers estimate a capital cost reduction determined by design simplification of 15% for PWR SMRs [30], and [18] highlight other saving determined by the smaller quantity of material (e.g. concrete, steel) used with respect to LRs. By contrast, [31] points out that the cost-saving is counterbalanced by the expected higher cost for validating and testing the new technology.

3.2.1.9. The cost uncertainties related to the FOAK. The cost uncertainty related to a FOAK Generation III + LR is lower with respect to a FOAK SMR because there are already several Generation III + LRs operating or under construction. In the evaluation of the uncertainties related to the investment cost for the installation of a certain amount of MWe, the investor should consider both the option of one LR (e.g. 1340 MWe) and the option of several SMRs (e.g. four of 335 MWe). The uncertainty associated with the first unit is greater in the second option, but the average uncertainty is potentially smaller for the SMRs [71]. [72] provide an overview of the cost uncertainties related to the SMR early design stage.

3.2.1.10. Adaptability to market conditions. SMRs are more adaptable to market conditions than LRs. SMRs have an expected shorter construction time allowing splitting the investment according to the market evolution and avoiding it if not needed [18]. The capability to better adapt to market conditions minimises also the cost of "not satisfied demands", which is obtained "*by multiplying the margin for the investor in the plant i at the time with the potential market for the plant i at the time t*" [20] (Page 5).

3.2.1.11. Availability. [7] point out that SMRs present a fuel cycle extension (from 18-24 months of the existing plants to 36–40 months) determining a 2–5% capital cost saving and a 3% O&M annual cost saving. Furthermore, some SMR units can be refuelled while the remaining ones are still in operation [12]. Therefore, two main considerations can be argued:

- SMR plant has a higher availability with respect to LR because of the fuel cycle extension; the fuel cycle extension also increases the "overall" availability.
- Considering an amount of reserves equal to the sum of the two largest generating units [73] and the possibility to refuel more SMR units while the remaining ones are still in operations [12], SMRs improve the overall availability because, in contrast to LR, the amount of reserves does not change increasing the overall plant availability.

3.2.1.12. Licensing time. The licencing time influences the time to market and, therefore, the competitiveness of SMRs. It is worth to clarify that there is a difference between design, construction and operation licensing, as shown in Ref. [20]. The information about SMR licensing time in the retrieved document mainly focuses on the design licensing time, and it is controversial. According to Ref. [20], considering the same licensing time for the LR and the first SMR, the licensing time for the following SMRs will be shorter because the design is identical to the first one, allowing a better time to market. However, [6] state that the licensing is one of the SMR challenges because of the difficulty of modifying the actual regulatory and legal framework, and [31] 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.

3.2.1.13. The possibility of NPP construction. Firstly, SMRs are suitable for small, remote or isolated areas where the power provided by LRs is not needed or the grid connection is not able to reliably handle so much power [13,30,74]. Secondly, SMR size allows incremental investment eliminating the huge financial resources needed for LRs and the associated financial risk [8,75]. These two SMR characteristics determine an expected increased possibility of NPP construction. In particular, [76] evaluate the SMR economic feasibility in three small islands (Jeju, Tasmania and Tenerife) in different generation mix scenarios. SMR results competitive in the case of an average generation cost <100 $/MWh for Jeju, <140 $/MWh for Tenerife, and <80 $/MWh for Tasmania.

3.2.1.14. Capacity factor. The capacity factor is "*the actual energy output of an electricity-generating device divided by the energy output that would be produced if it operated at its rated power output (Reference Unit Power) for the entire year*" [77]. A high capacity factor dramatically improves the economics of the plant. Indeed, according to Ref. [78], the capacity factor (in the paper availability) is the third most relevant driver of SMR and LR economics. Refuelling, unplanned shutdown, planned maintenance, and load following are key drivers of the capacity factor [33]. [79] evaluates SMR competitiveness in four scenarios. A key conclusion of the study is that an SMR capacity factor equal to or higher than current light water reactors is a key condition for SMR competitiveness. SMR vendors claim a capacity factor of 95% or more for their SMR. Operational learning (determined through familiarity with the designs and consistency of operations) might improve SMR capacity factors [33, 80]. Furthermore, since SMRs might have a simpler design and fewer components than LRs, there would be fewer chances of failure for components or systems [33].

3.2.2. Studies about SMR capital cost

Most of the quantitative studies about SMR life-cycle costs focus on SMR Capital Cost (CC) or components and sub-components of SMR CC (i. e. overnight cost, base construction cost). This section provides a summary and compares the quantitative information.

3.2.2.1. Journal/conference papers. Most of the studies focusing on SMR CC and its components and subcomponents retrieved from journal or conference papers highlight how the economic comparison SMR vs LR is strictly dependent on the factors considered in the analysis. In particular, [7] compare four 335 MWe SMRs (IRIS) and one 1340 MWe Generation III + PWR. SMR CC is 70% greater, considering only the factor size. Considering cost reduction determined by multiple units at a single site (14%), learning (8%), construction schedule (6%), and related design characteristics (17%), SMR CC is 5% higher.

Regarding the impact of the economy of multiples on the CC, [48,70] evaluate the opportunity to invest in SMRs or LRs in Italy and Switzerland. Both analyses show an SMR CC higher than the LR one, as shown in Fig. 5. However, both analyses highlight the merit of the economy of multiples in reducing the gap. [81] assesses the opportunity to invest in SMRs vs LRs in three different scenarios in India: 1) Total power output: 600–675 MWe, 2) Total power output: 1100–1350 MWe, and 3) Total power output: 2200–2500 MWe), and with different reactors to reach the total power output. The analysis highlights that the SMR and LR overall capital expenditure are comparable.

Regarding SMR Overnight Cost (OVC) [69], estimate a 225 MWe SMR OVC in different scenarios, highlighting the impact of the design simplification and the learning effect, and demonstrating the potential benefits of the co-siting economies, as shown in Fig. 5. [82] interviewed 16 experts from the nuclear industry or closely associated about the expected OVC of five scenarios including one GEN III + LR (1000 MWe) and two integral LW-SMRs (45 MWe, 225 MWe). The results highlight the merit of the co-siting economies in reducing the SMR OVC.

Regarding the base construction cost (BCC), [83] estimate and compare the NuScale SMR (12 modules of 57 MWe each) BCC and the PWR-12 BCC. The analysis shows a NuScale SMR BCC = 3465.72 $/kWe, and a PWR-12 BBC = 5887.12 $/kWe, determining a difference of 2421.42 $/kWe.

In summary, considering only the factor size in the economic comparison SMR vs LR limits the validity of the analysis. Indeed, as shown in section 3.2.1, considering only the factor size would mean applying the economy of scale principle, which relies upon the clause "*other things being equal*" [9]. In turn, this neglects the importance of unique SMR characteristics. The aforementioned studies show that several factors (e. g. economy of multiples, learning, construction schedule, design characteristics, etc.) need to be evaluated and considered. The studies point out the lack of a standardised approach in the evaluation of SMR competitiveness with respect to LRs; each study considers different factors, and the methodology is also often different.

3.2.2.2. Organisation/company documents. [33] highlights that SMR OVC can be reduced up to 20% by the way of: 1) modularisation and factory fabrication, 2) advanced manufacturing, 3) Building Information Modelling (4–10%), 4) advanced construction methods such as open-top construction (up to 2%), and 5) co-siting of multiple reactors (5–14%, considering between 2 and 12 reactors on the same site) [30]. provides several OVC estimations for several SMRs called PWR-X (each PWR-X is based on the characteristics of specific SMR designs), and [31] provides the OVC estimations for several NOAK and country-specific (domestic market) SMR plants.

Fig. 4 shows some of the SMR OVC estimations.

3.2.2.3. Comparisons SMR vs LR OVC. Most of the comparisons for SMRs vs LRs focus on the OVC. Fig. 5 shows some of the comparisons (%)

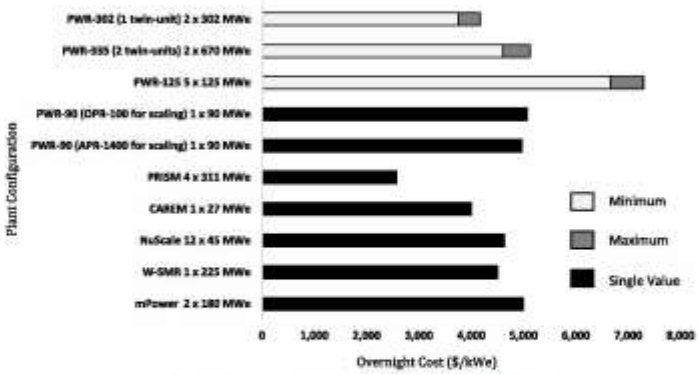
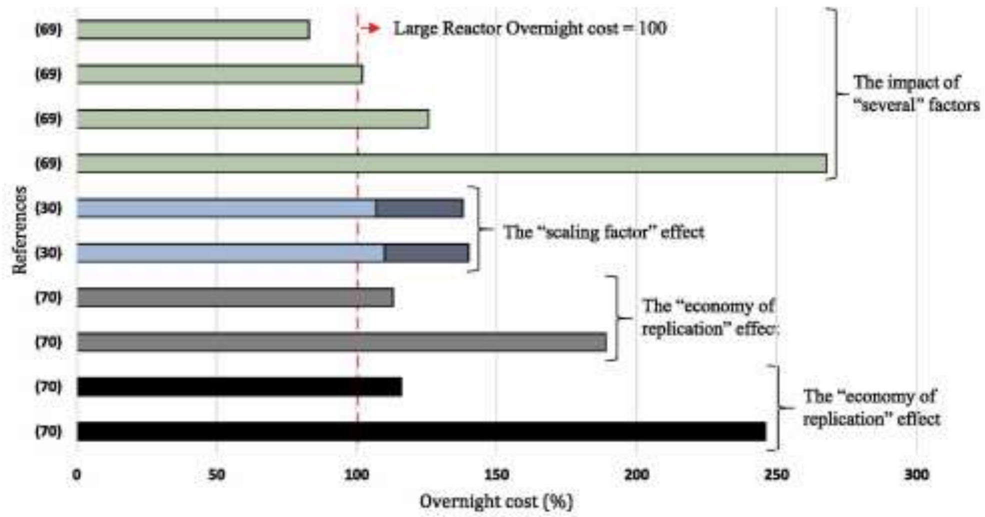


Fig. 4. SMR OVC Estimations - data from Refs. [30,31].



The highest SMR OVC is obtained scaling up from an estimation of an LR OVC without considering other factors. The following OVCs are obtained including the following factors sequentially in the comparison: design simplification and schedule reduction, additional learning determined by factory fabrication that determines a 40% NOAK cost reduction applied to indirect components, contingency, and owner's cost, and the learning curve applied to all components.

Respectively the minimum and the maximum from (30). The analysis highlights how the SMR OVC cost changes according to the different sizes of LR for the scaling up. The highest OVC is obtained scaling up from a 1500 MWe LR, while the lower value from a 1200 MWe LR.

Results by (70) showing how the economy of replication contribute to the reduction of the SMR OVC. The SMR OVC is 146% higher if it is considered only a 1600 MWe LR and a 150 MWe SMR. Considering more SMRs to reach the same total power, the gap is reduced to 16%.

Results by (70) showing how the economy of replication contributes to the reduction of the SMR OVC. The SMR OVC is 89% higher if it is considered only a 1600 MWe LR and a 300 MWe SMR. Considering more SMRs to reach the same total power the gap is reduced to 13%.

Fig. 5. Comparisons SMR vs LR OVC (%).

SMR vs LR OVC considering LR OVC = 100.

3.2.3. Studies about SMR O&M costs

This section summarises the key insights from the few documents focusing on SMR O&M costs.

[7] evaluate and compare the O&M costs of four 335 MWe SMRs (IRIS) and a 1340 MWe LR. Considering only the factor "size", SMR O&M costs are 51% greater. Considering cost reduction determined by multiple units at single sites (15%), additional outage cost (3%), and outage duration (4%), SMR O&M costs are 19% higher [31,33]. point out that SMR O&M costs are expected to be higher with respect to LRs. [31] highlights that the main reason is the loss of the economy of scale. [33] highlights that the co-siting economies might reduce the fixed O&M costs by 10%–20%, and the operational learning (determined through familiarity with the designs and consistency of operations) might further reduce the variable O&M costs (potential saving of 5%).

Furthermore, cost saving in O&M costs can be achieved through the shared control of multi-module reactors determining a reduction of the staffing cost [33]. However, [31] points out an expected SMR staff cost per MWe 40% higher with respect to LRs.

[30] highlights how the expected LUEC share of O&M and fuel costs for SMRs is 17–41%, which is amply below the correspondent of LRs, which is 45–58%.

3.2.4. Studies about SMR decommissioning cost

[58] provide the unique quantitative study about SMR decommissioning in the documents retrieved, comparing one 1340 MWe LR versus four 335 MWe SMRs (IRIS) and two 1340 MWe LRs versus eight 335 MWe SMRs (IRIS). If only the economy of scale is considered, the expected SMR decommissioning cost would be 3.09 times higher, both in the case of immediate and deferred decommissioning. Considering both the saving determined by multiples units at the same site and the technical saving, the gap is reduced but with a major impact in the case of "2 LRs vs 8 SMRs". However, SMR decommissioning is expected to be easier with respect to LRs because the modules can be replaced and disassembled in factory conditions [6]. [47] points out that the possibility of SMR immediate decommissioning determines a cost saving of 13%, and a cluster decommissioning is 20% cheaper than a unit is.

3.2.5. Indicators of economic and financial performance

Fig. 6, Fig. 7, and Fig. 8 summarise respectively the main quantitative information about SMR LCOE, SMR NPV and SMR IRR estimations.

3.2.6. Additional considerations about SMR investment

[71] shows that SMRs present an average debt lower than LRs but with a longer duration. SMRs also present an equity capital required lower than the LR. These two considerations are consistent with the results of the analysis carried out by Ref. [70] in the specific case of Italy.

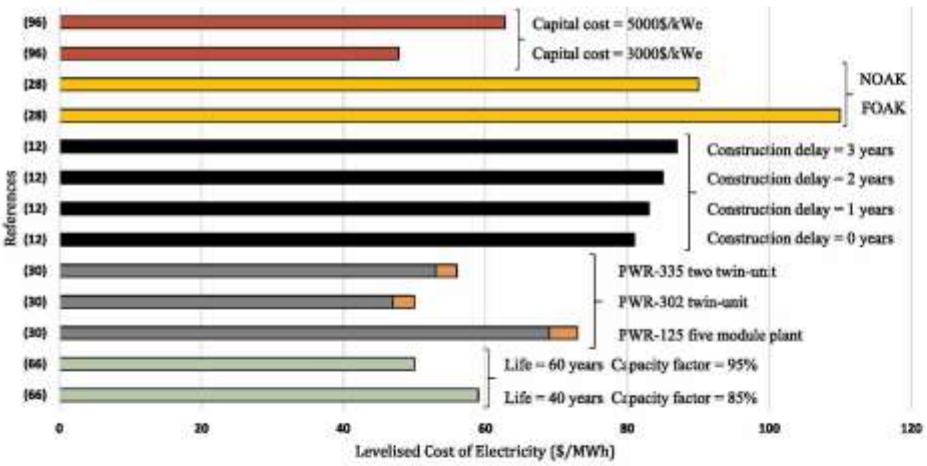


Fig. 6. SMR LCOE Estimations.

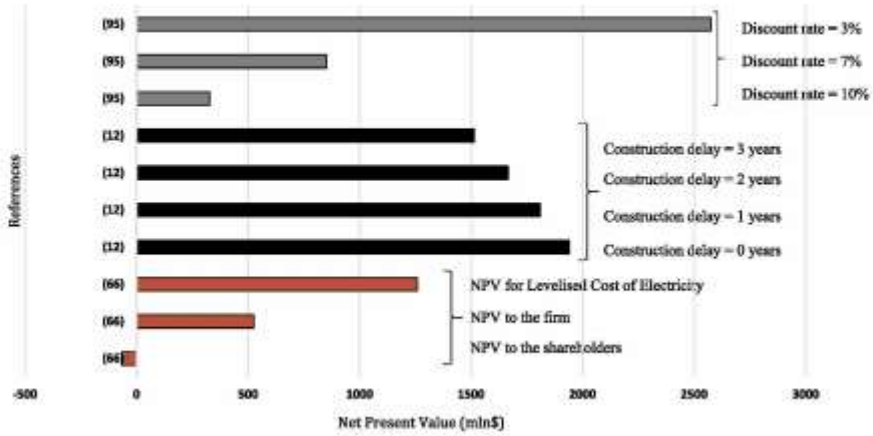


Fig. 7. SMR NPV Estimations.

[84] analyse the value of the management's flexibility to adapt later decision, comparing the investment profitability of 4 SMRs vs 1 LR on the same site both using the Real Options Analysis and the Discounted Cash Flow methodology. The results show that the managerial flexibility has a value, and it is higher in an SMR project (more options to take advantage) than in an LR project. However, profitability is higher for an LR project. Regarding the PP, [12] compare a 1260 MWe LR and a multimodule (1–7) SMR (180MWe) site, highlighting how the LR PP is less than the SMR one considering a staggered SMR schedule. However, considering an SMR simultaneous construction, the PP is similar. Furthermore, SMRs smaller size and relatively short construction time allow a better diversification of the investment. [68] present a model based on Real Options Analysis allowing quantitative evaluation of these two factors.

3.3. *What we do not know: a research agenda*

This chapter proposes a research agenda for further research on the economics and finance of SMRs, with the items ranked according to their relative importance. The items and the ranking of the agenda are based on the aforementioned SLR and countless meetings that the authors had in the last 14 years with SMR vendors, contractors, policymakers, utilities, government and financers.

3.3.1. *Performing analysis at programme/country level*

The body of literature focuses mostly on analysis at the plant-level (1 SMR vs 1 LR) or site-level (X SMRs vs 1 LR of equivalent total size). However, as shown in Ref. [59], the focus at the programme level is a major determinant. For instance, the "successful nuclear programme" in South Korea is mostly due to an approach at "programme level" [80], instead of a "plant-level" like in USA or "site-level" like in France [85].

A topic even less discussed, but still critical is the interdependency

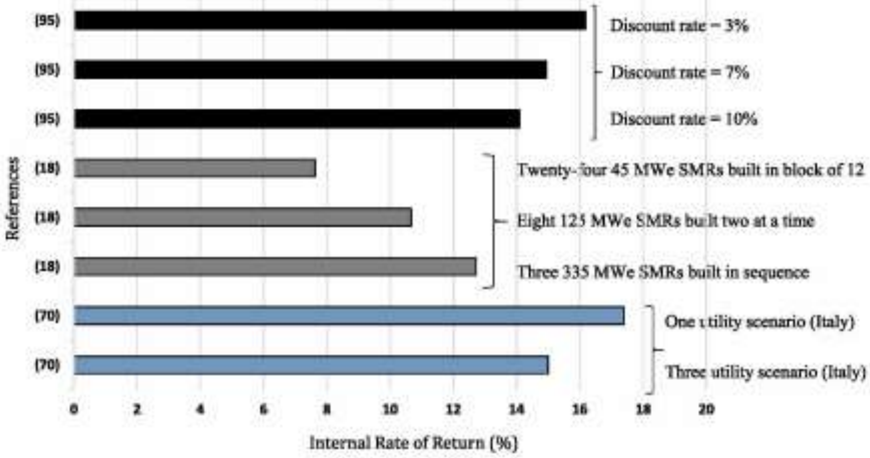


Fig. 8. SMR IRR Estimations.

between the programme and the strategy adopted by each country. Indeed, a key aspect for SMRs is the modularisation and, consequently, the factory fabrication of modules [50]. Therefore, a certain country might face a range of choices, e.g.

1) Develop SMR design and build the supply chain and the reactors in its own country, aiming to export the technology. The advantages are the creation of know-how, scientific development, and improvement of the import-export balance. The disadvantages are a high level of risk, the necessity to use relevant economic and financial resources, and longer lead time;
2) Import a proved reactor design (or in an extreme case, import the modules) from other countries. The main advantages, in this case, are: less risk upfront to develop the technology and shorter lead-time. The disadvantages are a reduced development of know-how and national capabilities, worsening of the import-export balance, and risky dependence on resources outside the country.

Several factors might push in a direction with respect to another: experience in building and operating nuclear reactors, availability of potential suppliers, finance available, electricity market structure, and regulatory regime etc. However, a comprehensive review of all these aspects and an overall framework to integrate them are not available.

3.3.2. *Exploring different financing mechanisms and their implications*

Financing is a critical issue for SMRs. Indeed, SMRs are scalable investments, with the cost of a single SMR being substantially less than a single LR. However, given a certain identical total power to be installed overall, the overall cost of a programme is similar for SMRs and LRs [78], ranging in the decades of billions of dollars. The financing of an SMR programme is a key issue for several countries, and different options are considered [34]. Financing is challenging because nuclear power plant projects are well known to be often delivered over budget and late (particularly in the EU and USA) [59], and therefore, investors lack confidence. Investing in nuclear project and programme is extremely risky, project financing is not applied like in other energy infrastructure [86], and several stakeholders are reluctant to do it. SMRs have pros and cons in this perspective. The pros are that the single investment has less "value at risk" than a large investment. This is particularly relevant for FOAK project, where the money is "gambled" on a much smaller investment. Furthermore, the fact that, for the same power installed, more units are installed, create more degrees of freedom. The cons are that there is now considerable experience in building LRs, even modern GENIII and GENIII+ (such as AP1000, EPR etc.) while virtually none in building modern "truly modular" SMRs, and there is a consistent upfront investment in building the factories producing the modules. [34] is the only published documents providing pros and cons of several financing structures for SMR development (in the specific case of the United Kingdom). Financing is an essential element because, as bankers say, if there is no financing, there is not project and needs further research.

3.3.3. *Develop a better understanding of O&M and decommissioning costs*

As also said in the above discussion, the number of studies related to O&M and particularly decommissioning costs is extremely low. O&M and decommissioning costs are traditionally believed, in the nuclear industry, to be a relatively small percentage of the life-cycle cost [87]. However, this idea could be empirically challenged. Regarding O&M costs, several reactors in the USA have been closed in recent years because the electricity price was so low to not even cover the O&M costs [88]. Regarding decommissioning, the cost keeps increasing, the projects are often over budget, and the stakeholders have limited understanding of why this happens [89]. More studies about O&M and decommissioning costs are needed before embarking in the construction.

3.3.4. *Explore the link between modularisation and circular economy*

Building on the previous point about decommissioning, there is the highly relevant and unexplored topic of "circular economy". According to Ref. [90]: "*The basic idea of the Circular economy 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*". In the case of nuclear power plants, this includes a range of solutions including recycling and reusing of components and systems. A key precondition to reap the advantages of modularisation in a "circular economy" perspective is the assessment of the lifecycle options of modules since the concept phase. Further research might investigate to what extent SMRs could leverage their modularisation for decoupling the life-cycle of modules (or systems) from the lifecycle of the plant. In theory, modularisation could reduce the resources needed in construction and waste generated in the deconstruction process.

3.3.5. Define new criteria for the cost-benefit analysis of nuclear reactors

The methodologies for the cost-benefit analysis are often inadequate or incorrectly applied to deal with a nuclear programme. Indeed, the development of a nuclear programme involves a wide range of stakeholders: government (also representing taxpayers), utilities, contractors, regulator(s), financers, local community etc. Indeed, the idea to apply the cost-benefit analysis to infrastructure is not a good idea since the cost-benefit analyses are not perceived at the infrastructure level, but at stakeholder level, where the stakeholders can be an organisation or even persons. Therefore, each stakeholder sees a different cost-benefit analysis that might be extremely positive for some stakeholders and extremely negative for others (and everything in the middle). Furthermore, considering that the entire life cycle of a nuclear infrastructure can be for 100 years, some stakeholders (company and people) are not even existing when the reactor is built. All this considered there is not a single reference providing the cost-benefit analysis of SMRs with respect to LRs or other reactors. There is either a classical cost-benefit analysis (infrastructure level) or an enhanced one (stakeholder level). A proper holistic study is needed.

3.4. Main areas of disagreement

This section provides a summary of the main areas of disagreement emerged from the SLR.

3.4.1. Overall SMR economic competitiveness

As summarised in the previous sections, SMR unique characteristics (factory fabrication, learning, co-siting economies, shorter construction time, etc.) should, in theory, compensate for the lack of the economies of scale and make SMR investment attractive. However, four documents [75,91–93] deny some SMR unique characteristics or even define SMR investment unattractive. According to Ref. [91], each SMR design has specific characteristics, but no one of them presents all the characteristics that should compensate for the lack of the economy of scale. In general, SMRs might reduce the construction cost with respect to LRs, but it is unlikely that SMRs will present a lower cost of generating each unit of electrical energy than LRs. [91] point out how that the SMR competitiveness is even worse if compared to other energy sources (e.g. coal and natural gas-based thermal power). According to Ref. [75], regulators claim an SMR cost (which cost is not specified) 30% higher than LRs. In particular, the expected cost reduction determined by factory fabrication is too optimistic because "mass manufacturing" presents problems in the case of very expensive pieces of equipment in a small number [75]. [75] also points out how challenging and requiring a huge amount of capital is the creation of a massive assembly line. This approach could also hinder competition driving innovation and cost reduction. Another aspect that should be considered in the evaluation of SMR economic competitiveness is that the introduction of new technologies raises the cost significantly.

Furthermore, learning cannot balance the diseconomies of scale because "this has been the case in the past" and because of the "astronomical number" of SMRs needed to benefit from the learning effect [75, 93].

3.4.2. SMR potential market

Although the SMR suitability for small, remote or isolated areas is very often recognised as one of the main SMR characteristics, or even a key advantage for increasing the possibility of NPP construction all over the world, [92,93] strongly deny this point. According to Refs. [13,30, 74], SMR size allows providing power where the bigger power of LRs is not needed, and where the grid connection is not able to reliably handle the power provided by traditional LRs. Furthermore, SMR size allows incremental investment reducing the financial risk and the huge financial resources associated with LRs. Therefore, in theory, Jordan and Ghana could be two good candidates for SMR applications by considering the grids with small capacity and the limited financial resources. However, [93] analyse the suitability of SMRs for Jordan, and point out that "*SMRs are only going to heighten the economic challenge. This problem of SMRs not being economically competitive with large nuclear reactors is, of course, not specific to Jordan*" (Page 241). [92] argue the same considerations in Ghana. Furthermore, [75] argue that there is no reason to believe that SMR characteristics would increase the demand for NPPs. [93] highlight that SMRs increase the need for construction sites considering that more SMRs are needed to obtain the same power of a LR.

4. Conclusions

Not a single "truly modular" SMR has been built so far. Economic and financial reasons are strongly hindering SMR development. However, there are plenty of studies about SMR economics and finance. Through an SLR, this paper aims to provide an overview of what we know and what we do not know about the economics and finance of land-based SMRs, and to suggest a research agenda. Instead of a traditional narrative review, an SLR has been performed to provide a holistic perspective and allow repeatability. One of the limitations of an SLR is the inclusion of papers of different perspectives (still published in respectable journals). Furthermore, more recent papers are, in principle, considered equal to older references that might have less up-to-date information and theories. The exclusion of certain papers because of the authors disagree on or consider too old is an arbitrary choice. The strength of an SLR is the high scientific rigour allowing a full reproducibility of the work. One or more option-based papers leveraging an arbitrary choice of references and data can be considered a follow up from this work.

As highlighted by the words "Small" and "Modular", SMRs present three main peculiarities with respect to large scale traditional reactors: smaller size, modularisation, and modularity. SMR size has three main implications: loss of the "economy of scale", for the same power installed more units can be built fostering phenomenon like the industrial learning, and the reduction of the up-front investment per unit. This latter makes SMR investment particularly attractive considering the multi-billions up-front investment of LRs. Modularisation has several implications: working in a better-controlled environment, standardisation and design simplification, reduction of the construction time, logistical challenges. Modularity allows having a favourable cash flow profile, taking advantage of the co-siting economies, cogeneration for the load following of NPPs, a higher and faster industrial learning, and better adaptability to market conditions. Furthermore, the interest in SMRs is growing because of the different applications: electrical, heat, hydrogen production, and seawater desalination.

The SLR highlights how most of the quantitative studies about SMR economics and finance focus on SMR capital cost, component and sub-components of the capital cost (i.e. overnight cost, base construction cost), indicators of economic and financial performances (LCOE, NPV, IRR). The number of studies focusing on O&M and decommissioning costs is extremely low, and there is a gap in knowledge about the cost-benefit analysis of the "modular construction".

There is a lack of a standardised approach in the evaluation of the economic and financial performances of SMRs, making a proper comparison impossible in most of the cases.

Most of the studies are at plant-level (1 SMR vs 1 LR) or site-level (X SMRs vs 1 LR of equivalent total size), neglecting the focus at the programme-level and the interdependency between the programme and the strategy of each country. Furthermore, most of the methodologies for the cost-benefit analysis are often inadequately applied, by not considering that the development of a nuclear programme involves a wide range of stakeholders.

The SMR world strongly needs a standardised approach at the programme level taking a holistic and realistic perspective in the evaluation of SMR economic and financial competitiveness to foster SMR development.

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 immensely grateful to the ESPRC and MPA. The authors also wish to thank Dr Chun Sing Lai and Mr Ata Babaei that provided substantial feedback. 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 1. Documents retrieved – Part A

Source/Area	SMR Economics and finance	SMR Construction	SMR O&M	SMR Decommissioning
[82] (Abdulla et al., 2013)	X			
[72] (Agar et al., 2018)	X			
[94] (Agar et al., 2019)	X			
[95] (Alonso et al., 2016)	X			
[46] (Aydogan et al., 2015)	X			
[18] (Barenghi et al., 2012)	X			
[83] (Black et al., 2019)	X	X		
[70] (Boarin et al., 2011a)	X			
[48] (Boarin et al., 2011b)	X			
[17] (Boarin and Ricotti, 2014)	X			
[12] (Boldon et al., 2014)	X	X		
[8] (Carelli and Ingersoll, 2014)	X	X	X	
[7] (Carelli et al., 2008)	X		X	
[75] (Cooper, 2014)	X			
[14] (Hidayatullah et al., 2015)	X		X	
[76] (Hong and Brook, 2018)	X			
[62] (Ingersoll et al., 2014a)	X			
[63] (Ingersoll et al., 2014b)	X			
[57] (Liman, 2018)	X			X
[15] (Lloyd and Roulstone, 2018)	X	X		
[53] (Lloyd et al., 2018)	X	X		
[9] (Locatelli et al., 2014)	X			
[60] (Locatelli et al., 2017a)	X			
[61] (Locatelli et al., 2018)	X			
[25] (Locatelli et al., 2015)	X			
[19] (Locatelli et al., 2017b)	X			
[81] (Locatelli et al., 2013a)	X			
[13] (Locatelli et al., 2010)		X		
[84] (Locatelli et al., 2012)	X			
[68] (Locatelli et al., 2017c)	X			
[58] (Locatelli and Mancini, 2010a)				X
[66] (Locatelli and Mancini, 2010b)	X			
[6] (Lokhov et al., 2013)	X			
[67] (Lyons and Roulstone, 2018)	X			
[20] (Mancini et al., 2009)	X			
[52] (Maronati and Petrovic, 2018)	X	X		
[11] (Maronati et al., 2017)	X	X		
[51] (Maronati et al., 2016a)	X	X		
[54] (Maronati et al., 2016b)	X			
[50] (Mignacca et al., 2018)	X	X		
[64] (Oktavian et al., 2018)	X			
[47] (Playbell, 2016)	X			
[91] (Ramana and Mian, 2014)	X			
[93] (Ramana and Ahmad, 2016)	X			
[79] (Shropshire, 2011)	X			
[65] (Shropshire et al., 2012)	X			
[71] (Trianni et al., 2009)	X			
[49] (Upadhyay and Jain, 2016)		X		
[69] (Vegel and Quinn, 2017)	X			
[56] (Wrigley et al., 2018)		X		
[55] (Wrigley et al., 2018b)		X		
[96] (Wyrwa and Suwala, 2017)	X			

References

[1] IAEA. Advances in small modular reactor technology developments. Available from: https://aris.iaea.org/Publications/SMR-Book_2016.pdf; 2016.
[2] Ingersoll DT. Deliberately small reactors and the second nuclear era. Prog Nucl Energy 2009 May;51(4-5):589–603.
[3] IAEA. Advances in small modular reactor technology developments. A supplement to: IAEA advanced reactors information system (ARIS). 2014. Vienna.
[4] Locatelli G, Mancini M, Todeschini N. Generation IV nuclear reactors: current status and future prospects. Energy Policy 2013;61:1503–20.
[5] Karol M, John T, Zhao J. Small and Medium sized Reactors (SMR): a review of technology. Renew Sustain Energy Rev 2015;44:643–56.
[6] Lokhov A, Cameron R, Sozoniuk V. OECD/NEA study on the economics and market of small reactors. In: International congress on Advances in nuclear power plants. Jeju Island, Korea: ICAPP; 2013. 2013.
[7] 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.
[8] Carelli MD, Ingersoll DT. Handbook of small modular nuclear reactors. Woodhead Publishing, Elsevier; 2014. p. 1–536.
[9] 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.
[10] GIF/EMWG. Cost estimating guidelines for generation IV nuclear energy systems. Available from: https://bit.ly/2Q8f4cDe; 2007.
[11] 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.
[12] 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.
[13] Locatelli G, Mancini M, Galli A. Introducing nuclear power plants in an OECD country: size influence on the external factors. In: 18th international conference on nuclear engineering. Xi'an, China: ICONE18; 2010.
[14] Hidayatullah H, Susyadi S, Subki MH. Design and technology development for small modular reactors - safety expectations, prospects and impediments of their deployment. Prog Nucl Energy 2015;79:127–35.
[15] Lloyd CA, Roulstone A. A methodology to determine SMR build schedule and the impact of modularisation. In: 26th international conference on nuclear engineering. London, United Kingdom: ICONE26; 2018. p. 1–8.
[16] GIF/EMWG. Cost estimating guidelines for generation IV nuclear energy systems. Available from: https://www.nrc.gov/docs/ML1408/ML14087A250.pdf; 2006.
[17] Boarin S, Ricotti ME. An evaluation of SMR economic attractiveness. Sci Technol Nucl Install 2014;2014:1–8.
[18] Barenghi S, Boarin S, Ricotti ME. Investment in different sized SMRs: economic evaluation of stochastic scenarios by INCAS code. In: International congress on Advances in nuclear power plants 2012. Chicago, USA: ICAPP 2012; 2012. p. 2783–92.
[19] Locatelli G, Fiordaliso A, Boarin S, Ricotti ME. Cogeneration: an option to facilitate load following in Small Modular Reactors. Prog Nucl Energy 2017;97:153–61.
[20] 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. Brussels, Belgium: ICONE17; 2009.
[21] Investopedia. What is finance? 2019. Available from: https://www.investopedia.com/ask/answers/what-is-finance/.
[22] Ehrhardt B. Financial management: theory and practice. thirteenth ed. South-Western Cengage Learning; 2011 Available from: http://213.55.83.214:8181/Business Ebook/Financial books/Financial_Management_Brigham_13th_Edition.pdf.
[23] Di Maddaloni F, Davis K. The influence of local community stakeholders in megaprojects: rethinking their inclusiveness to improve project performance. Int J Proj Manag 2017;35(8):1537–56.
[24] Sainati T, Locatelli G, Brookes N. Special Purpose Entities in Megaprojects: empty boxes or real companies? Proj Manag J 2017;48(2).
[25] Locatelli G, Boarin S, Pellegrino F, Ricotti ME. Load following with Small Modular Reactors (SMR): a real options analysis. Energy 2015;80:41–54.
[26] IAEA. Status of innovative small and medium sized reactor designs 2005. 2006.
[27] IAEA. Approaches for assessing the economic competitiveness of small and medium sized reactors. Available from: https://bit.ly/2TGZdIt; 2013.
[28] OECD/NEA. Small modular reactors: nuclear energy market potential for near-term deployment. Available from: https://www.oecd-nea.org/ndd/pubs/2016/7213-smrs.pdf; 2016.
[29] IAEA. Deployment indicators for small modular reactors. 2018.
[30] OECD/NEA. Current status , technical feasibility and economics of small nuclear reactors. Available from: https://www.oecd-nea.org/ndd/reports/2011/current-status-small-reactors.pdf; 2011.
[31] UxC Consulting. SMR market Outlook, vol. 30076; 2013.
[32] NNL. Small modular reactors (SMRs) feasibility study. Available from: http://www.nnl.co.uk/media/1627/smr-feasibility-study-december-2014.pdf; 2014.
[33] EY. Small modular reactors - can building nuclear power become more cost-effective?. Available from: https://go.ey.com/2FrQbIIn; 2016.
[34] EFWG. Market framework for financing small nuclear. Available from: https://bit.ly/2E0DdOF; 2018.
[35] MIT. The future of nuclear energy in a Carbon Constrained world. 2018.
[36] WNA. The economics of nuclear power. 2008.
[37] IAEA. Integrated approach to optimize operation and maintenance costs for operating nuclear power plants. 2006.
[38] NEA. The economics of the nuclear fuel cycle. Available from: http://www.oecd-nea.org/ndd/reports/efc/EFC-complete.pdf; 1994.
[39] IAEA. IAEA safety glossary. 2006. Available from: http://www-ns.iaea.org/downloads/standards/glossary/glossary-english-version2point0-sept-06-12.pdf.
[40] IAEA. Cost estimation for research reactor decommissioning. 2013. Available from: http://www-pub.iaea.org/MTCD/Publications/PDF/Pub1596_web.pdf.
[41] Lai CS, Jia Y, Xu Z, Lai LL, Li X, Cao J, et al. Levelized cost of electricity for photovoltaic/biogas power plant hybrid system with electrical energy storage degradation costs. Energy Convers Manag 2017;153(May):34–47.
[42] Lai CS, McCulloch MD. Levelized cost of electricity for solar photovoltaic and electrical energy storage. Appl Energy 2017;190:191–203.
[43] Investopedia. Net present value (NPV). Available from: https://www.investopedia.com/terms/n/npv.asp; 2019.
[44] Investopedia. Internal rate of return (IRR) definition. Available from: https://www.investopedia.com/terms/i/irr.asp; 2019.
[45] Investopedia. Economies of scale. Available from: https://www.investopedia.com/terms/e/economiesofscale.asp; 2019.
[46] Aydogan F, Black G, Taylor Black MA, Solan D. Quantitative and qualitative comparison of light water and advanced small modular reactors. J Nucl Eng Radiat Sci 2015;1(4):1–14.
[47] Playbell I. Economy, safety and applicability of small modular reactors. Proc Inst Civ Eng May, 2017;170(2):67–79.
[48] Boarin Locatelli G, Mancini M, Ricotti ME. Are SMR a reasonable choice for Switzerland? An application of the INCAS model. In: ASME 2011 small modular reactors Symposium. Washington, DC, USA: SMR 2011; 2011.
[49] Upadhyay AK, Jain K. Modularity in nuclear power plants: a review. J Eng Des Technol 2016;14(3).
[50] Mignacca B, Locatelli G, Alaassar M, Invernizzi DC. We never built small modular reactors (SMRs), but what do we know about modularization in construction?. In: 26th international conference on nuclear engineering. London,United Kingdom: ICONE26; 2018.
[51] 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.
[52] 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.
[53] 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. Charlotte, NC, USA: ICAPP; 2018. 2018.
[54] Maronati Petrovic B, Van Wyk JJ, Kelley MH, White CC. Impact of testing activities on small modular reactor total capital investment cost. In: 24th international conference on nuclear engineering ICONE24; 2016. Charlotte, North Carolina, USA.
[55] Wrigley PA, Wood P, Stewart P, Hall R, Robertson D. Module layout optimization using a genetic algorithm in light water modular nuclear reactor power plants. Nucl Eng Des 2018;341:100–11.
[56] Wrigley P, Wood P, Stewart P, Hall R, Robertson D. Design for plant modularisation: nuclear and SMR. In: 26th international conference on nuclear engineering, ICONE26; 2018. London, United Kingdom.
[57] Liman J. Small modular reactors: methodology of economic assessment focused on incremental construction and gradual shutdown options. Prog Nucl Energy 2018;108:253–9.
[58] Locatelli Mancini. Competitiveness of small-medium , new generation Reactors : a comparative study on decommissioning. J Eng Gas Turbines Power 2010;132.
[59] Locatelli G. Why are megaprojects, including nuclear power plants, delivered overbudget and late? Reasons and Remedies. Available from: https://arxiv.org/ftp/arxiv/papers/1802/1802.07312.pdf; 2018.
[60] Locatelli G, Boarin S, Fiordaliso A, Ricotti M. Load following by cogeneration: options for small modular reactors, gen IV reactor and traditional large plants. In: 25th international conference on nuclear engineering. Shanghai, China: ICONE25; 2017.
[61] 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.
[62] Ingersoll, Houghton ZJ, Bromm R, Desportes C. Integration of NuScale SMR with desalination technologies. In: ASME 2014 small modular reactors Symposium. Washington, DC, USA: SMR; 2014. 2014.
[63] Ingersoll, Houghton ZJ, Bromm R, Desportes C. NuScale small modular reactor for Co-generation of electricity and water. Desalination 2014;340(1):84–93.
[64] Oktavian MR, Febrita DI, Arief MM. Cogeneration power desalination in small modular reactors (SMRs) for load following in Indonesia. In: 4th international conference on science and technology (ICST); 2018. Yogyakarta, Indonesia.
[65] Shropshire D, Purvins A, Papaioannou I, Maschio I. Benefits and cost implications from integrating small flexible nuclear reactors with off shore wind farms in a virtual power plant. Energy Policy 2012;46:558–73.
[66] Locatelli Mancini M. Small medium sized nuclear coal and gas power plant: a probabilistic analysis of their financial performances and influence of CO2cost. Energy Policy 2010;38(10):6360–74.
[67] Lyons RE, Roulstone ARM. Production learning in a small modular reactor supply chain. In: International congress on Advances in nuclear power plants 2018. Charlotte, North Carolina, USA: ICAPP; 2018. 2018.
[68] Locatelli G, Pecoraro M, Meroni G, Mancini M. Appraisal of small modular nuclear reactors with 'real options' valuation. Proc Inst Civ Eng - Energy. 2017;170(2):51–66.
[69] Vegel B, Quinn JC. Economic evaluation of small modular nuclear reactors and the complications of regulatory fee structures. Energy Policy 2017;104:395–403.
[70] Boarin Locatelli G, Mancini M, Ricotti ME. Italy Re-opening the nuclear option: are SMR a suitable choice? An application of the INCAS model. In: ASME 2011 small modular reactors Symposium. Washington, DC, USA: SMR; 2011. p. 1–10. 2011.
[71] 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.
[72] Agar AS, Fry AJ, Goodfellow MJ, Goh YM, Newnes LB. Expected accuracy range of cost estimation for small modular reactors at the early concept design stage. In: 26th international conference on nuclear engineering. London, United Kingdom: ICONE26; 2018. p. 1–8.

[73] 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.
[74] Black G, Black MAT, Solan D, Shropshire D. Carbon free energy development and the role of small modular reactors: a review and decision framework for deployment in developing countries. Renew Sustain Energy Rev 2015;43:83–94.
[75] Cooper M. Small modular reactors and the future of nuclear power in the United States. Energy Res Soc Sci 2014;3(C):161–77.
[76] Hong S, Brook B. Economic feasibility of energy supply by small modular nuclear reactors on small islands: case studies of Jeju, Tasmania and Tenerife. Energies 2018;11(2587).
[77] IAEA. Pris - glossary. 2019. Available from: https://pris.iaea.org/PRIS/Glossary.aspx.
[78] 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.
[79] Shropshire D. Economic viability of small to medium-sized reactors deployed in future European energy markets. Prog Nucl Energy 2011;53(4):299–307.
[80] 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 Policy 2009 Dec;37(12):5494–508.
[81] Locatelli G, Mancini M, Belloni P. Assessing the attractiveness of SMR: an application of INCAS model to India. In: 21st international conference on nuclear engineering; 2013. Chengdu, China ICONE21-15932 ASSESSING.
[82] Abdulla A, Azevedo IL, Morgan MG. Expert assessments of the cost of light water small modular reactors. Proc Natl Acad Sci 2013;110(24):9686–91.
[83] Black GA, Aydogan F, Koerner CL. Economic viability of light water small modular nuclear reactors: general methodology and vendor data. Renew Sustain Energy Rev 2019;103:248–58.
[84] Locatelli G, Mancini M, Ruiz F, Solana P. Using real options to evaluate the flexibility in the deployment of SMR. In: International congress on Advances in nuclear power plants. ICAPP; 2012. 2012. 2012.
[85] Grubler A. The costs of the French nuclear scale-up: a case of negative learning by doing. Energy Policy 2010 Sep;38(9):5174–88.
[86] Sainati T, Locatelli G, Smith N. Project financing in nuclear new build, why not? The legal and regulatory barriers. Energy Policy 2019;129(May 2018):111–9.
[87] OECD/NEA. Nuclear energy today. Available from: www.oecd-nea.org; 2012.
[88] World Nuclear Association. Nuclear power in the USA. Available from: http://www.world-nuclear.org/information-library/country-profiles/countries-t-z/usa-nuclear-power.aspx; 2019.
[89] 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.
[90] Preston F, Lehne J. A wider circle? The circular economy in developing countries. Available from: https://www.chathamhouse.org/sites/files/chathamhouse/publications/research/2017-12-05-circular-economy-preston-lehne-final.pdf; 2017.
[91] 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.
[92] Ramana MV, Agyapong P. Thinking big? Ghana, small reactors, and nuclear power. Energy Res Soc Sci 2016;21:101–13.
[93] Ramana MV, Ahmad A. Wishful thinking and real problems: small modular reactors, planning constraints, and nuclear power in Jordan. Energy Policy 2016;93:236–45.
[94] Agar AS, Goodfellow MJ, Goh YM, Newnes LB. Stakeholder perspectives on the cost requirements of small modular reactors. Prog Nucl Energy 2019;112:51–62.
[95] Alonso G, Bilbao S, Del Valle E. Economic competitiveness of small modular reactors versus coal and combined cycle plants. Energy 2016;116:867–79.
[96] Wyrwa A, Suwała W. Prospects for the use of SMR and IGCC technologies for power generation in Poland. In: E3S web conf. vol. 22; 2017, 00191.

B.2 Publication II

Mignacca, B., Locatelli, G., Velenturf, A., 2020. Modularisation as enabler of circular economy in energy infrastructure. Energy Policy, Vol. 139 - **Scopus indexed journal, Impact Factor: 5.042, ABS 2**.

Energy Policy 139 (2020) 111371

Contents lists available at ScienceDirect

Energy Policy

journal homepage: http://www.elsevier.com/locate/enpol

ELSEVIER

Modularisation as enabler of circular economy in energy infrastructure

Benito Mignacca, Giorgio Locatelli*, Anne Velenturf

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

ARTICLE INFO

Keywords:
Modularisation
Circular economy
Sustainability
Energy infrastructure
Megaproject

ABSTRACT

Existing energy infrastructure have a technical and/or economic lifecycle predetermined by the lifetime of certain components. In energy infrastructure, the residual lifetime of civil structure or other components with a longer life is usually wasted. Modular energy infrastructure can be reconfigurable decoupling the life of the infrastructure from their modules, and extending module and/or infrastructure lifecycle. Modularisation could become a cornerstone to enable circular economy (CE) and enhanced sustainability. Remarkably, despite the growing interest among policymakers, practitioners and academics in both CE and modularisation, there is a lack of knowledge about the link between CE and modularisation in energy infrastructure. Through a Systematic Literature Review, this paper derives the gap in knowledge regarding the link between CE and modularisation in energy infrastructure. This link is then investigated in other sectors identifying relevant implications such as reduction of construction waste and achievement of the closed-loop material cycle. Furthermore, the case of Yamal Liquefied Natural Gas project is used to compare and contrast two perspectives: "Traditional modularisation" and "Modular CE". Lastly, the paper discusses existing policies, provides policy recommendations to foster "Modular CE" in energy infrastructure and suggests a research agenda.

1. Introduction

Policy-makers, practitioners and academics are increasingly discussing the topics of modularisation and Circular Economy (CE) in the energy sector. However, these topics are usually discussed individually, failing to recognise their interdependency. Recognising interdependency is crucial because modularisation can become a key enabler of CE and dramatically change the lifecycle of energy infrastructure.

The traditional narrative on modularisation, with respect to stick-built construction, deals with working in a better-controlled environment, increasing the quality of the components (reducing mistakes in construction, reworks etc.), reducing construction schedule, and maintenance cost because of a reduction of the probability of failure of components. (Carelli and Ingersoll, 2014; Maronati et al., 2017; Thomas, 2019; Vegel and Quinn, 2017). Modularisation could determine a cost-saving in labour and construction and also improve workers' safety on-site because they handle a smaller number of components (Locatelli et al., 2010). By contrast, the supply chain start-up cost is expected to increase (UxC Consulting, 2013). (Mignacca et al., 2018) summarise the quantitative information about two key implications of modularisation in infrastructure: schedule reduction (an average of 38%) and cost-saving (an average of 15%) (Micheli et al., 2019). provides a comprehensive view of barriers, drivers, and mechanism of implementation and impact of modularisation, enabling to identify modularisation opportunities in different domains.

Traditional stick-built energy infrastructure have a lifecycle predetermined by components that are difficult or very expensive to replace. The key idea discussed in this paper is that modular infrastructure could be made reconfigurable and extend/adapt their lifecycle by decoupling the life of the infrastructure from their modules. Modules can be designed in a way that, when a module reaches its end of life, it could be exchanged extending the life of the infrastructure. Furthermore, when the infrastructure needs to be retired, modules that are still functioning could be used in other infrastructure. In this way, the residual lifetime of certain modules with a longer life is not "wasted". In a wider perspective, CE forms a cornerstone of this novel strategy to manage sustainable modular infrastructure.

There is a plethora of definitions of CE, as reviewed by (Kirchherr et al., 2017). This paper is based on the definition of (Preston and Lehne, 2017): "*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*". This means:

1) Reusing and repairing products;

* Corresponding author.
E-mail addresses: cnbm@leeds.ac.uk (B. Mignacca), g.locatelli@leeds.ac.uk (G. Locatelli), a.velenturf@leeds.ac.uk (A. Velenturf).

https://doi.org/10.1016/j.enpol.2020.111371
Received 7 April 2019; Received in revised form 18 February 2020; Accepted 21 February 2020
Available online 26 February 2020

2) Recovering components and using them into new products or for new uses;
3) Restructuring a system so that the waste of one process can be the feedstock for another one.

In CE, the design not only focuses on functionality but also on managing the infrastructure end of life optimally, how the components can become parts of a new infrastructure/production chains (Molina-Moreno et al., 2017). Modularisation is already applied in the building construction sector contributing to circularity in four ways (EEA, 2017):

1) Waste is in a smaller quantity in a controlled environment (factory) than on a traditional construction site;
2) Less transport of material and components, thus reducing emissions;
3) Possibility of disassembling, relocating and refurbishing modules to reuse them, reducing the demand for raw material and the amount of energy;
4) Possibility of repairing/modifying parts or materials without destroying the building's basic structure.

Modularisation could reduce construction and demolition waste, and could improve deconstruction process facilitating the achievement of the closed-loop material cycle (Cheng et al., 2015; Lehmann, 2011a; Pulaski et al., 2004).

When an energy infrastructure reaches the end of life, it should be decommissioned. Decommissioning projects are the new, emerging, global, unavoidable challenges policymakers will face more and more severely in the future (Invernizzi et al., 2019). For instance, in the nuclear industry, there are 453 operational reactors in the world, 170 reactors in permanent shutdown, 55 in construction and only 17 had been completely decommissioned, which means that there will be the need to dismantle at least other 661 nuclear reactors (IAEA, 2019). However, nuclear plants are not the only energy infrastructure to generate decommissioning projects. The total global wind power installed is 540 GWe, the vast majority installed in the last 10 years (GWEC, 2019). Considering an operating life of about 25 years (Ghenai, 2012), in a decade or two, there will be decommissioning megaprojects in the wind power sector (Purnell et al., 2018). A similar consideration can be given considering about 500 GWe of solar power installed.[1] These numbers clarify the importance and the impact of managing energy infrastructure lifecycles, including extending the lifetime of the infrastructure and their modules.

The rest of the paper is structured as follows: Section 2 presents the Systematic Literature Review (SLR) leading to the gap in knowledge. Section 3 reports the key lessons learned from other sectors, primarily building and products. Section 4 presents a case study from YAMAL LNG and compares "Traditional modularisation" and "Modular CE". Section 5 provides policy recommendations to enable CE principles through modularisation. Section 6 concludes the paper suggesting a number of future research opportunities.

2. Systematic Literature Review

The authors conducted a SLR, instead of a traditional narrative review, to allow repeatability, objectivity and transparency. Fig. 1 summarises the research area and the research objective.

Remarkably, if the three elements (CE, modularisation, energy infrastructure) are searched together, there are no Scopus publications focusing on the link between modularisation and CE in energy infrastructure (even when adapting the keywords). Therefore, the authors decided to expand the search by dropping the keywords related to energy infrastructure and analyse all the papers concerned with CE and modularisation.

This paper combines the methodologies to conduct a SLR presented by (Di Maddaloni and Davis, 2017; Sainati et al., 2017). The selection process of the publications includes two sections. Section A deals with publications extracted from Scopus, and section B deals with reports published by relevant institutions.

Section A has three main stages. The first stage is the identification of relevant keywords related to the research objective. Several iterations led to this list:

- Circular economy: "*circular economy*", "*re-use*", "*reuse*", "*repair*", "*recover*", "*restructure*", "*replace*".
- Modularisation: "*modularisation*", "*modularisation*", "*modularity*", "*prefabrication*", "*pre-fabrication*".

In the second stage, a single string with the Boolean operator "AND"/"OR" is introduced in Scopus:

"*circular economy*" OR "*re-use*" OR "*reuse*" OR "*repair*" OR "*recover*" OR "*restructure*" OR "*replace*" AND "*modularisation*" OR "*modularisation*" OR "*modularity*" OR "*prefabrication*" OR "*pre-fabrication*" (search date: 04/02/2019).

Scopus was chosen because of the scientific merit of the indexed literature. A timeframe was not selected *a priori* but emerged to be 1968–2019 because the first publication is dated 1968. The first selection step used the aforementioned string (applied to title, abstract or keywords) and retrieved 917 publications (excluding 2 non-English publications and focusing on Article, Conference Paper, Review, Article in press, and Book Chapter).

Afterwards, the following subject areas were excluded because not related to the research objective: Computer Science, Mathematics, Physics and Astronomy, Medicine, "Biochemistry, Genetics and Molecular Biology", Neuroscience, Psychology, Arts and Humanities, Chemistry, Health Professions, Dentistry, Immunology and Microbiology, Nursing, Multidisciplinary, Chemical Engineering. The retrieved publications after the second stage were 366.

The third stage is the "filtering", which is characterised by a careful reading of the title and abstract of each publication filtering out publications not related to the research objective or duplication. After the filtering stage, 366 publications were removed, leaving 0 publications strictly focused on the research objective. However, 7 publications highlight the link between modular building and CE, and 12 publications highlight the link between CE and modular product. These publications have been carefully read and analysed. Fig. 2 summarises Section A of the selection process.

In section B of the selection process, following discussions with experts, the publications were searched on the ARUP, KPMG, Laing O'Rourke, Burges Salmon, and Ellen MacArthur Foundation websites[2] because of leading in publishing high-quality reports in relevant fields. Two keywords related to the research objective were used to search publications: "Circular Economy" and "Modular" (search date: 8/02/2019). No publications strictly related to the research objective were retrieved. Only (ARUP, 2016) shows the link between modularisation and CE but focusing on the building construction sector. Table 2 (in the Appendix) reports the retrieved publications in Section A and Section B of the selection process.

[1] Approximated number by http://www.solarb2b.it/wpcontent/uploads/2016/06/SPE_GMO2016_full_version.pdf.

[2] ARUP is "*an independent firm [...] working across every aspect of today's built environment*" (https://www.arup.com/our-firm). KPMG is "*a global network of professional services firms providing Audit, Tax and Advisory services*" (https://home.kpmg/cn/en/home/careers/who-we-are.html). Laing O'Rourke is "*a privately owned, international engineering enterprise [...]*" (http://www.laingorourke.com/who-we-are.aspx). Burges Salmon is an independent UK law firm (https://www.burges-salmon.com/about-us/). Ellen MacArthur Foundation is a "*UK registered charity with a mission to accelerate the transition to a circular economy*" (https://www.ellenmacarthurfoundation.org/policies).

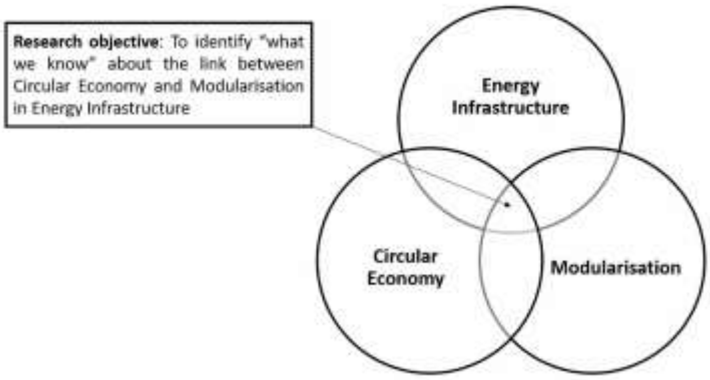


Fig. 1. Research area and objective.

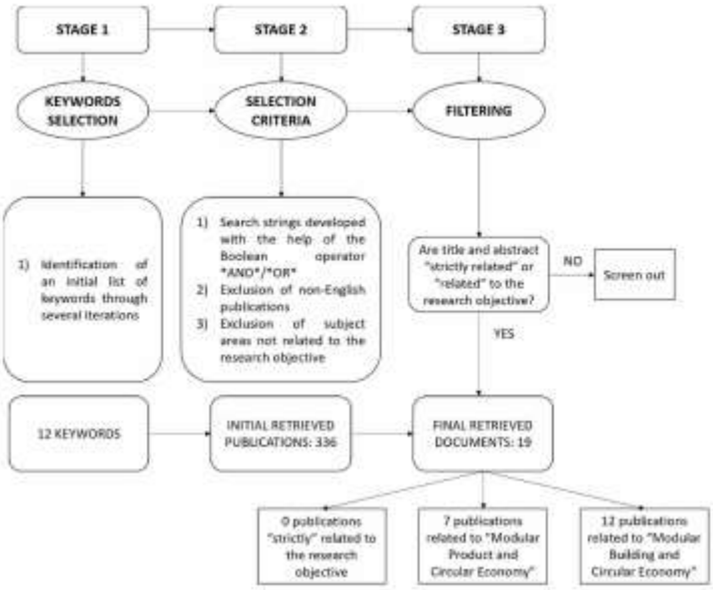


Fig. 2. Selection process – Section A. Layout adapted from (Di Maddaloni and Davis, 2017).

Fig. 3 presents the number of publications that highlighted the link between "modular product and CE" and "modular building and CE" per year.

3. Linking circular economy and modularisation: lessons learned

There were no publications focusing on the link between CE and modularisation in energy infrastructure. Few publications focus on this link in the building construction sector, and several publications point out the link between CE and modular products. Following the procedures from Section 2, the authors scrutinised in detail 20 publications (19 from Scopus plus (ARUP, 2016)) showing several concepts and practises related to the link between modularisation and CE. 12 publications refer to modular products, and 8 refer to the building construction sector. This section summarises the key concepts and practices highlighted in these 20 publications.

3.1. Modular buildings

3.1.1. Reduction of construction and demolition waste

According to (Cheng et al., 2015), prefabrication can reduce construction and demolition waste; however, the authors do not detail the reasons. (ARUP, 2016) points out that modularisation, coupled with the design for disassembly, allows easy changes to the structure reducing the construction waste. Furthermore, modularisation, using 3D print and additive manufacturing, might reduce waste and shorten the construction schedule, saving £800 m per year (ARUP, 2016). (Li et al., 2014)

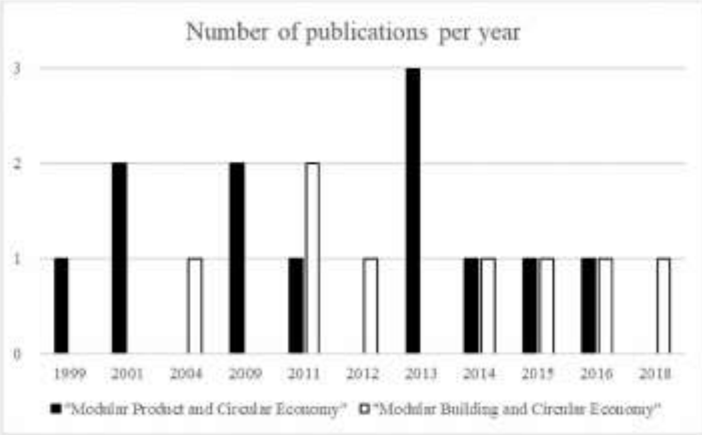


Fig. 3. Number of publications per year.

present a model to evaluate the impact of prefabrication on construction waste, and validate the model using data from a construction project in Shenzhen (China). The analysis reveals the possibility of reducing construction waste using prefabrication instead of the conventional method and points out that the policy of increasing the subsidy for prefabrication of square meter strongly influences the promotion of prefabrication adoption and construction waste reduction with respect to tax income benefits.

3.1.2. Achievement of closed-loop building material cycle

(Lehmann, 2011b, 2011a; Pulaski et al., 2004) highlight the importance of the design for deconstruction/disassembly to achieve the closed-loop building material cycle. They also recognise the merit of modularisation in improving the deconstruction fostering the closed-loop material cycle. Furthermore, simple and standardised connections simplify the assembly and disassembly process. The authors do not provide details about the reasons and the effective implications of modularisation.

3.1.3. Reduction of lifecycle energy requirements

Prefabrication can reduce the lifecycle energy requirement. In particular, (Aye et al., 2012) assess the lifecycle energy requirements of three different forms of construction for a residential building: prefabricated timber construction, prefabricated steel construction, and conventional concrete construction. Although the energy embodied in the prefabricated steel building is up to 50% higher than the conventional ones, the reuse of the main steel structure of the modules and other components in a new building could determine a saving of the 81% of that energy.

3.2. Modular products

The modular design could improve performances in disassemblability, maintainability, upgradability, reusability, and recyclability in products (Hata et al., 2001; Umeda et al., 2009). Modules that can be assembled in different ways allows applying the required changes (e.g. changes in products' requirements) without making a solution obsolete (Schulte, 2013). However, several factors need to be considered to achieve optimal performances in terms of CE.

3.2.1. Assessment in early design stages

The link between modular design and the enhanced performances in the lifecycle stages is achievable only if the lifecycle options of the components are evaluated and determined since the early product design stages (Umeda et al., 2009). The key points about the module design in a CE perspective are:

- The design of a modular product should avoid joining components made of different materials, and components with different physical life to facilitate the lifecycle options (Hata et al., 2001). This latter point is also stressed by (Yan and Feng, 2014) who argue that a different approach would waste resources.
- Common modules in a product family and the inclusion of the likely reusable components in the same module facilitates the reuse (Hata et al., 2001; Liu, 2013). Furthermore, technological stability, functional upgradability, long life, ease of quality assurance, and ease of cleaning and repair are key module characteristics to increase the possibility of reuse (Kimura et al., 2001).
- The inclusion of the likely upgrading components in the same module could enable the module to be replaced as a whole unit facilitating the upgrading process (Liu, 2013).
- The inclusion of unrecyclable or non-reusable components having the same processing method in the same modules could facilitate the processing process (Liu, 2013).
- Modular products might include electronic monitoring to predict the expiry date of the modules according to their use (Allwood et al., 2011).

3.2.2. Different modularisation methods and different goals

According to (Halstenberg et al., 2015), there are two groups of modularisation methods: "*methods for single product modularisation*" and "*methods for product family modularisation*". The first group has two main steps: conduct a single decomposition and create a single product architecture. The second group also has two steps: conduct multiple decompositions and aggregate the elements to a family product architecture.

(Halstenberg et al., 2015) present the "Target-oriented Modularisation Method" which allows defining product architecture based on specific goals. However, the authors only provide the generation method of different product architecture alternatives and do not provide details about choosing goals and related implications.

(Ji et al., 2013) highlight that the "material reuse modularisation" and "technical system modularisation" are two different concepts. The "material reuse modularisation" is not only an expansion of "technical system modularisation". On the contrary, modules determined by the "material reuse modularisation" might be inconsistent with the modules determined by the "technical system modularisation". The authors present a decision model that considers both modularisation measures.

According to (Schischke et al., 2016), there are different levels of modularisation and different related conventional environmental design strategies. Focusing on smartphones with a modular design (Schischke et al., 2016), point out five levels of modularisation (Add-on, Material, Platform, Repair, Mix & match) and, when applicable, the related conventional environmental design strategies (e.g. Ease of maintenance and repair, Disassembly and reassembly, Upgradability and adaptability). The Add-on modularisation main characteristic is the attachment of peripheral functionalities to a core (e.g. display-CPU). The possibility to separate some materials (e.g. batteries) easily is the main characteristic of material modularisation. In the case of platform modularisation, products are configured for a range of individual specs. The possibility to easily exchange the key components is the main characteristic of repair modularisation. Finally, the Mix & match modularisation level, which considers specs for all modules, standardised module interfaces, hot-swapping, maximum flexibility and includes repair modularisation presents the strongest correlation with the design for CE strategies (Schischke et al., 2016).

3.2.3. *Undergoing the reuse or recycling process "directly"*

The environmental load and the cost of logistics and recovery processes reduce when the module can undergo the reuse or recycling process directly (without the need for disassembly in components). This is a result of the methodology presented by (Umeda et al., 2009) and applied in the evaluation of the environmental load of two different modular structures. (Fukushige et al., 2009) present a modular design method based on the lifecycle scenarios. The method considers modules characterised by components suitable for the same lifecycle options, permitting modules undergoing the lifecycle options without disassembly, and evaluates the modular structure in terms of resource efficiency.

3.2.4. *Modularisation is a key enabler of the inverse manufacturing*

A lifecycle simulation system can evaluate the effect of modular design in a CE perspective. (Nonomura and Umeda, 1999) presents and applies a lifecycle simulation system showing that an appropriate modular design is a key enabler of inverse manufacturing.

4. Case study: Yamal Liquefied Natural Gas (LNG) modular project

As explained in the previous sections, there is a gap in knowledge about the link between modularisation and CE in energy infrastructure. This section presents the Yamal LNG modular project to compare two perspectives: "Traditional modularisation" and "Modular CE". "Modular CE" is a novel theoretical concept introduced in this paper, and can be defined as "*the factory fabrication, transportation and installation on-site of modules aiming to facilitate the reuse/repair/replacement/recycling of modules/components/materials*". Therefore, this new perspective retains the implications (factory fabrication, transportation and installation on-site of modules) of "Traditional modularisation" but also expands to include the development of sustainable energy infrastructure. YAMAL LNG project is an emblematic case to analyse being the world's largest modular project (Alten, 2019), and, being very recent, it allows verifying the absolute novelty of the "Modular CE" strategy.

4.1. *Case summary*

Yamal LNG project encompasses the construction of a plant for production, treatment, liquefaction, storage and export of LNG from South Tambey condensate gas field in the northeast of the Yamal Peninsula in Siberia (Auverny-Bennetot et al., 2019; Yamal LNG, 2015). This is an internal project worth $27.6 billion and delivered in the period 2011–2018 (Alten, 2019; NS Energy, 2018). The project started with Front-End Engineering in 2011, followed by the first piling works at the end of 2013, and the first LNG carrier in 2017. The LNG complex reached its full capacity (16.5 million tonnes per year) in December 2018, one year earlier than planned (Alten, 2019; Auverny-Bennetot et al., 2019). The characteristics of this remote area (i.e. wilderness area, lack of infrastructure, extreme weather, etc.) drove the choice of modularisation (Alten, 2019). With 150 modules mainly fabricated in shipyards in Asia, YAMAL LNG project is considered the world's largest modular project (Alten, 2019).

4.2. *Comparative analysis*

The authors had a series of communications including one in-depth interview with a YAMAL LNG senior project manager, discussing the role of modularisation over the life cycle of modular energy infrastructure, with particular focus on the YAMAL LNG case. Leveraging the body of knowledge from the previous sections, the communications & in-depth interview, the participation at a seminar about the YAMAL LNG project, a critical analysis of the literature, and the authors' experience and reflection, it was possible to identify the key drivers, enabling factors, challenges, advantages and disadvantages of the "Traditional modularisation", listed under the "Traditional modularisation" column in Table 1. Leveraging the results of the SLR in section 2 and discussions with experts in CE, the authors present a new perspective of "Modular CE" in Table 1.

Table 1
The first column compares "Traditional modularisation" vs "Stick-built". The second column compares "Modular CE" vs "Traditional modularisation". "Modular CE" retains enabling factor, challenges, advantages and disadvantages of "Traditional modularisation".

	Traditional modularisation	Modular CE
Drivers	- Environmental conditions - Cost saving - Schedule reduction	- Develop sustainable energy infrastructure - Addressing the United Nations Sustainable Development Goals
Enabling factors	- Modular design considered since early design stages - Availability of technology for lifting and transportation	- CE principles considered since early design stages - Market for second hand modules/components/materials
Challenges	- Licensing and regulation - Logistics - Potential lack of know-how	- Design for deconstruction/disassembly - Design and interface standardisation
Advantages	- Improved quality - Reduction of mistakes in construction and rework - Increased productivity - Improved worker's safety - Increased possibility of construction	- Reduction of construction and demolition waste - Facilitation of design toward adaptability and inverse manufacturing - Limitation of the usage of new raw materials - Reduction of lifecycle energy requirements - A module could undergo the reuse or recycling process directly - Easier maintenance and replacement - Longer life of the infrastructure
Disadvantages	- Supply chain start up cost - Lack of adaptability to changes - Increased coordination, planning and communication	- Cost could increase - Schedule could increase - Higher complexity

4.2.1. *Traditional modularisation*

This section provides peculiarities of the YAMAL LNG project and highlights how the transition to "Traditional modularisation" influences the lifecycle of energy infrastructure. The rationale behind the choice of "Traditional modularisation" in the case of YAMAL LNG project was to overcome the extreme environmental conditions on-site (e.g. extreme cold until -50 °C, strong wind >40 m/s, wilderness area, etc.). Several non-process modules (e.g. pipe racks) and process modules (e.g. modules to move the gas from gaseous state to liquid state) were built in yards located in China and Indonesia and transported on-site with specific vessels. Moving the yards from the construction site (Siberia) to China and Indonesia allowed:

- Quality improvement and reduction of mistakes in construction and reworks through specialised yards with a better-qualified workforce.
- Cost-saving through a lower labour cost and construction schedule reduction.

Furthermore, the transition from stick-built construction to "Traditional modularisation" determined:

- An increased level of complexity in the management of suppliers. For example, political pressures in "country X" where a sub-contractor was located led to the shipment on-site of uncompleted modules. Moreover, "supplier Y" (fixed-price contract) delivered modules not respecting the design specifications. In both cases, modules were completed on-site where the labour cost was much higher than in "country X".
- Transportation challenges. Long and detailed studies to foresee how structures in the modules could move during the maritime transport were needed. No structure damages occurred in the case of YAMAL LNG project.

The analysis of the YAMAL LNG project pointed out how the link between modularisation and CE is currently not considered and, indirectly, confirmed the novelty of "Modular CE" strategy introduced in this paper.

The lifecycle of energy infrastructure is usually characterised by standard phases: design, procurement, construction, operations, and decommissioning. The transition from "Stick-built construction" to "Traditional modularisation" substantially modifies the first three phases of the infrastructure lifecycle: design, procurement and construction. However, the operations and decommissioning phases are not different from a stick-built infrastructure. The "Modular CE" changes this paradigm.

4.2.2. *Modular CE*

This section provides further details about the novel theoretical concept of "Modular CE", and highlights how the transition from "Traditional modularisation" to "Modular CE" influences the lifecycle of energy infrastructure.

As aforementioned, "Modular CE" is "*the factory fabrication, transportation and installation on-site of modules aiming to facilitate the reuse/repair/replacement/recycling of modules/components/materials*". Therefore the rationale behind the choice of Modular CE is to develop sustainable energy infrastructure and addressing the United Nations Sustainable Development Goals (United Nations, 2015). Indeed, this novel strategy could both give value to the residual lifetime of still useable modules when the infrastructure needs to be retired, and facilitate the exchange of modules (when a module reaches the end of life) extending the life of the energy infrastructure. However, the opportunity to exchange modules and/or move modules between energy infrastructure should be considered in the early design stages. In other words, design for deconstruction/disassembly should be considered in the case of energy infrastructure, in the same ways as it is in the building construction sector (ARUP, 2016; Lehmann, 2011b, 2011a; Pulaski et al., 2004). This represents one of the main challenges of "Modular CE", as well as design and interface standardisation (further details in Section 5).

Regarding the lifecycle of energy infrastructure, there is a major step forward in this case. Indeed, through the opportunity of a more straightforward replacement/refurbishment of modules and components, and the possibility to reuse modules (and/or components and materials), "Modular CE" can be a game-changer all over the infrastructure lifecycle (not only design, procurement and construction as "Traditional modularisation").

5. Enabling CE principles through modularisation: reflections and policy recommendations

Based on the SLR, case study analysis and expert discussions, this section first offers an overview of the policy and regulatory context, and then proposes two new policies to exploit the advantages of modularisation in a circular perspective and a reflection to further improve the "Modular CE".

5.1. *Policy and regulatory context development*

Progress to integrate CE approaches with energy infrastructure has been slow due to a silo-mentality in policy and regulation. Policies should adopt a whole-system joined-up approach to accelerate change in industry practice. This section will further elaborate on these points by using the United Kingdom (UK) policy as a meaningful case.

The subjects of energy, infrastructure and CE are generally in separate policy siloes. In the UK energy is handled by the Department for Business, Energy and Industrial Strategy (BEIS); infrastructure is part of the portfolio of the Treasury's Infrastructure and Projects Authority; and resources and CE are with the Department for Environment, Food and Rural Affairs (DEFRA). Climate change is slowing starting to bring energy and resource policy together.

The merging of energy and climate change policy resulted in the Climate Change Act (2008), which introduced legally binding targets for carbon reductions across industries. The Clean Growth Strategy (2017) set out plans to grow the economy while limiting greenhouse gas emissions, with a strong focus on energy efficiency improvements across the economy (BEIS, 2017). However, energy efficiency measures alone will be insufficient to achieve the aspired 'net-zero' target by 2050.

CE can significantly reduce carbon emissions, potentially to the tune of 200 MtCO2e by 2032 (Green Alliance and CIE-MAP, 2018). Material processing and manufacturing require vast amounts of energy. Modular CE strategies that promote reuse and repair save embodied carbon invested in the production of energy infrastructure components. Valuing such solutions, when compared to linear 'take-make-use-dispose' practices, requires a longer-term approach in the assessment of costs and benefits than currently practised by Government. The Green Book guidance, for example, sets out the Government's approach to the evaluation of new infrastructure projects which, despite recent additions to integrate social and environmental values with the economic, in practice still is believed to be limited to short-term economic thinking (HM Treasury, 2018, 2015). This poses a disadvantage for CE strategies that generate more economic, social and environmental value over a longer period (Velenturf and Jopson, 2019). While collaboration between departments responsible for energy, resources and CE, and infrastructure is increasing (Velenturf, 2018), policies must be integrated further to make the most of the decarbonisation potential of a joined-up approach.

This is visible in strategies, policies and regulations for the separate energy sectors, e.g. oil & gas and renewables. In Scotland, persistent efforts have been made to apply CE principles to the decommissioning of North Sea oil & gas infrastructure (e.g. (RSA, 2015),). However, these installations were: a) Not designed with the end-of-use in mind, and b) Generally bespoke for specific locations and purposes. This poses challenges for the reuse and repurposing of components (BEIS, 2018). In addition, the State is functioning as a decommissioner of last resort, with a significant proportion of decommissioning costs being passed down to taxpayers (NAO, 2019).

To prevent the issues encountered in the oil & gas sector, changes were made for offshore renewables, but progress in policy, regulation and industry practice has been minor. Operators must now present decommissioning plans before getting permission to develop new installations (Energy Act, 2004), but the success of this approach appears limited so far. Offshore wind decommissioning plans were found to be formulaic in nature, generally assume reverse engineering of commissioning processes, and vaguely refer to future best practice in waste management at the time of decommissioning (Jensen et al., submitted). Decommissioning costs are likely to have been underestimated by at least a factor four, similar to mistakes made before in the oil & gas sector (BEIS, 2018; Purnell et al., 2018). Moreover, industry standards aim for a design life of 20–25 years, maximising durability to limit the costs of operations and maintenance but, crucially, still without considering the impacts on decommissioning costs, the ability to reuse components in new developments and the recyclability of materials (Purnell et al., 2018).

Insight into a CE that optimises the value of resources and the planning, management and decommissioning of energy infrastructure is still largely segregated across the policy landscape. New approaches at the strategic level in Government as well as in industry practices are necessary to move forward. In the following sections, we present two new policies to promote Modular CE.

5.2. Working toward standardisation

Standardisation is a buzzword in several sectors. However, design standardisation represents one of the main challenges of "Modular CE" in energy infrastructure, as shown in Table 1. Standardisation is key to enable the reuse of modules, components and materials. The reuse is critical in two main cases: 1) Premature retirement, and 2) Parts have still useful life when energy infrastructure reach the end of life. However, the complete standardisation of energy infrastructure is unrealistic, at least in the short and middle term. For example, in the case of the oil & gas sector, the peculiar characteristics of the extracted gas determine different needs and, consequently, different plants. However, the "complete plant standardisation" is not essential since the standardisation of module interfaces might be already a giant leap forward in the right direction. A peculiar example to understand the criticality of standard interfaces is a desktop computer workstation. Current computer workstations, even if very different, can be considered modular and have standard interfaces. If for example, module X (e.g. keyboard or a screen) reaches the end of life, it can be easily replaced, and the workstation kept in place. If the "computer case" reaches its end of life, the peripherals can be used in another workstation. Similar considerations can be done for the modules (CPU, RAM, hard drive) inside a computer case. In the energy sector, in the case of wind farm, the tower (that can be considered a module) could still have useful time when the wind turbine gearbox reaches the end of life. In that case, standard interfaces can enable the reuse of the tower. Moreover, concrete foundations have a long life that could be used for several cycles if designed for future use with larger turbines. Policy-makers should develop appropriate policies fostering the standard design and interfaces, and promoting the re-use of modules and components across plants to develop more sustainable energy infrastructure.

5.3. Implementation by sector and at different levels

The transition from "Traditional modularisation" to "Modular CE" is a complex process. Its implementation at different degrees (e.g. complete vs partial plant standardisation, or "only" standardisation of the interfaces) might already be largely technically feasible. However, considering the different level of complexity (e.g. wind farm vs nuclear power plant), firstly its implementation should be at sector level (wind farm, nuclear etc.). Secondly, it should be considered at country-level and ultimately internationally.

At country-level, industries, universities and government need to develop a common strategy to promote the CE in energy infrastructure by harnessing the advantages of modularisation.

A regulatory framework is needed to obligate industries to consider and apply (if possible) "Modular CE" principles. For example, regulators could define the minimum percentage of modules, components and materials that can be easily removed and, if possible, reused when the infrastructure reaches the end of life. Regulators could also obligate the development of modules undergoing the reuse or recycling process directly.

Furthermore, the transition from "Traditional modularisation" to "Modular CE" might be not cost-effective, at least in the short term. In this case, incentives from the government to industries developing modular infrastructure in a CE perspective could be a solution.

A second-hand market needs to be created to reuse modules, similar to what exists for components and materials. Innovation (and therefore, technology obsolescence) and changes in regulation represent two main barriers to the creation of a second-hand market. Indeed, although the infrastructure could be designed and built through "Modular CE", when the infrastructure reaches the end of life (e.g. after 40 years), technology could be obsolete, or regulations could be changed. In general, international supply chains represent one of the main barriers to the implementation at country-level of "Modular CE". Indeed, it is highly unlikely that all the modules of an energy infrastructure are built in only one country. This would be in contrast with several main drivers of modularisation (e.g. lower labour cost in other countries, higher expertise of the workforce in other countries, etc.). Therefore, it is highly unlikely to "fully" harness the advantages of modularisation in a CE perspective at country-level. However, in theory, "Modular CE" implemented at country-level presents higher benefits in terms of sustainability with respect to "Traditional modularisation".

At the international level, barriers like technology obsolescence, changes in regulation and international supply chains could be, in theory, overcome relatively more easily. Indeed, if after X years country Y moves on to newer technologies for several reasons, a technology could still be used in country Z. However, an agreement and a common strategy between country Y and Z before the design stages are needed. Economic and regulatory reasons could lead country Z to use a lesser advanced technology with respect to country Y. Moreover, "Modular CE" implemented at international-level is not in contrast with the main drivers of modularisation. Therefore, policy-makers should develop policies aiming to foster the development of modular energy infrastructure through international joint ventures.

Furthermore, research centres linking industries, universities and governments focusing on the implications of "Modular CE" are strongly recommended as well as initiatives of open innovation (Greco et al., 2017; Perkmann and Walsh, 2007). The implications of this novel approach need to be investigated in the details and from different perspectives (e.g. economics, regulation, technical requirements, etc.). A strong industries-universities-governments network could create the momentum needed for the development of modular energy infrastructure in a CE perspective.

5.4. From modularisation to modularity

"Modularisation" and "modularity" are often used interchangeably although they have completely different meanings. Modularisation is the "*process of converting the design and construction of a monolithic or stick-built plant to facilitate factory fabrication of modules for shipment and installation in the field as complete assemblies*" (GIF/EMWG, 2007) (Page 24) (GIF/EMWG, 2005). defines modularity as a "*Generic term, representing a comparative use of many standardized smaller units, with a lesser* *number of larger units, for the same installed capacity (MWe)*" (Page 22). Furthermore, standardisation is "*a framework of agreements to which all relevant parties in an industry or organization must adhere to ensure that all processes associated with the creation of a good or performance of a service are performed within set guidelines*" (Investopedia, 2019).

Fig. 4 compares the definitions of modularisation and modularity, also highlighting the meaning of stick-built and pure standardisation.

Modularisation and modularity are two different concepts with different implications and should be treated as such. Table 1 summarises the main implications of modularisation. Modularity allows incremental capacity addition, co-siting economies, cogeneration and load following (Mignacca and Locatelli, 2020). "Modular CE" strategy can deliver the highest benefits from a "CE" perspective when a standard plant is assembled on-site from factory-produced modules of a smaller capacity than a monolithic plant (modularity effect). Indeed, considering standard modular plants of a smaller capacity than a traditional modular plant, more modular plants are needed to reach the same power output. Therefore, the need for second-hand modules/components/materials would increase, and it would be easier to create a second-hand market. Moreover, module lifting and transportation (one of the challenges of modularisation (Mignacca et al., 2019)) would be much is easier in the case of smaller modular plants and, therefore, smaller modules and components. For example, the rotor diameter of a wind turbine Enercon E−53 (800 kW) is 52.9 m (Wind-turbine-models, 2019a), while the rotor diameter of a wind turbine Enercon E−126 (7,58 MW) is 127 m (Wind-turbine-models, 2019b). The greater effort (and therefore cost) needed in the design to implement this novel strategy would, in theory, be compensated from the economy of multiples (e.g. the economic merit of "mass production" of certain systems). On the other hand, the lack of the economy of scale (the economic merit of increasing the size of a system) should be considered. "Modular CE" strategy is not applicable (or with very fewer benefits) in the case of stick-built or pure standardisation. Indeed, the absence of modules does not allow a "fully" implementation of "Modular CE" strategy. However, moving from modularisation to modularity (considering CE principles), in order to develop even more sustainable energy infrastructure than "Modular CE" presented in this paper, is a major leap forward. The first (and currently more realistic) short-term step would be providing policies and regulations fostering the link between modularisation and CE (i.e. "Modular CE"). Afterwards, in a long term perspective, policies and regulations promoting the development of even more sustainable infrastructure harnessing the modularity effect are needed.

6. Conclusions and policy implications

Policies fostering the development of sustainable infrastructure leveraging the principles of CE are essential for the energy sector. Traditional stick-built energy infrastructure have a lifecycle pre-determined by the lifetime of their components. Modular infrastructure might be reconfigurable and extend/adapt their lifecycle decoupling the life of the infrastructure from their modules. In a wider perspective, CE would be a cornerstone of this novel strategy to manage sustainable modular infrastructure.

This paper, through a SLR, identified the "*what we know*" about the link between CE and modular energy infrastructure. Remarkably, despite the growing interest of policymakers, academics and industry in both CE and modularisation, there were no publications focusing on the link between CE and modularisation in the energy sector. State of the art includes few publications highlighting this link in the building construction sector, and several publications pointing out the link between a modular product and CE. There were no publications bringing the ideas of energy infrastructure, modularisation and CE together.

Policies aiming to promote modularisation could improve performances in disassembly, maintainability, upgradability, reusability, and recyclability. The inclusion of components with similar characteristics (e.g. same likelihood of reuse or recycling) in the same infrastructure module facilitates the achievement of the CE goals. Furthermore, modularisation could reduce construction and demolition waste. Modularisation could also reduce the lifecycle energy requirement and material consumption of energy infrastructure and as such form a key part of achieving targets of both energy and resource policies. To make the most of this potential a further integration is required for the policy areas on energy, resources and CE, and infrastructure.

In the case of a modular product, there are several modularisation methods, and each method is related in a different way to CE. A precondition to achieving the expected advantages of "Modular CE" is the assessment of the lifecycle options of components/modules in the early design stages. Furthermore, several methods that allow evaluating the impact of "Modular CE" have been developed already at an academic level, less at an industrial level and are almost absent at the policy level. The stakeholders involved in the planning and delivery of energy infrastructure should familiarise with these concepts and practises to develop sustainable energy infrastructure reducing waste, CO_2 emissions, minimising the use of raw materials, etc.

This paper presents the Yamal LNG case to compare and contrast two

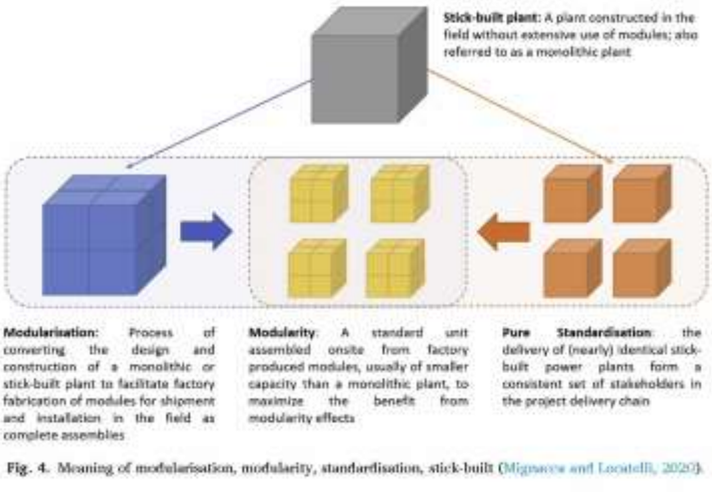


Fig. 4. Meaning of modularisation, modularity, standardisation, stick-built (Mignacca and Locatelli, 2020).

perspectives: "Traditional modularisation" and "Modular CE", showing how modularisation can increase the sustainability even for "traditional" infrastructure such as gas plants. Furthermore, this paper provides two main policy items to fully exploit the advantages of modularisation in a circular perspective: working towards standardisation, and implementation by sector and at different levels, and suggests how moving from modularisation to modularity could even allow the development of more sustainable energy infrastructure.

The gap in knowledge about policies to foster more sustainable infrastructure leveraging modularisation is a strong motivation for doing further research. This paper paves the way to a number of future research opportunities. Among the others, the following research questions are, according to the authors, the most relevant.

- Policy and legislation: What are the implications of the link between CE and modular energy infrastructure from a legal point of view? In a wider perspective, what are the relationships between countries with different policies and legislation about energy infrastructure? How could differences between countries' policy and legislation affect the choices of business regarding investment and developments? To what extent could harmonisation between countries be promoted?
- Innovation: Could innovation be a barrier to the link between CE and modularisation? Could new technology innovation make the re-use of modules unworthy (i.e. technologically outdated)?
- Module lifting and transportation: Module lifting and transportation is one of the critical points of modularisation. In the case of a modular energy infrastructure designed to exploit the benefits of modularisation fully in a CE perspective, module lifting and transportation could be more critical than in the case of "Traditional modularisation". How are module lifting and transportation exactly related to the link between modularisation and CE?
- Value of resources/geographical inhomogeneity/policy at an international level: The value of a module could be different according to the country because the circumstances could be different (e.g. legislation, labour cost). To what extent could this disparity address the issues related to innovation and legislation?
- Standardisation of the interfaces: A precondition of the link between modularisation and CE is the standardisation of interfaces. Who should be responsible for the standardisation of the interfaces?
- End of life cost: What is the impact of the link between modularisation and CE on the end of life cost? Could cost be decreased?
- Emerging technologies: What is the impact of emerging technologies such as the Internet of Things, digital twin and cyber-physical systems in the development of energy modular infrastructure in a CE perspective?

Finally, learning the right way to fully exploit the benefits of modularisation in a CE perspective harnessing the experience, at policy and industrial level, accumulated over the years in other sectors could be a key success factor to develop sustainable modular energy infrastructure.

CRediT authorship contribution 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. **Anne Velenturf:** 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 immensely grateful to the MPA members for their support. The authors are especially grateful to Eng. Francesco Sangalli that shared his relevant experience. 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 1

Table 2
Publications - Link highlighted

Publication/Link highlighted	Modular Product and Circular Economy	Modular Building and Circular Economy
Nunomura and Umeda (1999)	X	
Hata et al. (2001)	X	
Kimura et al. (2001)	X	
Pulaski et al. (2004)		X
Fukushige et al. (2009)	X	
Umeda et al. (2009)	X	
Allwood et al. (2011)	X	
Lehmann (2011a)		X
Lehmann (2011b)		X
Aye et al. (2012)		X
Ji et al. (2013)	X	
Liu (2013)	X	
Schulte (2013)	X	
Li et al. (2014)		X
Yan and Feng (2014)	X	
Cheng et al. (2015)		X
Halstenberg et al. (2015)	X	
ARUP (2016)		X
Schischke et al. (2016)	X	
Minunno et al. (2018)		X

References

Greco, M., Locatelli, G., Lisi, S., 2017. Open innovation in the power & energy sector: bringing together government policies, companies' interests, and academic essence. Energy Pol. 104, 316–324. https://doi.org/10.1016/J.ENPOL.2017.01.049.

Allwood, J.M., Ashby, M.F., Gutowski, T.G., Worrell, E., 2011. Resources , conservation and recycling material efficiency : a white paper. Resour. Conserv. Recycl. 55, 362–381. https://doi.org/10.1016/j.resconrec.2010.11.002.

Alten, 2019. Yamal LNG: a titanic gas project in Arctic Siberia. URL. https://www.alten.com/yamal-lng-project-gas-arctic-anotech-energy/. accessed 9.20.19.

ARUP, 2016. The Circular Economy in the Built Environment.

Auverny-Bennetot, C., Demol, J., Nicolini, E., Allenovskiy, A., Petrishin, A., 2019. Yamal LNG: REX on a mega Oil&Gas project built on the permafrost. In: XVII ECSMGE-2019, p. 2019.

Aye, L., Ngo, T., Crawford, R.H., Gammampila, R., Mendis, P., 2012. Life cycle greenhouse gas emissions and energy analysis of prefabricated reusable building modules. Energy Build. 47, 159–168. https://doi.org/10.1016/j.enbuild.2011.11.049.

BEIS, 2017. The Clean Growth Strategy Leading the Way to a Low Carbon Future.

BEIS, 2018. Offshore Renewables Decommissioning Guidance for Industry - Proposed Updates.

Carelli, M.D., Ingersoll, D.T., 2014. Handbook of Small Modular Nuclear Reactors. Woodhead Publishing, Elsevier. https://doi.org/10.1533/9780857098535.2.149.

Cheng, J.C.P., Won, J., Das, M., 2015. Construction and demolition waste management using BIM technology. In: Proc. 23rd Ann. Conf. Of the Int'l. Group for Lean Construction. Perth, Australia. https://doi.org/10.5772/46110.

Climate Change Act, 2008. Climate Change Act 2008. URL. http://www.legislation.gov.uk/ukpga/2008/27/contents. accessed 12.18.19.

Consulting, UxC., 2013. SMR Market Outlook.

Di Maddaloni, F., Davis, K., 2017. The influence of local community stakeholders in megaprojects: rethinking their inclusiveness to improve project performance. Int. J. Proj. Manag. 35, 1537–1556. https://doi.org/10.1016/j.ijproman.2017.08.011.

EEA, 2017. Circular by Design - Products in the Circular Economy. European Environmental Agency Report. https://doi.org/10.2800/860754. No. 6/2017.

Energy Act, 2004. Energy Act 2004. URL. http://www.legislation.gov.uk/ukpga/2004/20/contents. accessed 12.19.19.

Fukushige, S., Tonoike, K., Inoue, Y., Umeda, Y., 2009. Product modularization and evaluation based on lifecycle scenarios. In: Proceedings of the 5th International Conference on Leading Edge Manufacturing in 21st Century, LEM 2009.

Ghenai, C., 2012. Life cycle analysis of wind turbine. In: Sustainable Development - Energy, Engineering and Technologies - Manufacturing and Environment. https://doi.org/10.5772/29184.

GIF/EMWG, 2005. Cost Estimating Guidelines for Generation IV Nuclear Energy Systems.

GIF/EMWG, 2007. Cost Estimating Guidelines for Generation IV Nuclear Energy Systems.

Green, Alliance, CIE-MAP, 2018. Using Resource Efficiency to Cut Carbon and Benefit the Economy.

GWEC, 2019. Global statistics. URL. http://www.solarelb2b.it/wp-content/uploads/2016/06/SPE_GMO2016_full_version.pdf. accessed 2.22.19.

Halstenberg, F.A., Buchert, T., Bonvoisin, J., Lindow, K., 2015. Target-oriented modularization– addressing sustainability design goals in product modularization Friedrich. Procedia CIRP 29, 603–608. https://doi.org/10.1016/j.procir.2015.02.166.

Hata, T., Kat, S., Kimura, F., 2001. Design of product modularity for life cycle management. In: 2nd International Symposium on Environmentally Conscious Design and Inverse Manufacturing, pp. 93–96.

IAEA, 2019. Power reactor information system. URL. https://pris.iaea.org/PRIS/home.aspx. accessed 2.22.19.

Invernizzi, D.C., Locatelli, G., Grönqvist, M., Brookes, N.J., 2019. Applying value management when it seems that there is no value to be managed: the case of nuclear decommissioning. Int. J. Proj. Manag. 37, 668–683. https://doi.org/10.1016/j.ijproman.2019.01.004.

Investopedia, 2019. Standardization. URL. https://www.investopedia.com/terms/s/standardization.asp. accessed 9.24.19.

Jensen etal, n. d. Low Carbon Infrastructure Decommissioning: Embedding Circular Economy in End Of Life Planning.

Ji, Y., Jiao, R.J., Chen, L., Wu, C., 2013. Green modular design for material efficiency : a leader-follower joint optimization model. J. Clean. Prod. 41, 187–201. https://doi.org/10.1016/j.jclepro.2012.09.022.

Kimura, F., Kato, S., Hata, T., Masuda, T., 2001. Product modularization for parts reuse in inverse manufacturing. CIRP Ann 50, 89–92.

Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: an analysis of 114 definitions. Resour. Conserv. Recycl. 127, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005.

Lehmann, S., 2011a. Optimizing urban material flows and waste streams in urban development through principles of zero waste and sustainable consumption. Sustainability 155–183. https://doi.org/10.3390/su3010155.

Lehmann, S., 2011b. Resource recovery and materials flow in the city: zero waste and sustainable consumption as paradigms in urban development. Sustain. Dev. Law Policy 11.

Li, Z., Qiping, G., Alshawi, M., 2014. Measuring the impact of prefabrication on construction waste reduction : an empirical study in China. Resour. Conserv. Recycl. 91, 27–39. https://doi.org/10.1016/j.resconrec.2014.07.013.

Liu, L., 2013. The exploration of recycling design of furniture products based on structure. Adv. Mater. Res. 695–697, 44–48. https://doi.org/10.4028/www.scientific.net/AMR.695-697.44.

Locatelli, G., Mancini, M., Gallì, A., 2010. Introducing nuclear power plants in an OECD country: size influence on the external factors. In: 18th International Conference on Nuclear Engineering, ICONE18. Xi'an, China. https://doi.org/10.1115/ICONE18-29953.

Maronati, G., Petrovic, B., Wyk, J.J. Van, Kelley, M.H., White, C.C., 2017. EVAL: a methodological approach to identify NPP total capital investment cost drivers and sensitivities. Prog. Nucl. Energy 104, 190–202. https://doi.org/10.1016/j.pnucene.2017.09.014.

Micheli, G.J., Trucco, P., Sabri, Y., Mancini, M., 2019. Modularization as a system life cycle management strategy: drivers, barriers, mechanisms and impacts. Int. J. Eng. Bus. Manag. 11 https://doi.org/10.1177/1847979018825041.

Mignacca, B., Locatelli, G., 2020. Economics and finance of Small Modular Reactors: a systematic review and research agenda. Renew. Sustain. Energy Rev. 118 https://doi.org/10.1016/j.rser.2019.109519.

Mignacca, B., Locatelli, G., Alaassar, M., Invernizzi, D.C., 2018. We never built small modular reactors (SMRs), but what do we know about modularization in construction? In: 26th International Conference on Nuclear Engineering. ICONE26, London, United Kingdom.

Mignacca, B., Alawneh, A.H., Locatelli, G., 2019. Transportation of small modular reactor modules: what do the experts say? In: International Conference on Nuclear Engineering, Proceedings. ICONE.

Minunno, R., O'Grady, T., Morrison, G.M., Gruner, R.L., Colling, M., 2018. Strategies for applying the circular economy to prefabricated buildings. Building. https://doi.org/10.3390/buildings8090125.

Molina-Moreno, V., Leyva-Díaz, J.C., Sánchez-Molina, J., Peña-García, A., 2017. Proposal to foster sustainability through circular economy-based engineering: a profitable chain from waste management to tunnel lighting. Sustain. Times 9. https://doi.org/10.3390/su9122229.

NAO, 2019. Oil and Gas in the UK – Offshore Decommissioning.

Nonomura, A., Umeda, Y., 1999. Life cycle simulation for the inverse manufacturing. In: Proceedings First International Symposium on Environmentally Conscious Design and Inverse Manufacturing. IEEE, Tokyo, Japan. https://doi.org/10.1109/ECODIM.1999.747703.

NS Energy, 2018. Novatek's $27bn Yamal LNG project reaches full capacity. URL. https://bit.ly/37RhsVE. accessed 10.1.19.

Perkmann, M., Walsh, K., 2007. University–industry relationships and open innovation: towards a research agenda. Int. J. Manag. Rev. 9, 259–280. https://doi.org/10.1111/j.1468-2370.2007.00225.x.

Preston, F., Lehne, J., 2017. A wider circle?. In: The Circular Economy in Developing Countries A Wider Ci.

Pulaski, B.M., Hewitt, C., Horman, M., Guy, B., 2004. Design for deconstruction. Mod. Steel Construct. 44, 33–37.

Purnell, P., Velenturf, A.P.M., J, P.D., Cliffe, N., Jopson, S.J., 2018. Developing Technology, Approaches and Business Models for Decommissioning of Low Carbon Infrastructure.

RSA, 2015. North Sea Oil and Gas Rig Decommissioning & Re-use Opportunity Report.

Sainati, T., Locatelli, G., Brookes, N., 2017. Special Purpose Entities in Megaprojects : empty boxes or real companies? Proj. Manag. J. 48.

Schischke, K., Proske, M., Nissen, N.F., Lang, K., 2016. Modular Products : smartphone design from a circular economy perspective modularity. In: Electronics Goes Green 2016+ (EGG), pp. 1–8. https://doi.org/10.1109/EGG.2016.7829810. Berlin, Germany.

Schulte, U.G., 2013. New business models for a radical change in resource efficiency. Environ. Innov. Soc. Transitions 9, 43–47. https://doi.org/10.1016/j.eist.2013.09.006.

Thomas, S., 2019. Is it the end of the line for Light Water Reactor technology or can China and Russia save the day? Energy Pol. 125, 216–226. https://doi.org/10.1016/j.enpol.2018.10.062.

Treasury, H.M., 2015. Valuing Infrastructure Spend: Supplementary Guidance to the Green Book.

Treasury, H.M., 2018. The Green Book - Central Government Guidance on Appraisal and Evaluation.

Umeda, Y., Fukushige, S., Tonoike, K., 2009. Evaluation of scenario-based modularization for lifecycle design. CIRP Ann. - Manuf. Technol. 58, 1–4. https://doi.org/10.1016/j.cirp.2009.03.083.

United Nations, 2015. Transforming Our World: the 2030 Agenda for Sustainable Development.

Vegel, B., Quinn, J.C., 2017. Economic evaluation of small modular nuclear reactors and the complications of regulatory fee structures. Energy Pol. 104, 395–403. https://doi.org/10.1016/j.enpol.2017.01.043.

Velenturf, A.P.M., 2018. British infrastructure not ready for circular economy. In: Priorities for UK Waste and Recycling Policy and Developing the Circular Economy. Westminster Energy, Environment & Transport Forum.

Velenturf, A.P.M., Jopson, J.S., 2019. Making the business case for resource recovery. Sci. Total Environ. 648, 1031–1041. https://doi.org/10.1016/j.scitotenv.2018.08.224.

Wind-turbine-models, 2019a. Enercon E-53 - 800,00 kW - wind turbine. URL. https://en.wind-turbine-models.com/turbines/530-enercon-e-53. accessed 12.11.19.

Wind-turbine-models, 2019b. Enercon E-126 7.580. URL. https://en.wind-turbine-models.com/turbines/14-enercon-e-126-7.580. accessed 12.11.19.

Yamal, L.N.G., 2015. About the project. URL. http://yamallng.ru/en/. accessed 9.20.19.

Yan, J., Feng, C., 2014. Sustainable design-oriented product modularity combined with 6R concept : a case study of rotor laboratory bench. Clean Technol. Environ. Policy 95, 95–109. https://doi.org/10.1007/s10098-013-0597-3.

B.3 Publication III

Mignacca, B., Locatelli, G., 2021. Modular circular economy in energy infrastructure projects: Enabling factors and barriers. Journal of Management in Engineering (accepted, to be scheduled for an issue) - **Scopus indexed journal, Impact Factor: 3.928, ABS 2**.

Modular circular economy in energy infrastructure projects:

Enabling factors and barriers

Benito Mignacca, School of Civil Engineering, University of Leeds, Woodhouse Lane, Leeds LS2 9JT (UK) e-mail: cnbm@leeds.ac.uk

Professor Giorgio Locatelli, School of Civil Engineering, University of Leeds, Woodhouse Lane, Leeds LS2 9JT (UK) e-mail: g.locatelli@leeds.ac.uk CORRESPONDING AUTHOR

Abstract

There is a growing body of literature surrounding Circular Economy (CE) and energy infrastructure projects. However, most of this literature focuses on CE initiatives related to material recovering and recycling. The body of knowledge about reusing components is limited and mostly related to the need for reusing rather than providing solutions on how to reuse components. Modularization can be a step towards a solution, enabling entire modules or their components to retain their functionality in other infrastructures. Leveraging 23 semi-structured interviews with nuclear and oil and gas experts, mainly based in the UK and US with international experience, this paper deals with the link between modularization and CE (defined Modular CE) to identify enabling factors and barriers for the reuse of modules or their components. Relevant enabling factors are the monitoring of module and component conditions, standardization of module and component designs, and early planning. Relevant barriers are the lack of a second-hand market, economics, and regulatory challenges. The results are relevant to the stakeholders involved in planning, building, operating, and decommissioning energy infrastructures.

Keywords

Modularization, Modularity, Standardization, Infrastructure, Sustainability, Circular Economy

Introduction

Modularization is the "*process of converting the design and construction of a monolithic or stick-built plant to facilitate factory fabrication of modules for shipment and installation in the field as complete assemblies*" (GIF/EMWG, 2007) (Page 24). The transition from traditional stick-built construction to modularization is a key driver for reducing construction time and cost of Energy Infrastructure Projects (EIPs), as described at length in the literature (Choi et al., 2019, 2016; Nabi and El-Adaway, 2020; O'Connor et al., 2014). Building on (Invernizzi et al., 2020a), EIPs can be defined as "the planning, construction, upgrading, and decommissioning of energy infrastructures". This paper deals with an under-researched topic, i.e. the link between modularization and EIP environmental sustainability through the implementation of Circular Economy (CE) initiatives. There is a plethora of definitions of CE (Kirchherr et al., 2017); this paper adopts Preston and Lehne's (2017) definition: "*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*" (Page 4). In other words, CE is concerned with maintaining resources at their highest value possible through CE initiatives such as reuse, repairing and recycling of components and materials (Ellen MacArthur Foundation, 2020; Minunno et al., 2020; Rausch et al., 2020; Velenturf and Purnell, 2021).

The opportunity to improve the EIP environmental sustainability by leveraging modularization has been mostly overlooked by academics, practitioners and policy-makers. (Mignacca et al., 2020b) recently highlighted this gap in knowledge by utilising a systematic literature review. They also theoretically conceptualized the link between modularization and CE, presenting the Modular CE, i.e. "*the factory fabrication, transportation and installation on-site of modules aiming to facilitate the reuse/repair/replacement/recycling of modules/components/materials*" (Page 5). (Mignacca et al., 2020b) focused on two main objectives of the Modular CE: 1) Extending infrastructure lifetime, and 2) Extending module and component lifetime.

Regarding the first objective, traditional stick-built construction can hinder the repairing and replacing of components; it might be challenging and too expensive to remove components, limiting the opportunity of repairing and replacing during operations, ultimately determining the infrastructure lifetime. Modularization could extend the infrastructure lifetime by enabling an easier repairing and replacement of modules and components.

Regarding the second objective, when the infrastructure reaches its end-of-life (e.g. due to economic, legal or functional reasons), some components have still a residual lifetime, which is usually wasted. Modularization could facilitate the reuse of components with residual lifetime by reusing entire modules (or their components), retaining their functionality in other infrastructures.

In this setting, modularization could facilitate the implementation of CE initiatives. There is extremely limited empirical or theoretical literature supporting the link between modularization and CE in EIPs. By engaging with practitioners, this research focuses on the second objective of the Modular CE, aiming to empirically investigate which factors enable or hinder the opportunity of reusing energy infrastructure modules or their components.

Needs and research questions

As part of the United Nations' Sustainable Developments Goals (SDGs), SDG 9 (Industry, Innovation and Infrastructure) is focused on infrastructures. Infrastructures are also considered within SGD 11 (Sustainable Cities and Communities) and SDG 6 (Clean Water and Sanitation) (United Nations, 2020). Globally, infrastructures will require $94 Trillion until 2040 for brand new investment, replacement investment and spending on maintenance (Infrastructure Outlook, 2020). Out of this $94 Trillion, $28 Trillion will be required for energy infrastructures. These numbers give an idea of the *grand challenge* of implementing sustainable initiatives in infrastructure projects in general, and in EIPs in particular, to achieve the SDGs. The implementation of Modular CE initiatives would, for instance, reduce the need for raw materials and the embodied carbon invested in the production of modules and components. Remarkably, there is no empirical research investigating the factors enabling or hindering the reuse of modules or their components in EIPs. This paper aims to fill this gap by addressing two Research Questions (RQs):

RQ1: Which factors enable the opportunity of reusing energy infrastructure modules or their components?

RQ2: Which factors hinder the opportunity of reusing energy infrastructure modules or their components?

Scope and organization of the paper

The scope of this paper concerns EIPs. The reasons relate to the characteristics of energy infrastructures: relatively short life-cycles (compared to, for instance, roads and rails), making the reuse of modules and components extremely relevant; the budget to be invested until 2040, i.e. $28 Trillion (Infrastructure Outlook, 2020); and their environmental impact. The paper is organized as follows: a review of the literature on the main areas investigated in this paper, i.e. modularization and CE in EIPs; the methodology adopted to answer the aforementioned RQs; the results and related discussions; conclusions, contributions and future research recommendations.

Literature review

Modularization in energy infrastructure projects

Most of the literature concerning modularization in EIPs deals with working in a better-controlled environment leading to quality improvement, construction schedule and cost reduction (Choi et al., 2019, 2016; Ikpe et al., 2015; Mignacca et al., 2018; O'Connor et al., 2015, 2014). Modularization is essential to build infrastructures in remote areas characterized by logistic or environmental challenges, such as extreme temperatures (Auverny-Bennetot et al., 2019). Modularization can bring further benefits (e.g. in terms of cost and schedule reduction) if coupled with standardization. (O'Connor et al., 2015) stressed this point and highlighted two approaches to integrate design standardization with modularization: "Modular Standardized Plant", i.e. standardization of plant design and modularization of the design to obtain standard modular plants; and "Standard Modules", i.e. modularization of the design and standardization of some modules. The degree of standardisation is a key aspect for EIP planning and delivery (Choi et al., 2020c; Shrestha et al., 2020). The most relevant standardization critical success factors are the discipline to maintain standardization, operations and maintenance considerations and the definition of the standardization approach (Shrestha et al., 2021).

Modularization also presents challenges, such as a higher project management effort (Carelli and Ingersoll, 2014), the need for designing collision-free cranes before construction (Han et al., 2015), a higher cost for transportation activities (Mignacca et al., 2019), the managing of excessive geometric variability risks (Enshassi et al., 2019), and uncertainties in off-site logistics (Yang et al., 2021).

Prior research investigated the factors influencing the successful implementation of modularization. (O'Connor et al., 2014) identified 21 critical success factors; the top five-ranked are: 1) "Module Envelope Limitations" (i.e. preliminary transportation evaluation); 2) "Alignment on Drivers" as early as possible among relevant stakeholders; 3) "Owner's Planning Resources & Processes" (i.e. early modular feasibility analysis supported by owner's front-end planning and decision support systems, work processes, and team resources support); 4) "Timely Design Freeze" by owner and contractors; and 5) "Early Completion Recognition", i.e. business cases should include economic benefits derived from earlier project completion. (Choi et al., 2016) investigated the effect of each of the 21 critical success factors (or a critical success factor combination) on cost and schedule performance. A key result is the mix of sufficient solutions for cost success, i.e. "owner-furnished/long-lead equipment specification", "timely design freeze", and "a combination of vendor involvement and owner delay avoidance". Another key result is the mix of sufficient solutions for schedule success, i.e. "a combination of vendor involvement and management of execution risks", "timely design freeze", and "a combination of owner-furnished/long-lead equipment specification and management of execution risks". (Choi et al., 2020a) showed the innovative technologies and approaches most impactful on modularization success, i.e. standardization, materials logistics management, and automated design.

The literature also discussed models defining the optimum level of modularization to maximize its benefits. (Choi et al., 2019) presented a business analysis model identifying the optimum level of off-site work hours considering the owners' objectives. The model estimates the total cost saving according to a different percentage of modularization, considering implications such as safety and quality benefits, transportation cost and yard management.

Circular economy in energy infrastructure projects

The literature about CE in EIPs is minimal, and in some cases, ambiguous. In the next sections, prior literature of CE in EIPs is categorized in three domains: 1) Raw material (e.g. steel); 2) Module (e.g. pump) and component (e.g. valve); and 3) System (infrastructure as a whole).

Raw material domain

The majority of the literature regarding CE in EIPs deals with raw materials, describing CE initiatives aimed at recovering and recycling. (Busch et al., 2014) stressed the importance of monitoring the critical materials (i.e. materials at risk of supply disruption, such as rare earth elements, cobalt, and lithium) embedded in infrastructures, thereby enabling opportunity for material recovering and reusing. The authors presented a stocks and flows model to quantitatively evaluate CE initiatives.

(Lapko et al., 2019) identified enabling factors (e.g. legislation support for waste reduction and collection of end-of-life products) and bottleneck conditions (e.g. lack of appropriate recycling technology and instability of market for recycled materials) for the implementation of a closed-loop supply chain for critical raw materials in the case of photovoltaic panels and wind turbine technologies. (Heath et al., 2020) focused on the materials of crystalline silicon photovoltaic modules, suggesting initiatives that could improve the effectiveness of photovoltaics recycling, such as recycling infrastructures able to deal with several modules designs and considering the trade-offs among costs and revenues and environmental impact. (Roelich et al., 2014) presented a method for monitoring changes in material criticality (i.e. "*potential for supply disruption of a particular material, and the impact of this disruption on the system of interest*" (Page 379)) during the transition to low-carbon infrastructures. Furthermore, (Christmann, 2018; Dong et al., 2019; Ng et al., 2016; Reuter et al., 2015) discussed the importance of sustainable management of metals (such as lead and zinc and their minor elements) and minerals both in terms of higher reusing and recycling.

(Krausmann et al., 2017; Schiller et al., 2017) stressed the fact that the industrialized nations have accumulated and keep accumulating anthropogenic material stock in terms of infrastructures and other durable goods. According to (Schiller et al., 2017), this stock should be considered as future capital stock and be properly exploited and managed, and not only focused on the input of raw material.

(Schiller et al., 2017) presented an approach allowing analysis of the anthropogenic material stock of a national economy.

Module and component domain

The distinction between module and component is complex (Brusoni and Prencipe, 2001). For instance, a pump can be considered both a module (including components such as bearings) and a component (as part of a reactor pressure vessel). In general, modules and components are functional units and are treated as such in this research. The literature in this domain is scarce and mostly highlights the need for CE initiatives rather than CE solutions. According to (Invernizzi et al., 2020b), policy-makers need to act proactively in developing policies favouring CE solutions (e.g. the reusing of components) for future energy infrastructures to tackle the challenge of decommissioning megaprojects. (Jensen et al., 2020) highlighted this need in the case of low carbon infrastructures, focusing on offshore wind. (Invernizzi et al., 2020b) argued that existing energy infrastructures could also adopt CE solutions; however, costs and benefits can be optimized if the design (and construction) phases consider CE principles. The aforementioned model of (Busch et al., 2014) also includes components with their own stocks and flow dynamics to evaluate the potential for reuse quantitatively.

Regarding the modules, (Mignacca et al., 2020a) focused on the specific case of Small Modular nuclear Reactors (SMRs), providing a ranking of the factors favouring or hindering the reuse of SMR modules. The ranking shows that standardization of module designs and interfaces are critical factors for the reuse of modules. (Mignacca et al., 2020b) conceptualized the Modular CE, arguing that modularization could favour the implementation of CE initiatives, such as reusing and replacement. Remarkably, there is no empirical research about the identification and examination of the factors favouring and hindering the reuse of energy infrastructure modules or their components. The theoretical conceptualization is compared to the empirical results of this research in the discussions.

System domain

The system domain focuses on CE initiatives by considering the infrastructure as a unit of analysis. This literature deals with topics such as using infrastructure waste as feedstock for other infrastructures or products. A much-discussed topic is represented by the opportunity to reclaim energy from waste and, more generally, resources from waste (Fuldauer et al., 2019; Liguori and Faraco, 2016; Purnell, 2019; Venkata Mohan et al., 2016; Vondra et al., 2019). For instance, (Vondra et al., 2019) focused on the biogas plants (i.e. plants that rely on anaerobic digestion to produce methane gas from organic waste), highlighting how an unsustainable treatment procedure for residual liquid digestate could determine the escape of bio-resources from the CE, generating net waste. (Vondra et al., 2019) recommended a vacuum evaporator system and presented a techno-economic analysis tool to favour the decision-making regarding its implementation.

(Velenturf et al., 2019) reported a series of technologies under development that can recover organic and inorganic fractions from waste, such as "*biorefineries that incorporate microbially-mediated metal recovery approaches to produce new catalysts from liquid wastes, for the production of liquid and gaseous fuels in addition to generating electricity from bio-hydrogen via fuel cell catalysts*" (Page 967). Another key topic in this area is cogeneration, i.e. the generation of two different valuable products from a single primary energy source, saving a significant amount of energy (Locatelli et al., 2018, 2017). According to (Iacovidou et al., 2017), traditional decision-making methods such as life-cycle assessment and cost-benefit analysis do not address the multi-dimensional value spanning the economic, social, environmental and technical domains. (Iacovidou et al., 2017) provided a novel approach that allows assessing and evaluating complex value in said domains by adopting a whole-system perspective and providing multi-dimensional outputs.

Research methodology

Research context

The context of this research is EIPs, particularly nuclear and oil and gas. The vast majority of nuclear reactors in operations are stick-built, but recently considerable effort has been invested in moving to modular structures (Locatelli and Mignacca, 2020; Wrigley et al., 2021). Four modular reactors, called AP1000, have been built in China, and two are under construction in the US (World Nuclear Association, 2020). Furthermore, a new class of reactors, called SMRs, has been proposed and discussed over the last two decades. Modularization is one of the main characteristics of SMRs (Lloyd et al., 2021; Mignacca and Locatelli, 2020a). The oil and gas sector is also relevant to the research as modularization has been practised for the last 40 years (Bjørnstad, 2009).

Research approach

In order to investigate the factors enabling and hindering the reuse of modules or their components, and given the exploratory nature of this research, the authors adopted the inductive approach. The inductive approach does not formulate hypotheses at the beginning (Thomas, 2003), and it is appropriate to explore a new phenomenon, identify the patterns and contribute to new generalizations (Bryman and Bell, 2015; Saunders, 2011).

Data collection and sampling strategy

Data were collected through semi-structured interviews following (DiCicco-Bloom and Crabtree, 2006)'s recommendations. Experts (interviewees) and researchers have the opportunity, in semi-structured interviews, to ask for details, clarifications or follow-up questions (Rubin and Rubin, 2011). Experts were selected by combining purposive sampling (Palinkas et al., 2015) and snowball sampling (Goodman, 1961). Two criteria guided the selection of the experts: 1) At least 10 years of experience in the nuclear or oil and gas sector, and 2) Sufficient expertise about modularization. Fourteen experts were selected by purposive sampling (initial sample), who then involved another ten experts in the research (snowball sampling). A total of 23 interviews were conducted between April and November 2019, corresponding to a total of 24 experts (two participants preferred to be interviewed at the same time). At the time of the interview, the 24 experts had on average 29 years of experience in the nuclear or oil and gas sector, mostly in the UK and US. These experts worked, at the time of the interviews, for 20 different companies. The appendix provides detailed information about the experts. Data collection stopped when data saturation was obtained, i.e. when data collection became redundant, and the content was clear to the authors (Hennink et al., 2017). Three out of the 23 interviews were pilot interviews to verify the knowledge of the experts about CE and the clarity of the questions. One of the three pilot interviews was conducted with a cross-sectorial end-of-life management expert in order to ensure the "circular economy" lens of the research. The 3 pilot interviews lead to the final version of the questionnaire. Table 1 shows the final semi-structured questionnaire used as a basis for the dialogue and the related purpose.

Purpose	Semi-structured questionnaire questions
Preliminary questions	1. Could you tell me your definition of modularization? 2. Could you give examples of modules in your field?
RQ1: Which factors enable the reuse of energy infrastructure modules or their components?	3. What is necessary for deciding to build a "modular plant" instead of a traditional plant built on-site? 4. What is necessary to reuse the modules as a whole? 5. What is necessary to reuse the components of modules?
RQ2: Which factors hinder the reuse of energy infrastructure modules or their components?	6. What are the barriers of modularization? 7. What are the barriers to reuse the modules as a whole? 8. What are the barriers to reuse the components of modules?
Circular economy knowledge	9. Have you ever heard about the circular economy?
Snowball sampling	10. Could you kindly advise some experts like you to contact for an interview?

Table 1: Semi-structured questionnaire questions - Layout adapted from (Locatelli et al., 2020)

The expected length of each interview was 30 minutes, but 2 interviews lasted around an hour. On average, interviews lasted 31 minutes. Interviews were conducted via Skype except for one that was conducted in person and one where the interviewee emailed the answers. All the participants gave permission for recording the interview, and anonymity was guaranteed.

Data analysis

Interviews were transcribed and analyzed through thematic analysis (Nowell et al., 2017), i.e. "*a method for identifying, analyzing and reporting patterns (themes) within data*" (Braun and Clarke, 2006) (Page 79). It is "*a form of pattern recognition within the data, where emerging themes become the categories for analysis*" (Fereday and Muir-Cochrane, 2006) (Page 82). The thematic analysis researcher does not necessarily relate frequency with importance, where the content analysis researcher would, but rather focuses on the relationship between a theme and the RQs (Vaismoradi et al., 2013). Considering the exploratory nature of the research, thematic analysis was conducted in order to avoid missing themes that could be relevant to this and future research.

After the interviews were verbatim transcribed, the interviewer (one of the authors) carried out the coding process (i.e. the identification, analysis and reporting of patterns (themes) within the transcripts). NVivo 12, a Computer-assisted Qualitative Data Analysis Software, was used to facilitate a systematic categorization of the information. A two-step coding process was followed, as suggested by (Saldaña, 2015): 1) Summarising in a few words each relevant section. These represented a theme or sub-theme (nodes); and 2) Reorganizing the long initial list of nodes in a smaller number of themes and sub-themes based on similarities (final coding). The coding can start both from themes or sub-themes (Nowell et al., 2017). In this case, the final coding started from sub-themes.

After the first coding process, several discussions between the authors led to the final list of themes and sub-themes. Table 2 reports two examples of the main steps of the coding process.

The two step-process in Table 2 led to the identification of 2 themes (enabling factors and barriers) and 10 sub-themes. The "enabling factors" theme includes four sub-themes: monitoring of module and component conditions, design standardization of modules and components, suitable dimension for transportation and inspection, and early planning. The "barriers" theme includes six sub-themes: regulation, political pressures, lack of a market, economics, lack of maintenance, and module and component contamination.

Extract from the interviews	Preliminary coding (Nodes)	Final coding (Sub-themes)	Final coding (Themes)
Does its condition affect the performance of a new plant that it will be inserted	Performance of new infrastructure	Monitoring of module and component conditions	Enabling factors
When you get the end of your design life, it may be that there are auxiliary systems of modules in which case you might be able to refurbish and reuse them but [...] you're talking 60-80 years into the future, so one would have to see the condition of those modules	Understanding module conditions		
This is one of the design requirements, as engineers [...] we put design requirements on our systems, if you impose a design requirement that it should be easy to disassemble	Planned easy to disassemble	Early planning	
In order to be able to do that, your modularisation approach and your design [...] has to account for that [...] at the beginning, so making sure that you can safely detach modules	Planned safe detachment		

Table 2: Examples of the coding process

Results

Enabling factors

Monitoring of module and component conditions

A relevant factor enabling the reuse is the monitoring of module and component conditions. An interviewee explained why and for which stakeholders monitoring is relevant: "*Requirement for reuse is monitoring the condition of the pump or motor or pipe; because if you're going to be the receiver of a used module, you want to make sure that it has a lifetime, it's not [going to] break the week after you get it; and also allows the initial user of the module to determine when it's no longer feasible for my facility to continue using the module".*

Monitoring is already a common practice in some circumstances, even if it cannot be fully accurate, as one interviewee highlighted: *"We have very good [...] ageing monitoring programs in place that are becoming even broader and cheaper because of the information technology boom. Sensors can relay transmitted frequencies or thicknesses back to a central location rather than have to send people out* *with a handheld instrument to do all the monitoring [...]. If you're monitoring [...] the thickness of a pipe because pipes tend to rust and corrode with use [...], you don't monitor every inch of a pipe, you try to pick the most limiting locations and assume that everything else is better shaping than. So you have to convince yourself and any prospective users that you've selected the right points, the most telling points [...]. If you don't, then you sell them a part that breaks a week later; he's probably going to sue you. So that it's becoming easier [...], we have fewer surprises, but that's still a challenge because whether you are buying a used car or a used module from nuclear power plants or component, you want to have some assurance that it will last a while".*

Design standardization of modules and components

The interviewees stressed the importance of standardizing modules and components to enable their reuse or make it more cost-effective: "*If you got a module or a set of components standardized [...], you'll be able to replace them and reuse [them] in somewhere else [...]. Standardization will allow to optimize that reuse, will make that more cost-effective [...]; systems or different work plants will be working on the same conditions, and you can use and standardize components [...], [this is the] main driver for reusing*". Some decades ago, standardization was a key enabling factors to reuse components, as one interviewee highlighted: "*For the "X plant" in "Country Y", when it shut down [...] in the late 1970s and into the early 1980s, a number of their components [...] were used in another plant because there were other plants [which] needed exactly [the] same components [...]*".

Some comments about the relevance of standardization were not strictly related to the reuse but to the Modular CE initiatives in general. On this matter, one interviewee commented about the opportunity of easier and more cost-effective upgrades: "*If you have a fleet of [identical] modules, then you can maintain them all in the same way at low cost, and you can optimize them all in the same way. [...] If you look at today's nuclear fleet, all of the control systems are different, and if you had an enhancement, it's very difficult to roll it out across the fleet; whereas if you've got a fleet of modular plants and they're all the same device, you can keep the software in much better control and control the updates lot better"*.

Suitable dimensions for transportation and inspection

The transportation of large dimension modules is a significant challenge in traditional modularization. In the case of reusing modules, module dimensions need to be suitable for inspection and transportation to other infrastructures. On this matter, one interviewee stated: "*The modules should be respected in size and weight, so that they can be removed from the site and returned to a place where they can be refurbished or reloaded if necessary with fuel, and inspected properly […]. The size of the module itself […] needs to be smaller enough to remove, […] transport, and inspect"*.

Early planning

The interviewees stressed the importance of early planning to allow the implementation of the Modular CE initiatives in general (e.g. easier replacement), and the reuse of modules and components in particular: "*We have […] reused some parts from nuclear power plants, either that have permanently shut down or some parts wear out […]. We haven't done a real good job of pre-planning […]. For example, some of our large parts were installed in the concrete walls […], so we had to cut holes in the walls to remove the large parts when they wore out, […] we didn't anticipate that need and designed for it […]. I think […] a modular plant with some pre-planning, you can benefit or maximize the reuse of those materials whether it's modular walls, pipes, pumps, whatever".* Another interviewee stated: "*First of all, the design has to be done from the very beginning with the intention of reusing it […]. If you don't plan for that at the beginning, then reusing becomes quite expensive if you have to cut the piping system, you have to cut the wiring*". Furthermore, "design for disassembly" was mentioned as a design feature to consider in early planning: "*For reusing, […] I would look for design features that allow […] the modules to be disassembled*".

Barriers

Regulations

Interviewees argued that regulatory challenges could hinder the opportunity of reusing. One of the key aspects is the demonstration that modules or components can be used "safely" in other infrastructures: "*If after 20 years you decide […] to move a module from point A to point B, you're [going to] have to demonstrate that it has enough life left in it to make it worthwhile. You can't take a 20-year-old module and put it in […] a new plant and try and get a 40-year licence without doing a […] lot more work to demonstrate that something that was right for 40 years can now work for 60 […]; you have the whole lifetime justification to do*". Overcoming regulation challenges can be more complex in the case of reusing modules or components in different countries: *"In the "Country X" they used "Code Z" […], when we brought that design to the "Country Y" to license it through the generic design assessment process […], "Country Y" regulators just said that code doesn't apply […]. "Vendor A" had to effectively go back to first principles calculations to demonstrate why the civil structures were acceptable for the nuclear power station*".

Regulation challenges can determine choosing to build a new module or component instead of demonstrating its suitability for the reuse: "*Coming from "Country X" to "Country Y", […] a piece of equipment that was already […] used in "Country X", no longer in use, it was […] effectively in a nice frame, so I thought that could just be lifted. […] Then I […] said no […], when I thought about […] how do I demonstrate his pedigree to the "Country Y" regulator for a piece of second-hand equipment […], how do I translate codes and standards, wiring standards, […] all those different things. I came to the conclusion that […] we will be better constructing it in "Country Y*".

Political pressures

A relevant challenge is the role of politics in limiting the opportunity of reusing. An interviewee explained how a political strategy to increase job opportunities in a country set limitations on the import of equipment by setting country localization requirements: "*Coming from "Country X" to "Country Y", […] a piece of equipment that was already used in "Country X", no longer in use, it was […] effectively in a nice frame. [..] I thought that could just be lifted, and then […] I said no […]; there was another driver in "Country Y" because I was there in "Year Z" and so "Country Y governor" […] was in charge, they made good progress […], wanted to continue that progress and […] put as much work in "Country Y" […]. So it wasn't a major driver, but it was a lot of pressure on there*".

Lack of a market

The lack of a market for second-hand modules and components is a major barrier to their reusing. The interviewees pointed out several factors that could hinder the creation of a second-hand market. Technology obsolescence determined by technological progress can be a major barrier: "*Even if it's only a few years old, the turbine supply might say […] this new turbine it's got the Gen-4 blade set in it that gives a 9.5 per cent efficiency advantage out of the turbine, and you get your calculator out, […]*

and it saves you ten times more money than […] using the old device". One interviewee mentioned the "not invented here syndrome" and the interest of the vendors as two factors hindering the creation of a second-hand market: "*I think […] is the not invented here syndrome, how do you get over that, and that requires a coherence at the top of the organization […]. The vendor might want to sell 12 rather than one moving around. [It] depends [on] what the relationship between the vendor [and] the operator is; […] if that's a transactional relationship driven purely by cost, then the vendor might design something that […] isn't […] transportable".* The difficulty in performing maintenance and obtaining spare parts could also hinder the creation of a second-hand market: "*The ability to perform maintenance and obtain spare parts becomes more and more difficult over 60-80 years*".

In the case of plants for gas treatment or compression, the peculiarity of the gas can also hinder the opportunity of reusing: "*If you have a treatment or compression plant that is designed in a specific way for a particular gas that comes out from a well, […] the well in place A can be completely different from the well in place B both in terms of gas flow rate and composition; […] in this case, it is very difficult and complicated, and the loss in efficiency […] can be a bit heavy".* Remarkably, in the case of very small modules, a market (although very limited) already exists: "*I'll do an example. Many extraction wells, all of them more or less with similar characteristics but they are activated in different times; if you build a module, a small module with everything is needed for gas treatment, oil treatment [etc.] for one of these wells; then when the well is closed […] because in these areas they have not a long life, so it is used 3,4,5 years in this well, and then it is taken, moved to another place for 3,4 years and […] so on. This is a very particular market, usually very small; we are talking about small wells […]; therefore, everything around is also small".*

Economics

The choice of reusing a module or component or deciding to build or buy a new one can be driven by economic reasons, and the reuse option may not be cost-effective. On this matter, one interviewee stated: "*It will be a relatively expensive process […], and it will also be the cost-benefit of doing this versus the cost of buying a brand new reactor assembly of the same design […]. [If] you have a facility that's building […] 10 or 15 of these a year, so you are now already at the economics of the nth unit being produced, […] the marginal cost of producing an additional unit [is] relatively [low]. If you* *compare that with the costs of dismantling the other facility, taking it apart and moving it to a new location having to work with radioactive components, it may not be cost-effective. The analysis would need to be done, but my initial reaction would be that perhaps it would not be cost-effective*".

The cost and availability of a module or component could also influence the choice of reusing: "*I think [...] the primary driver will probably be either cost and/or availability of that specific component. [...] If it's a consumable type off-the-shelf commercial grade, you might not reuse it [...] because there's a cost of [...] disassembly, reassembly, but if it's high-value [...]".* Furthermore, an additional design effort is needed to allow the reuse, which results in an additional cost that could limit the opportunity of reusing: "*Any additional design effort which is required to design a power station that could be recycled or reused will incur additional costs, and it's difficult to see how that cost could be recovered, given that seems unlikely that today a customer would be willing to pay that extra premium".* Although most of the interviewees agree on the fact that economics could hinder the opportunity of reuse, one interviewee stated: "*It can be a big saving [...] in terms of time and in terms of cost, maybe not so much in term of quality if [...] you think about the three dimensions [...]; because those components have a life-cycle which is extremely lower with respect the other components of the other plant, but [...] maybe I am reusing that turbine to another plant which has already ordered and whose turbine is exhausted, so [...] it would be a good way to saving money and time".*

Lack of maintenance

In some circumstances, module and components are not properly maintained, preventing their reuse: "*When I was in "Country X" I was construction manager of the revamping of the refinery of "Company Y", and it was crazy the situation over there [...], lack of maintenance [...], one furnace got fired, there was the other besides that continued to work, was full of leakage of gas everywhere, constant danger of explosion, they didn't care, they continued to refine and postponing the maintenance [...]. In certain situations, in some countries [...], the maintenance is so poor that the risks are so high [...].* Another interviewee argued: "*Barriers would be [...] lack of maintenance to maintain the mechanical structural integrity; if modules are not strong enough, then you can't move them to reuse".*

Module and component contamination

Modules and components can get contaminated, preventing the reuse: "*The barriers would be if […] a part of the plant [is] radioactively contaminated, then the module itself may become slightly radioactive. That's not a showstopper; there are ways to decontaminate pipes or walls and so on".* The interviewees provided the following suggestions to deal with this barrier:

- Proper shielding during transportation: "*Moving large radioactive assemblies has been done before but typically […] these are transported for burial, for disposal […]. The transportation of components was done over roads and so on with proper shielding […], but they were mainly, as far as I know […], destined for burial and disposal, not for reuse*".

- Focusing on the balance of plant: "*It would be best to focus on the balance of plant, because […] in the case of a fission plant they're not hot […]; [there is the] whole area of the core that you can't reuse because it's hot, it's radioactive, it's impractical*".

- Considering the differences between the technologies: "*In balance of plant fairly straightforward on a PWR [Pressurized Water Reactor], less easy on a BWR [Boiling Water Reactor] […] where the steam goes directly into the turbine and hence is likely to be more active*".

- Length of plant operation does not influence the contamination challenge: "*It doesn't really matter […] you've operated one or two years, you're [going to] have the activation of materials, the contamination will be there whether you operate for two years or fifty years".*

Discussions

The words modularization and modularity are often used interchangeably in EIP scientific and industrial literature, although they have different meanings. Figure 1 clarifies the difference between modularization and modularity in EIPs and provides a graphical summary of the construction strategies discussed in this paper.

The Modular CE is a novel strategy in EIPs, theoretically conceptualized in (Mignacca et al., 2020b). The Modular CE refers to a series of initiatives fostered by modularization, such as the reuse, repairing and recycling of modules, components and materials. The idea of leveraging modularization to favour CE implementation and improving EIP sustainability comes from modular products (e.g. computers), where the link between modularization and CE is already recognized and, to a certain extent, implemented. However, the Modular CE has never been empirically investigated in EIPs. This paper fills this gap in knowledge by empirically identifying enabling factors and barriers for the reuse of energy infrastructure modules or their components.

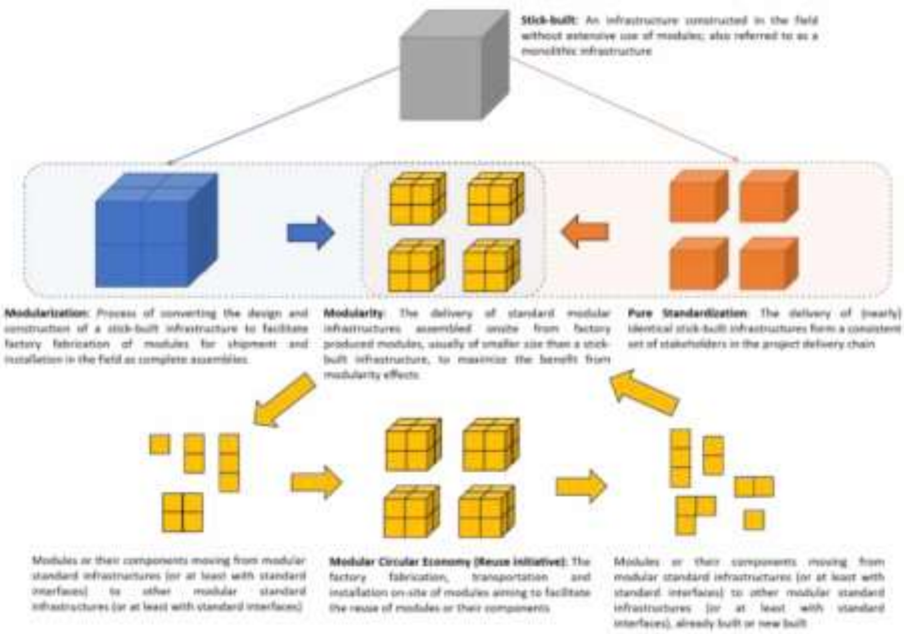


Figure 1: Modularisation, Modularity, Pure Standardization, Modular Circular Economy – Data from *(Mignacca and Locatelli, 2020b)*

Figure 2 summarises the factors favouring or hindering the reuse of modules or their components, showing: new factors that emerged from the interviews; factors that emerged from the interviews consistent with the theoretical conceptualization of (Mignacca et al., 2020b); and theoretically conceptualized factors that have not emerged from the interviews. Furthermore, Figure 2 provides relevant insights on how enabling factors and barriers are influenced, positively or negatively, by other factors.

(Mignacca et al., 2020b) stressed the importance of standardization at two different levels: the standardization of modules (and their components) and the standardization of modular infrastructures (i.e. modularity). The interviewees fully acknowledged the importance of standardization of modules and their components but only tangentially mentioned the standardization at infrastructure level.

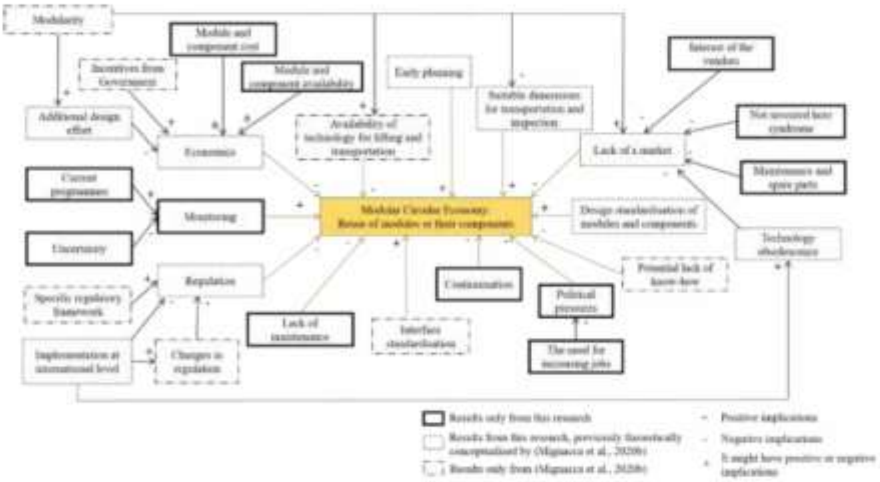


Figure 2: Enabling factors and barriers for the reuse of modules and components - Comparison with the literature about Modular CE in EIPs

The standardization of modules and components designs seems more realistic (at least in the short-term) with respect to the standardization of infrastructures as whole systems. Indeed, components such as turbines have a higher degree of standardisation than a whole power plant. This is consistent with the study of (Choi et al., 2020b), which highlights that in defining the standardization strategy, the impetus may be firstly given at component level, followed by module level, and eventually at infrastructure level.

Another key enabling factor mentioned by the interviewees is the monitoring of module and component conditions to evaluate their residual lifetime. This is also highlighted by (Allwood et al., 2011) in the case of modular products and by (Mignacca et al., 2020a) in the specific case of SMRs. The interviewees stressed the importance of considering Modular CE principles since the early design stages. This is in line with the recent study of (Wijewansha et al., 2021) on CE, who also highlighted the relevance of considering CE principles before "freezing the designs".

Reuse is seen by most of the interviewees as an expensive, challenging process, sometimes unjustified and disadvantageous. The traditional "take-make-use-dispose" approach currently has limited implications from an economic point of view in EIPs, the nuclear sector being an exception where the cost of disposing of waste and components is relevant and widely investigated. In this regard, (Cooperman et al., 2021) recently highlighted how the cost of disposing of wind turbine blades in the US is relatively low with respect to the overall energy life-cycle cost, which thereby hinders the implementation of CE initiatives. According to the authors, this paradigm needs to change in EIPs. Both CE initiatives in general and Modular CE initiatives in particular need to be enforced by economic drivers in order to foster the transition to more sustainable EIPs and contribute to the achievement of the SDGs. A driver could be implementing a pay-as-you-throw approach, as in the case of some municipalities (Batllevell and Hanf, 2008), making the infrastructure's owner pay on the basis of the waste generated at the end of the infrastructure lifetime. Symmetrically, another driver would be to provide economic incentives (e.g. tax relief) for companies reusing modules or components. This approach could change the economic balance and, therefore, the perspective of the industry about the opportunity of reusing.

Currently, one of the focuses of the energy infrastructure industry is to increase the economic attractiveness by maximizing infrastructure lifetime; however, equal attention should be paid to the decommissioning phase and the opportunity to save modules and components. The lack of attention to the decommissioning phase and the opportunity to save modules and components is, to some extent, confirmed by the answers of the interviewees to question 9 of the questionnaire about CE knowledge, i.e. "Have you ever heard about the circular economy?"; most of the interviewees were not aware of the meaning of CE or even the concept.

Another key barrier that emerged from the interviews, consistently with the theoretical conceptualization, is the lack of a second-hand market. According to the interviewees, factors hindering the evolving of a second-hand market are: technology obsolescence determined by technological progress, difficulty in performing maintenance and obtaining spare parts after a long period of time, the "not invented here syndrome" hindering the willingness to include used modules and components in infrastructures, and the interest of the vendors to sell more modules and components that could hinder future uses of modules and components. Regarding technology obsolescence, the theoretical conceptualization suggests that it could be overcome by an implementation of the reuse initiative at the international level. Indeed, if country X wants to move to more efficient technologies with respect to technology A, country Y could be interested in technology A. However, the implementation at the international level could make the regulatory challenges associated with the reuse even more complicated, as pointed out by the interviewees, due to the different regulatory frameworks. Furthermore, shipping modules or components from a country with more environmentally advanced legislation to a country with more permissible legislation could have relevant environmental and moral implications that need to be carefully considered. The role of legislation (and policies) is also stressed as relevant in implementing traditional CE principles (Khan and Haleem, 2021).

A second-hand market will evolve if ad hoc initiatives are promoted by policy-makers, such as the pay-as-you-throw approach, incentives for reuse and, in general, the development of reuse strategies involving relevant stakeholders within a specific regulatory framework.

In summary, Figure 3 presents a comprehensive sense-making about the main forces pulling from "Circular Economy" to "Modular Circular Economy" and from "Circular Economy" to "Traditional Linear Economy". The authors derived Figure 3 informed by the empirical results presented and discussed in this paper and the theoretical conceptualization of the Modular CE.

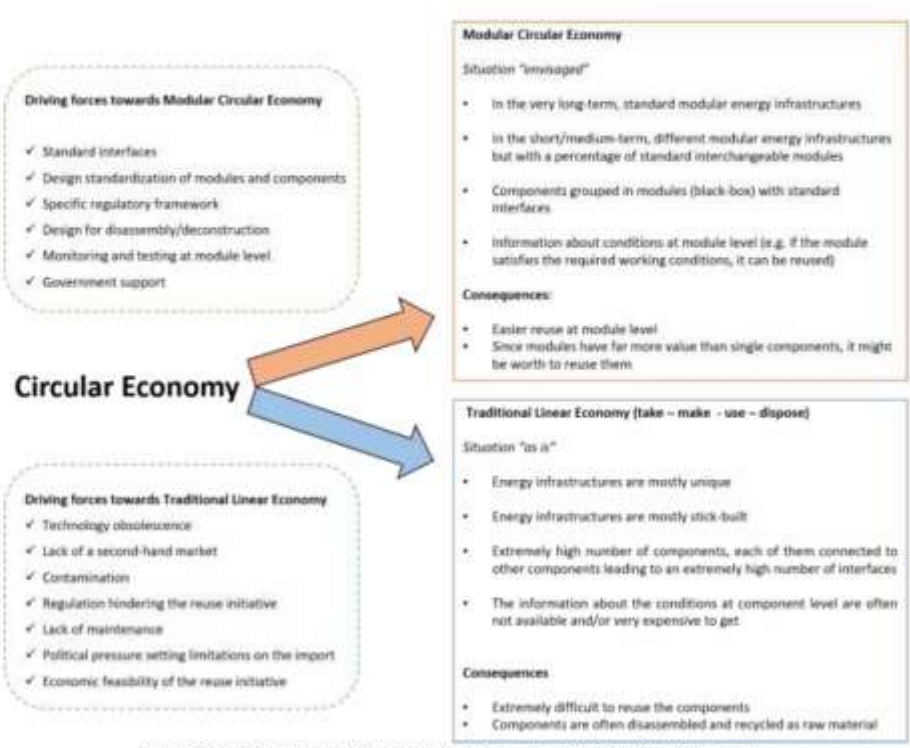


Figure 3: Driving forces towards Modular Circular Economy and Traditional Circular Economy

The remarkable novelty of the Modular CE is shifting the main focus from component to the module level, leading to the easier implementation of CE initiatives. The component level is still considered, however, as less valuable. Moreover, a key insight is extending the life of energy infrastructures by replacing modules. Figure 4 compares the traditional CE and the Modular CE approach in a general way.

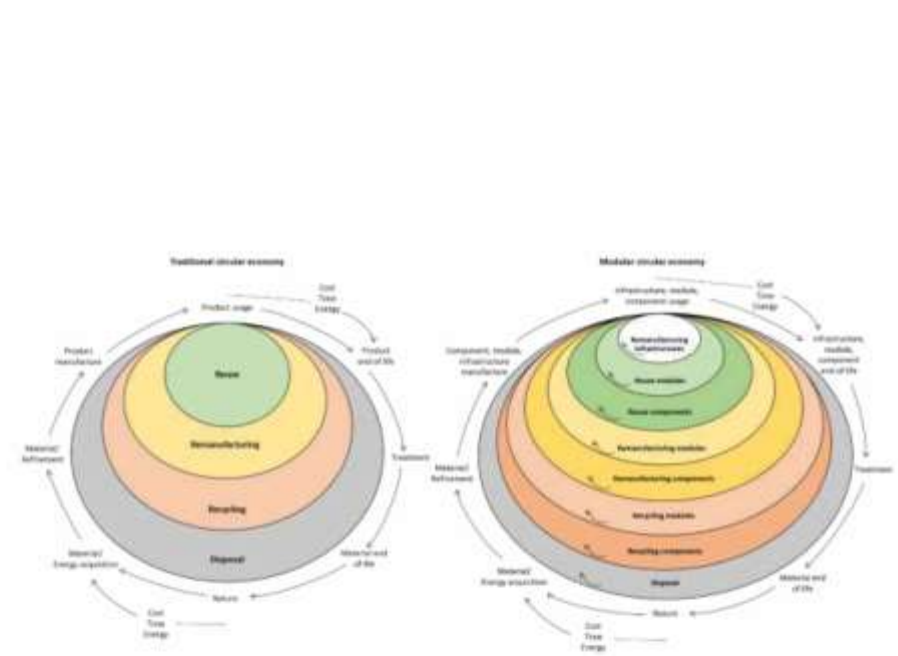


Figure 4: Traditional circular economy approach (Data from (Mihelcic et al., 2003)) vs Modular circular economy approach

Three main considerations about Modular CE can be derived from Figure 4: 1) Extending the life of infrastructures by replacing modules and/or their components (i.e. remanufacturing infrastructures) is expected to be the most valuable initiative; 2) The module level is expected to be more valuable than the component level for all the CE initiatives; 3) Distinguishing between infrastructure-modules-components creates more alternatives than the standard conceptualization of CE.

Finally, based on the results of this research and their reflections and experience, the authors recommend the following guidelines for EIP stakeholders (primarily designers and policy-makers) to foster CE: promote modular infrastructures with respect to stick-built, foster the standardization of modules and components, design modular infrastructures having disassembly in mind, include and improve the systems to monitor the conditions of modules and components, promote ad hoc policies to promote reuse instead of disposal (e.g. the pay-as-you-throw), enhance the knowledge of practitioners about CE and sustainability practices, and encourage the standardization of modular infrastructures.

Conclusion

In this paper, factors enabling and hindering the reuse of modules or their components in EIPs have been established. Upon interviewing experts in the nuclear and oil and gas sector and examining the data collected through thematic analysis, two RQs have been answered. Regarding the first RQ, i.e. "*Which factors enable the opportunity of reusing energy infrastructure modules or their components?*", the authors identified four enabling factors: monitoring of module and component conditions, design standardization of modules and components, suitable dimensions for transportation and inspection, and early planning. Regarding the second RQ, i.e. *"Which factors hinder the opportunity of reusing energy infrastructure modules or their components?",* the authors identified six barriers: regulation, political pressures, lack of a market, economics, lack of maintenance, and module and component contamination. The authors presented and compared the empirical results of this research with the theoretical conceptualization of the Modular CE, highlighting: new factors that emerged from the interviews; factors that emerged from the interviews that are in line with the theoretical conceptualization; and theoretical conceptualization factors that did not emerge from the interviews.

Furthermore, results have been discussed through the lens of the existing literature and the author's reflections and experience, leading to seven main steps to foster Modular CE in EIPs, as reported at the end of the discussion section.

This research presents three relevant limitations. First, data have been collected only in the oil and gas and nuclear industry. Although both are relevant for this research, Modular CE needs to be investigated in other industries. The wind and solar sectors are the next logical step, given their increasing relevance. More advanced technologies (such as nuclear fusion) could also be considered since they are now at the design stage, where Modular CE can provide its higher contribution. Second, this research focused on reuse, neglecting other Modular CE initiatives such as recycling. This can be relevant for sectors such as the wind industry, where the management of blades life cycle is a relevant unresolved issue (Cooperman et al., 2021). Last, this paper is purely qualitative; therefore, a quantitative analysis might be relevant. This quantitative analysis could consider the economic or environmental merit of the Modular CE.

Contributions

Contribution to the body of knowledge

There is a growing body of literature about CE and EIPs. However, it is limited and mostly focused on the material and system domains. The body of knowledge about the reuse of modules and components in EIPs deals with the need for reusing rather than providing solutions on how to reuse. Modularization can be a step forward towards the solution. This research empirically investigated which factors enable or hinder the opportunity of reusing energy infrastructure modules or their components.

Contribution to the industry

When infrastructure reaches its end-of-life, the reuse of components in other infrastructures potentially saves on raw materials and the embodied carbon already invested in construction. This has implications globally for achieving SDGs related to infrastructures. Modular CE strategy could favour CE by reusing the entire module (or its components) in other infrastructures. For companies designing future energy infrastructures, it is essential to consider which factors could favour or hinder the implementation of the Modular CE in general and the reuse of modules or their components in particular. We identified and examined these factors.

Future research recommendations

This research paves the way to future exciting research, including:

- Defining new criteria of modularization success based on the implementation of CE initiatives;
- Investigating other Modular CE initiatives such as how modularization could foster material recycling in energy infrastructures;
- Empirically studying solutions to the barriers of the Modular CE identified by this research and the previous theoretical conceptualization;
- Assessing how different levels of standardization influence the implementation of the Modular CE;
- Investigating the opportunity of implementing Modular CE initiatives in other complex products and systems, such as airports, and in other industries, such as the renewable industry;
- Quantitatively evaluate the economic and environmental impact of the Modular CE.

Data availability statement

Some or all data, models, or code generated or used during the study are proprietary or confidential in nature and may only be provided with restrictions. The authors, upon request, can provide the transcriptions of the interviews removing some parts in order to grant anonymity.

Acknowledgments

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 grateful to all the experts for the support received. The authors also wish to thank Dr Kate Lawrence, Mr Richard Allarton, and Mr Joseph Watton, who provided substantial feedback and comments. 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 organization involved.

Appendix: Profiles of the interviewees

	Position (At the time of the interview or latest position if retired)	Sector/s of experience	Main country/ies of experience	Experience (Years)
1	Project Manager	Oil and gas	Belgium, Algeria, Indonesia, Russia, Philippines, Poland	20
2	Head of Onshore Business Strategy	Oil and gas	Italy	10
3	Executive Director	Oil and gas	Saudi Arabia, Singapore, United States	24
4	Technical Director	Oil and gas	United States, China, Canada,	47
5	Product Leader	Oil and gas	Italy	22
6	Managing Director	End-of-life management	Italy, Netherlands, United Kingdom	18
7	Principal consultant	Nuclear	United Kingdom, South Africa, United Arab Emirates	37
8	Strategy and Business Development Manager	Nuclear	United Kingdom	16
9	Senior Advisor	Nuclear	Romania	45
10	Chief Executive Officer	Nuclear	United Kingdom	31
11	Principal Engineer	Nuclear	United Kingdom	40
12	General Manager	Nuclear	United Kingdom	30
13	Programme Director	Nuclear/Oil and gas	United Kingdom	20
14	Senior Reactor Systems Engineer	Nuclear	United States, Italy, Belgium	45
15	Director	Nuclear	United States	40
16	Senior Staff Engineer	Nuclear	United States	48
17	Senior Strategic Advisor	Nuclear	United Kingdom	18
18	Engineering Director	Nuclear	United States	15
19	Modules Team Leader	Nuclear	United Kingdom	10
20	Executive Director	Nuclear	United States	45
21	Consultant	Nuclear	United States	38
22	Project Manager	Nuclear	United States	26
23	Managing Director	Nuclear	United Kingdom and South Africa	40
24	Senior Engineer	Nuclear	Japan	21

Table 3: Profiles of the interviewees

References

Allwood, J.M., Ashby, M.F., Gutowski, T.G., Worrell, E., 2011. Resources , Conservation and Recycling Material efficiency : A white paper. Resour. Conserv. Recycl. 55, 362–381. https://doi.org/10.1016/j.resconrec.2010.11.002

Auverny-Bennetot, C., Demol, J.., Nicolini, E., Allenovskiy, A., Petrishin, A., 2019. Yamal LNG: REX on a mega Oil&Gas Project built on the permafrost, in: XVII ECSMGE-2019. p. 2019.

Batllevell, M., Hanf, K., 2008. The fairness of PAYT systems: Some guidelines for decision-makers. Waste Manag. 28, 2793–2800. https://doi.org/10.1016/j.wasman.2008.02.031

Bjørnstad, S., 2009. Shipshaped: Kongsberg industry and innovations in deepwater technology, 1975-2007.

Braun, V., Clarke, V., 2006. Using thematic analysis in psychology. Qual. Res. Psychol. 3, 77–101. https://doi.org/10.1191/1478088706qp063oa

Brusoni, S., Prencipe, A., 2001. Unpacking the Black Box of Modularity: Technologies, Products and Organizations. Ind. Corp. Chang. 10, 179–205.

Bryman, A., Bell, E., 2015. Business research methods. Oxford University Press, USA.

Busch, J., Steinberger, J.K., Dawson, D.A., Purnell, P., Roelich, K., 2014. Managing critical materials with a technology-specific stocks and flows model. Environ. Sci. Technol. 48, 1298–1305. https://doi.org/10.1021/es404877u

Carelli, M.D., Ingersoll, D.T., 2014. Handbook of Small Modular Nuclear Reactors, Woodhead Publishing, Elsevier. https://doi.org/10.1533/9780857098535.2.149

Choi, J.O., O'Connor, J.T., Kim, T.W., 2016. Recipes for Cost and Schedule Successes in Industrial Modular Projects: Qualitative Comparative Analysis. J. Constr. Eng. Manag. 142, 4016055.

Choi, J.O., O'Connor, J.T., Kwak, Y.H., Shrestha, B.K., 2019. Modularization Business Case Analysis Model for Industrial Projects. J. Manag. Eng. 35, 1–11. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000683

Choi, J.O., Shrestha, B.K., Kwak, Y.H., Shane, J.S., 2020a. Innovative Technologies and Management Approaches for Facility Design Standardization and Modularization of Capital Projects. J. Manag.

Eng. 36, 1–11. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000805

Choi, J.O., Shrestha, B.K., Kwak, Y.H., Shane, J.S., 2020b. Critical Success Factors and Enablers for Facility Design Standardization of Capital Projects. J. Manag. Eng. 36, 04020048. https://doi.org/10.1061/(asce)me.1943-5479.0000788

Choi, J.O., Shrestha, B.K., Shane, J.S., Kwak, Y.H., 2020c. Facility Design Standardization Decision-Making Model for Industrial Facilities and Capital Projects. J. Manag. Eng. 36, 04020077. https://doi.org/10.1061/(asce)me.1943-5479.0000842

Christmann, P., 2018. Towards a More Equitable Use of Mineral Resources. Nat. Resour. Res. 27, 159–177. https://doi.org/10.1007/s11053-017-9343-6

Cooperman, A., Eberle, A., Lantz, E., 2021. Wind turbine blade material in the United States: Quantities, costs, and end-of-life options. Resour. Conserv. Recycl. 168, 105439. https://doi.org/10.1016/j.resconrec.2021.105439

DiCicco-Bloom, B., Crabtree, B.F., 2006. The qualitative research interview. Med. Educ. https://doi.org/10.1111/j.1365-2929.2006.02418.x

Dong, D., Tukker, A., Van der Voet, E., 2019. Modeling copper demand in China up to 2050: A business-as-usual scenario based on dynamic stock and flow analysis. J. Ind. Ecol. 23, 1363–1380. https://doi.org/10.1111/jiec.12926

Ellen MacArthur Foundation, 2020. Financing the circular economy Capturing the opportunity.

Enshassi, M.S.A., Walbridge, S., West, J.S., Haas, C.T., 2019. Integrated Risk Management Framework for Tolerance-Based Mitigation Strategy Decision Support in Modular Construction Projects. J. Manag. Eng. 35, 05019004. https://doi.org/10.1061/(asce)me.1943-5479.0000698

Fereday, J., Muir-Cochrane, E., 2006. Demonstrating Rigor Using Thematic Analysis: A Hybrid Approach of Inductive and Deductive Coding and Theme Development. Int. J. Qual. Methods 5, 80–92. https://doi.org/10.1177/160940690600500107

Fuldauer, L.I., Ives, M.C., Adshead, D., Thacker, S., Hall, J.W., 2019. Participatory planning of the future of waste management in small island developing states to deliver on the Sustainable Development Goals. J. Clean. Prod. 223, 147–162. https://doi.org/10.1016/j.jclepro.2019.02.269

GIF/EMWG, 2007. Cost estimating guidelines for generation IV nuclear energy systems.

Goodman, L.A., 1961. Snowball Sampling, Source: The Annals of Mathematical Statistics.

Han, S.H., Hasan, S., Bouferguène, A., Al-Hussein, M., Kosa, J., 2015. Utilization of 3D Visualization of Mobile Crane Operations for Modular Construction On-Site Assembly. J. Manag. Eng. 31, 04014080. https://doi.org/10.1061/(asce)me.1943-5479.0000317

Heath, G.A., Silverman, T.J., Kempe, M., Deceglie, M., Ravikumar, D., Remo, T., Cui, H., Sinha, P., Libby, C., Shaw, S., Komoto, K., Wambach, K., Butler, E., Barnes, T., Wade, A., 2020. Research and development priorities for silicon photovoltaic module recycling to support a circular economy. Nat. Energy 5, 502–510. https://doi.org/10.1038/s41560-020-0645-2

Hennink, M.M., Kaiser, B.N., Marconi, V.C., 2017. Code Saturation Versus Meaning Saturation: How Many Interviews Are Enough? Qual. Health Res. https://doi.org/10.1177/1049732316665344

Iacovidou, E., Millward-Hopkins, J., Busch, J., Purnell, P., Velis, C.A., Hahladakis, J.N., Zwirner, O., Brown, A., 2017. A pathway to circular economy: Developing a conceptual framework for complex value assessment of resources recovered from waste. J. Clean. Prod. 168, 1279–1288. https://doi.org/10.1016/j.jclepro.2017.09.002

Ikpe, E., Kumar, J., Jergeas, G., 2015. Analysis of Modularization Compared to Total Project Cost in Alberta Oil and Gas Projects. Glob. Adv. Res. J. Manag. Bus. Stud. 4, pp 116-120.

Infrastructure Outlook, 2020. Forecasting infrastructure investment needs and gaps [WWW Document]. URL https://outlook.gihub.org/?utm_source=GIHub+Homepage&utm_medium=Project+tile&utm_campaign=Outlook+GIHub+Tile (accessed 2.8.21).

Invernizzi, D.C., Locatelli, G., Brookes, N., Davis, A., 2020a. Qualitative comparative analysis as a method for project studies: The case of energy infrastructure. Renew. Sustain. Energy Rev. 133. https://doi.org/10.1016/j.rser.2020.110314

Invernizzi, D.C., Locatelli, G., Velenturf, A., Love, P.E., Purnell, P., Brookes, N.J., 2020b. Developing policies for the end-of-life of energy infrastructure: Coming to terms with the challenges of decommissioning. Energy Policy 144, 111677. https://doi.org/10.1016/j.enpol.2020.111677

Jensen, P.D., Purnell, P., Velenturf, A.P.M., 2020. Highlighting the need to embed circular economy in low carbon infrastructure decommissioning: The case of offshore wind. Sustain. Prod. Consum.

24, 266–280. https://doi.org/10.1016/j.spc.2020.07.012

Khan, S., Haleem, A., 2021. Investigation of circular economy practices in the context of emerging economies: a CoCoSo approach. Int. J. Sustain. Eng. https://doi.org/10.1080/19397038.2020.1871442

Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: An analysis of 114 definitions. Resour. Conserv. Recycl. 127, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005

Krausmann, F., Wiedenhofer, D., Lauk, C., Haas, W., Tanikawa, H., Fishman, T., Miatto, A., Schandl, H., Haberl, H., 2017. Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use, in: Proceedings of the National Academy of Sciences of the United States of America. pp. 1880–1885. https://doi.org/10.1073/pnas.1613773114

Lapko, Y., Trianni, A., Nuur, C., Masi, D., 2019. In Pursuit of Closed-Loop Supply Chains for Critical Materials: An Exploratory Study in the Green Energy Sector. J. Ind. Ecol. 23, 182–196. https://doi.org/10.1111/jiec.12741

Liguori, R., Faraco, V., 2016. Biological processes for advancing lignocellulosic waste biorefinery by advocating circular economy. Bioresour. Technol. 215, 13–20. https://doi.org/10.1016/j.biortech.2016.04.054

Lloyd, C.A., Roulstone, T., Lyons, R.E., 2021. Transport, constructability, and economic advantages of SMR modularization. Prog. Nucl. Energy 134, 103672. https://doi.org/10.1016/j.pnucene.2021.103672

Locatelli, G., Boarin, S., Fiordaliso, A., Ricotti, M.E., 2018. Load following of Small Modular Reactors (SMR) by cogeneration of hydrogen: A techno-economic analysis. Energy 148, 494–505. https://doi.org/10.1016/j.energy.2018.01.041

Locatelli, G., Fiordaliso, A., Boarin, S., Ricotti, M.E., 2017. Cogeneration: An option to facilitate load following in Small Modular Reactors. Prog. Nucl. Energy 97, 153–161.

Locatelli, G., Greco, M., Invernizzi, D.C., Grimaldi, M., Malizia, S., 2020. What about the people? Micro-foundations of open innovation in megaprojects. Int. J. Proj. Manag. https://doi.org/10.1016/j.ijproman.2020.06.009

Locatelli, G., Mignacca, B., 2020. Small Modular Nuclear Reactors, in: Future Energy. Elsevier, pp. 151–169. https://doi.org/10.1016/B978-0-08-102886-5.00008-6

Mignacca, B., Alaassar, M., Locatelli, G., Invernizzi, D.C., 2018. We never built small modular reactors (SMRs), but what do we know about modularization in construction?, in: International Conference on Nuclear Engineering, Proceedings, ICONE. https://doi.org/10.1115/ICONE26-81604

Mignacca, B., Alawneh, A.H., Locatelli, G., 2019. Transportation of small modular reactor modules: What do the experts say?, in: International Conference on Nuclear Engineering, Proceedings, ICONE.

Mignacca, Locatelli, G., 2020a. Economics and finance of Small Modular Reactors : A systematic review and research agenda. Renew. Sustain. Energy Rev. 118, 109519. https://doi.org/10.1016/j.rser.2019.109519

Mignacca, Locatelli, G., 2020b. Economics and finance of Molten Salt Reactors. Prog. Nucl. Energy 129, 103503. https://doi.org/10.1016/j.pnucene.2020.103503

Mignacca, Locatelli, G., Sainati, T., 2020a. Deeds not words: Barriers and remedies for Small Modular nuclear Reactors. Energy 118137. https://doi.org/10.1016/j.energy.2020.118137

Mignacca, Locatelli, G., Velenturf, A., 2020b. Modularisation as enabler of circular economy in energy infrastructure. Energy Policy 139. https://doi.org/10.1016/j.enpol.2020.111371

Mihelcic, J.R., Crittenden, J.C., Small, M.J., Shonnard, D.R., Hokanson, D.R., Zhang, Q., Chen, H., Sorby, S.A., James, V.U., Sutherland, J.W., Schnoor, J.L., 2003. Sustainability Science and Engineering: The Emergence of a New Metadiscipline. Environ. Sci. Technol. 37, 5314–5324.

Minunno, R., O'Grady, T., Morrison, G.M., Gruner, R.L., 2020. Exploring environmental benefits of reuse and recycle practices: A circular economy case study of a modular building. Resour. Conserv. Recycl. 160, 104855. https://doi.org/10.1016/j.resconrec.2020.104855

Nabi, M.A., El-Adaway, I.H., 2020. Modular Construction: Determining Decision-Making Factors and Future Research Needs. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000859

Ng, K.S., Head, I., Premier, G.C., Scott, K., Yu, E., Lloyd, J., Sadhukhan, J., 2016. A multilevel sustainability analysis of zinc recovery from wastes. Resour. Conserv. Recycl. 113, 88–105. https://doi.org/10.1016/j.resconrec.2016.05.013

Nowell, L.S., Norris, J.M., White, D.E., Moules, N.J., 2017. Thematic Analysis: Striving to Meet the Trustworthiness Criteria. Int. J. Qual. Method 16, 1–13. https://doi.org/10.1177/1609406917733847

O'Connor, J.T., O'Brien, W.J., Choi, J.O., 2015. Standardization strategy for modular industrial plants. J. Constr. Eng. Manag. 141, 1–10. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001001

O'Connor, J.T., O'Brien, W.J., Choi, J.O., 2014. Critical success factors and enablers for optimum and maximum industrial modularization. J. Constr. Eng. Manag. 140, 1–11. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000842

Palinkas, L.A., Horwitz, S.M., Green, C.A., Wisdom, J.P., Duan, N., Hoagwood, K., 2015. Purposeful Sampling for Qualitative Data Collection and Analysis in Mixed Method Implementation Research. Adm. Policy Ment. Heal. Ment. Heal. Serv. Res. 42, 533–544. https://doi.org/10.1007/s10488-013-0528-y

Preston, F., Lehne, J., 2017. A Wider Circle? The Circular Economy in Developing Countries.

Purnell, P., 2019. On a voyage of recovery: a review of the UK's resource recovery from waste infrastructure. Sustain. Resilient Infrastruct. 4, 1–20. https://doi.org/10.1080/23789689.2017.1405654

Rausch, C., Sanchez, B., Edwards, C., Haas, C., 2020. A computational model for product cycling of modular buildings, in: EG-ICE 2020 Workshop on Intelligent Computing in Engineering.

Reuter, M.A., Matusewicz, R., Van Schaik, A., 2015. Lead, zinc and their minor elements: Enablers of a circular economy. World Metall. - ERZMETALL 68, 134–148.

Roelich, K., Dawson, D.A., Purnell, P., Knoeri, C., Revell, R., Busch, J., Steinberger, J.K., 2014. Assessing the dynamic material criticality of infrastructure transitions: A case of low carbon electricity. Appl. Energy 123, 378–386. https://doi.org/10.1016/j.apenergy.2014.01.052

Rubin, H.J., Rubin, I.S., 2011. Qualitative interviewing: The art of hearing data. Sage.

Saldaña, J., 2015. The coding manual for qualitative researchers. Sage.

Saunders, M.N.K., 2011. Research methods for business students, 5/e. Pearson Education India.

Schiller, G., Müller, F., Ortlepp, R., 2017. Mapping the anthropogenic stock in Germany: Metabolic evidence for a circular economy. Resour. Conserv. Recycl. 123, 93–107.

https://doi.org/10.1016/j.resconrec.2016.08.007

Shrestha, B.K., Asce, S.M., Choi, J.O., Asce, A.M., Young, ;, Kwak, H., Asce, M., Shane, J.S., 2021. Recipes for Standardized Capital Projects' Performance Success. https://doi.org/10.1061/(ASCE)ME.1943

Shrestha, B.K., Choi, J.O., Kwak, Y.H., Shane, J.S., 2020. How Design Standardization CSFs Can Impact Project Performance of Capital Projects. J. Manag. Eng. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000792

Thomas, R.M., 2003. Blending qualitative and quantitative research methods in theses and dissertations. Corwin Press.

United Nations, 2020. THE 17 GOALS | Sustainable Development [WWW Document]. URL https://sdgs.un.org/goals (accessed 11.24.20).

Vaismoradi, M., Turunen, H., Bondas, T., 2013. Content analysis and thematic analysis: Implications for conducting a qualitative descriptive study. Nurs. Heal. Sci. 15, 398–405. https://doi.org/10.1111/nhs.12048

Velenturf, A.P.M., Archer, S.A., Gomes, H.I., Christgen, B., Lag-Brotons, A.J., Purnell, P., 2019. Circular economy and the matter of integrated resources. Sci. Total Environ. https://doi.org/10.1016/j.scitotenv.2019.06.449

Velenturf, A.P.M., Purnell, P., 2021. Principles for a Sustainable Circular Economy. Sustain. Prod. Consum. https://doi.org/10.1016/j.spc.2021.02.018

Venkata Mohan, S., Nikhil, G.N., Chiranjeevi, P., Nagendranatha Reddy, C., Rohit, M. V., Kumar, A.N., Sarkar, O., 2016. Waste biorefinery models towards sustainable circular bioeconomy: Critical review and future perspectives. Bioresour. Technol. https://doi.org/10.1016/j.biortech.2016.03.130

Vondra, M., Touš, M., Teng, S.Y., 2019. Digestate evaporation treatment in biogas plants: A techno-economic assessment by Monte Carlo, neural networks and decision trees. J. Clean. Prod. 238. https://doi.org/10.1016/j.jclepro.2019.117870

Wijewansha, A.S., Tennakoon, G.A., Waidyasekara, K.G.A.S., Ekanayake, B.J., 2021. Implementation of circular economy principles during pre-construction stage: the case of Sri Lanka. Built Environ.

Proj. Asset Manag. https://doi.org/10.1108/BEPAM-04-2020-0072

World Nuclear Association, 2020. Advanced Nuclear Power Reactors | Generation III+ Nuclear Reactors - World Nuclear Association [WWW Document]. URL https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/advanced-nuclear-power-reactors.aspx (accessed 10.21.20).

Wrigley, P.A., Wood, P., O'Neill, S., Hall, R., Robertson, D., 2021. Off-site modular construction and design in nuclear power: A systematic literature review. Prog. Nucl. Energy 134, 103664. https://doi.org/10.1016/j.pnucene.2021.103664

Yang, Y., Pan, M., Pan, W., Zhang, Z., 2021. Sources of Uncertainties in Offsite Logistics of Modular Construction for High-Rise Building Projects. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000905

B.4 Publication IV

Mignacca, B., Locatelli, G., Sainati, T., 2020. Deeds not words: Barriers and remedies for Small Modular nuclear Reactors. Energy, Vol. 206 - **Scopus indexed journal, Impact Factor: 6.082, ABS 3.**

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	[13,56]; In-depth discussions
- 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	
- Availability of slots for the licensing (resource availability in the regulatory body to review the design)	In-depth discussions
- Risks involved in the licensing process	
- 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	[13,56]; In-depth discussions
- 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	
- Create an entirely new regulatory framework for SMRs	[52,57]; In-depth discussions
- 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	

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.)	In-depth discussions
- 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	
- Difficulty in module transportation	[15], In-depth discussions
- Economic feasibility	
- Lack of design standardisation	
- Lack of standardisation of the interfaces	
- Licensing and regulatory constraints	
- Technology obsolescence	

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	[15], In-depth discussions
– Political support	
– Standardisation of the design	
– Standardisation of the interfaces	
– The creation of a second-hand market	
– Continuous monitoring of module conditions	In-depth discussions
– Cost to dispose of a potentially reusable module	
– 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].

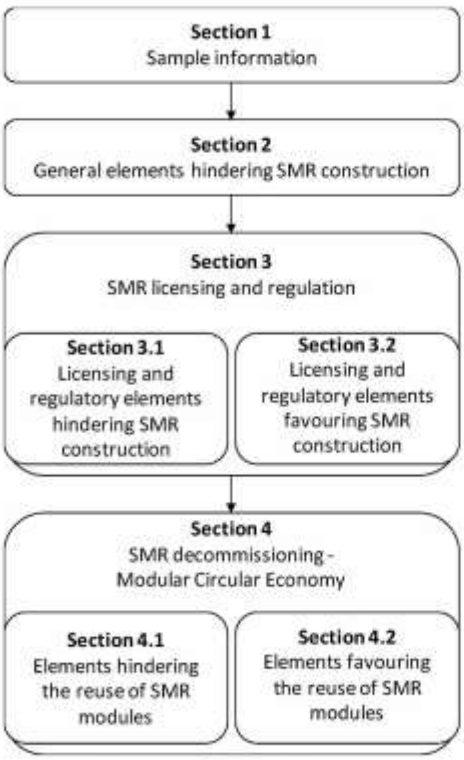


Fig. 1. Structure of the questionnaire survey.

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%)

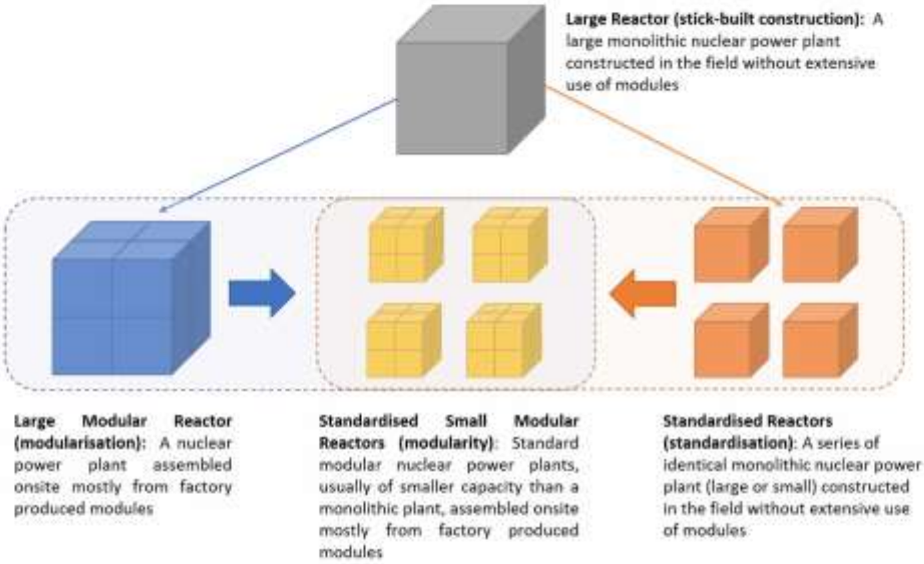


Fig. 2. Classification of NPPs. Adapted from [16].

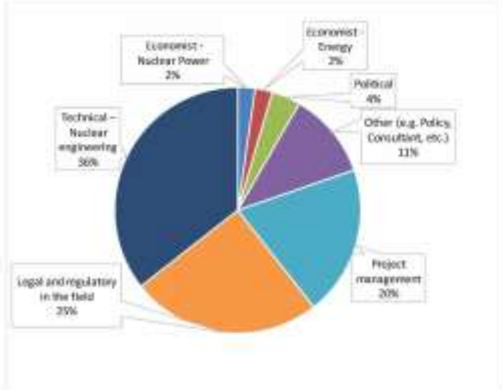


Fig. 3. Experts' areas of expertise.

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

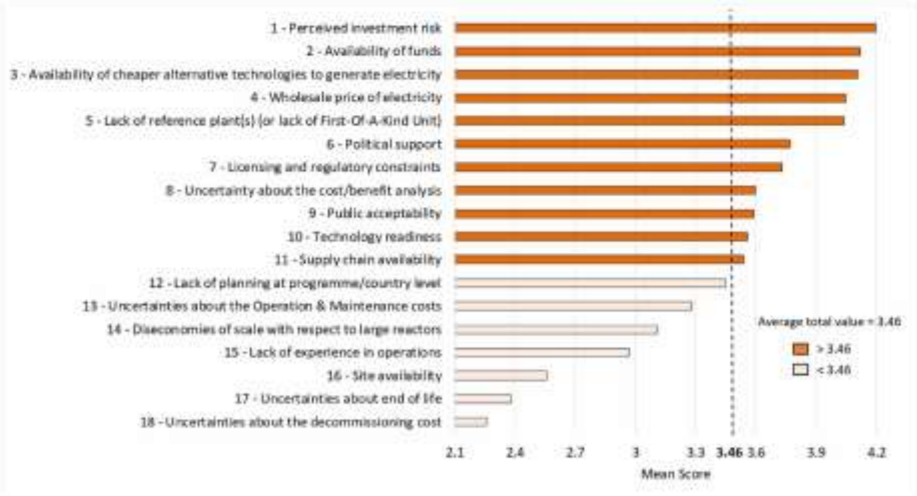


Fig. 4. Ranking of the general elements hindering SMR construction.

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

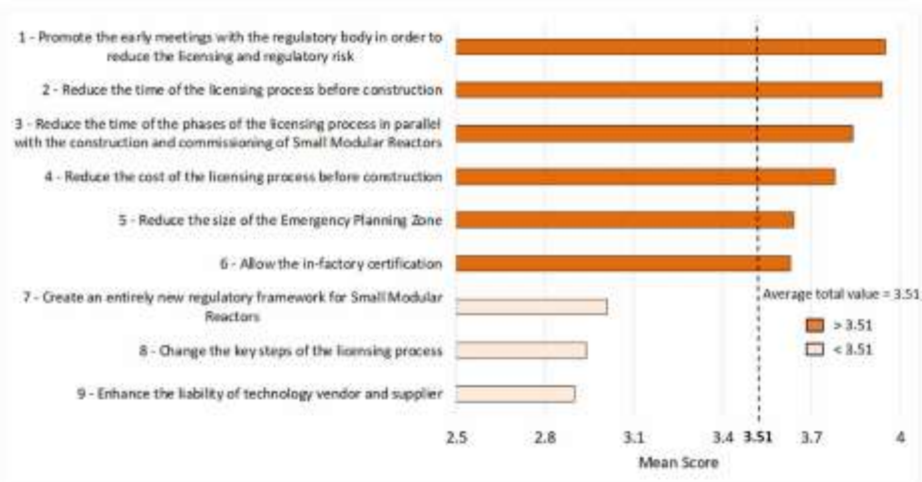


Fig. 6. Ranking of the licensing and regulatory elements favouring SMR construction.

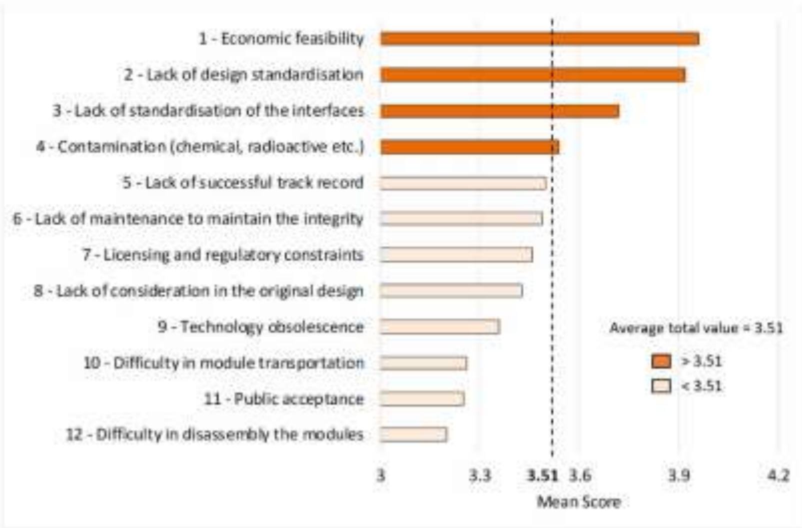


Fig. 7. Ranking of elements hindering the reuse of SMR modules.

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

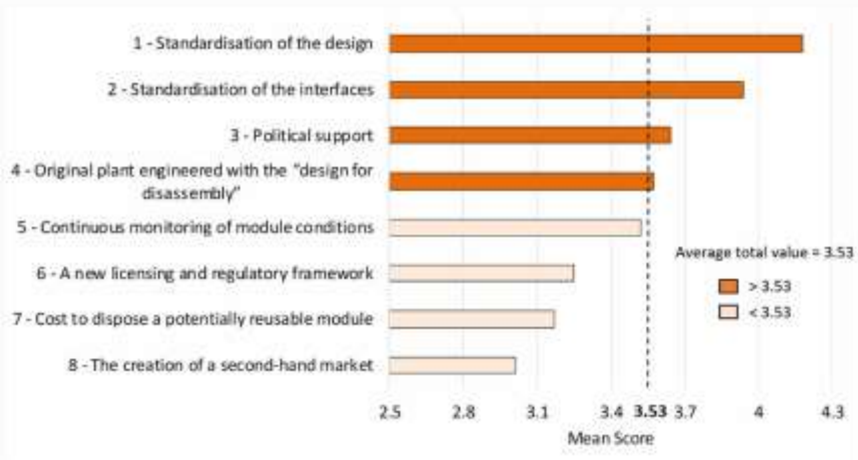


Fig. 8. Ranking of the elements favouring the reuse of SMR modules.

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

	Frequency							
General elements hindering SMR construction	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

	Frequency							
Licensing end regulatory elements	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

	Frequency							
Licensing and regulatory elements	1	2	3	4	5	Mean	SD	Rank
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

	Frequency							
Elements	1	2	3	4	5	Mean	SD	Rank
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

	Frequency							
Elements	1	2	3	4	5	Mean	SD	Rank
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] Nunnally 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] Vujić J, Bergmann RM, Škoda R, Miletić 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 RM, 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.

C. Overall discussion and conclusion

This section provides an overall discussion of this PhD research, its contribution to knowledge in terms of theory and practice, the overall limitations and suggests future research opportunities.

C.1 Contribution to knowledge - theory

There is a growing body of knowledge about modularisation and CE in energy infrastructures. However, before this PhD research, CE and modularisation were analysed separately in energy infrastructures. In addition, before this PhD research, the difference between modularisation and modularity was often neglected in peer-reviewed literature, leading to an unclear definition of the implications of modularisation and modularity.

First, this research clarified the difference between modularisation and modularity in energy infrastructures, as presented in Publication 1 and 2. Shedding light on this difference is relevant for future research. Second, this research identified the main advantages, disadvantages and economic implications of modularisation in the case of SMRs. Last, this research identified and theoretically conceptualised the link between modularisation and CE (i.e. Modular CE) in energy infrastructures, as shown in Publication II.

The introduction of the Modular CE is the key novelty of this PhD research and its most relevant contribution to theory. Figure 2 compares traditional CE and Modular CE.

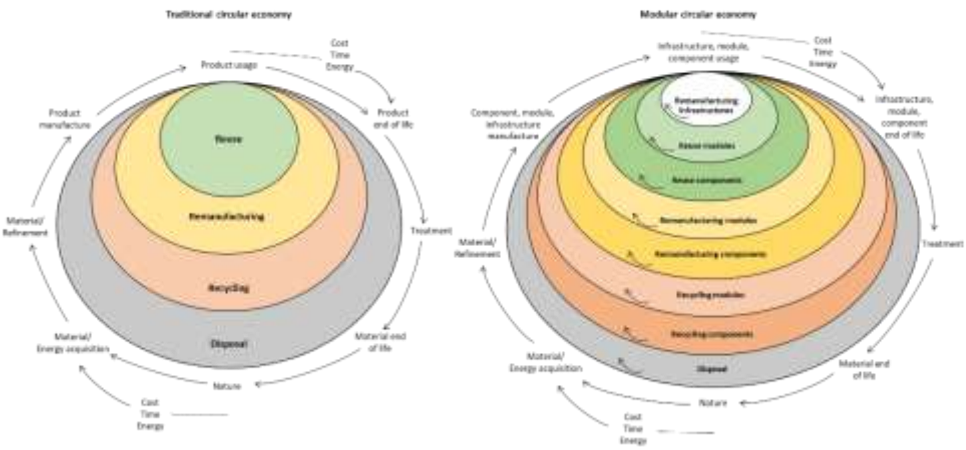


Figure 2: Traditional CE vs Modular CE - Extracted from (Mignacca and Locatelli, 2021)

C.2 Contribution to knowledge - practice

When infrastructure reaches its end-of-life, the reuse of components in other infrastructures potentially saves on raw materials and the embodied carbon already invested in construction. Modular CE could favour the implementation of CE initiatives, as explained in Publication II, III and IV. For companies designing future energy infrastructures, it is essential to consider options for improving energy infrastructure environmental sustainability. Therefore, the industry can benefit from the Modular CE.

This PhD research focused on the reuse initiatives, contributing to practice by identifying and examining enabling factors and barriers for the reuse of modules, ultimately providing a set of guidelines for the implementation of the Modular CE in energy infrastructures. Moreover, this research also identified and ranked the most relevant factors in the specific case of SMRs by conducting a survey involving 97 SMR experts, as in Publication III.

C.3 Overall limitations and future research opportunities

This exploratory research is affected by a number of limitations. First, data have been collected only in the oil and gas and nuclear industry. Although both are relevant for this research, Modular CE needs to be investigated in other industries. The wind and solar sector are the next logical step, given their increasing relevance. More advanced technologies (such as nuclear fusion) could also be considered since they are now at the design stage, where Modular CE can provide its higher contribution. Also, modular CE can be investigated outside the energy sectors, for instance, in other complex product and systems. Second, this research focused on reuse, neglecting the other Modular CE initiatives such as recycling. This can be relevant for sectors such as the wind industry, where the management of blades life cycle is a relevant unresolved issue (Cooperman et al., 2021).

Third, this research is mostly qualitative (except the survey in Publication III); therefore, a quantitative analysis might be relevant. This quantitative analysis could consider the economic or environmental merit of the Modular CE.

Last, this research is at a microeconomic level. Explorative research at a macroeconomic level might be relevant.

The absolute novelty of the Modular CE paves the way to several future research opportunities, as detailed in each publication. For instance:

Policy and legislation: Investigating the implications of the Modular CE from a policy and legal point of view; in a wider perspective, examining the relationships between countries with different policies and legislation about energy infrastructures; investigating to what extent harmonisation between countries could be promoted.

Standardisation of the interfaces: Identifying who should be responsible for the standardisation of the interfaces.

Standardisation of modular energy infrastructures: Identifying and examining enabling factors and barriers for the standardisation of modular energy infrastructures.

Other Modular CE initiatives: Investigating how modularisation could foster other CE initiatives, such as repairing and recycling.

Modular CE in other complex product systems: Investigating the opportunity of implementing Modular CE initiatives in other complex products and systems, such as airports, and in other industries, such as the renewable industry;

Quantitative analysis of the Modular CE: Quantitatively evaluate the economic and environmental merit of the Modular CE in energy infrastructures.

C.4 Concluding remarks

Policymakers, practitioners and academics are increasingly discussing the transition from traditional stick-built construction to modularisation in order to reduce time and cost and of energy infrastructures and the transition from a linear economy to CE to reduce their environmental impact. However, these topics were discussed separately before the candidate's publications. Recognising interdependency is crucial because modularisation can become a key enabler of CE initiatives. This PhD research investigated the link between modularisation and CE, focusing on the case of Small Modular Reactors (SMRs). The aim of this research has been achieved by addressing the four primary objectives in Section A.2. Research objective I, II, III and IV have been achieved respectively through the research presented in Publication I, II, III and IV in Section B. The research presented in these publications contributed to knowledge both in terms of theory and practice and paved the way for several research opportunities.

C.5 Other activities related to this PhD research

C.5.1 Presentations in conferences and workshops

1. Presentation of the PhD findings at the Leeds Project Management Doctoral Group and at the Leeds Nuclear Group Meeting, 2021 (both online):
    - "*Modular circular economy in energy infrastructures: The case of Small Modular Reactors*"
2. Invited presentation at the OFGEM (Office of Gas and Electricity Markets) lunchtime seminar series (online), 2020:
    - "*Small Modular Nuclear Reactors: Economics, finance, barriers and remedies*"
3. Presentation at the 6th School of Civil Engineering Postgraduate Researcher Conference, Leeds, United Kingdom, 2019, of the paper "*Transportation of small modular reactor modules: What do the experts say?"*
4. Presentation at the ARCOM (Association of Researchers in Construction Management) Large Infrastructure Project Delivery Workshop, Melbourne, Australia, 2019 (online):
    - *"Linking modularisation and circular economy in energy infrastructure: State of the art and a way forward"*
5. Presentation at the 27th International Conference on Nuclear Engineering, Ibaraki, Japan, 2019, of the paper *"Transportation of Small Modular Reactors: What do the experts say?"*
6. Invited presentation at the Small Modular Reactor Construction Seminar at the University of Cambridge, United Kingdom, 2019:
    - "*Small Modular Reactors: Let's learn from other modular projects*"
7. Presentation at the Nuclear Future Seminar, Sheffield, United Kingdom, 2018:
    - *"The role of modularisation in the lifecycle of Small Modular Reactors (SMRs) in a "circular economy" perspective"*

8. Presentation at the 26th International Conference on Nuclear Engineering, London, United Kingdom, 2018, of the paper *"We never built Small Modular Reactors but what do we know about modularisation in construction?".*
9. Presentation at the 5th School of Civil Engineering Postgraduate Researcher Conference, Leeds, United Kingdom, 2018:
    - *"The role of modularisation in the lifecycle of Small Modular Reactors (SMRs) in a "circular economy" perspective"*

C.5.2 Teaching activities

1. Currently supervising 3 MSc students for their dissertation.
2. The candidate was responsible for the coursework of CIVE2910 (Introduction to Project Management) in 2021, supporting undergraduates and marking their coursework at the end of April 2021.
3. The candidate reviewed teaching notes for the module CIVE5233M (Risk Management) in 2021.
4. Guest lecture "Nuclear Fission: From Large Reactors to Small Modular Reactors" at the University of Sheffield (Online), 2020.
5. The candidate mentored and is currently mentoring other PhD Students in their 1st or 2nd year.

C.5.3 External collaborations

1. The candidate is collaborating with Dr Victor Nian from the National University of Singapore on a study investigating the economics of nuclear power plants and related policy implications in Southeast Asia. The paper deriving from this study will be submitted to a scientific journal in 2021.
2. "Sustainability Ambassador" for the University of Leeds at the Major Project Association since May 2020.

3. Member of the CRP (Coordinated Research Project) on the economics of Small Modular Reactors, organised by the International Atomic Energy Agency since December 2020.
4. The candidate worked as a rapporteur (volunteer work) at the event "Lessons from decommissioning" held in Leeds on 7th Mar 2019, organised by the Major Project Association.
5. Peer reviews of scientific articles for the following journals from 2019 to 2021:
    - International Journal of Project Management
    - Progress in Nuclear Energy
    - Energy Sources
    - Applied Economics
    - Energy
    - Applied Energy
    - Nuclear Energy and Technology.

C.5.4 Grants and awards

1. School of Civil Engineering Postgraduate Award Prize 2021 for Academic Performance.
2. PGR and Postdoc Travel Grant – School of Civil Engineering (700£).
3. Major Projects Association PhD Research Grant Application (4000£ in three years).
4. University of Sheffield travel and accommodation bursary to attend the Nuclear Future Seminar (90£).

D. Appendix

D.1 Publication V

Mignacca, B., Locatelli, G., Alaassar, M., Invernizzi, D.C., 2018. We never built small modular reactors (SMRs), but what do we know about modularisation in construction? The proceedings of the 26th International Conference on Nuclear Engineering, London - **Scopus indexed proceedings**

Proceedings of the 2018 26th International Conference on Nuclear Engineering
ICONE26
July 22-26, 2018, London, England

ICONE26-81604

WE NEVER BUILT SMALL MODULAR REACTORS (SMRs), BUT WHAT DO WE KNOW ABOUT MODULARIZATION IN CONSTRUCTION?

Benito Mignacca
University of Leeds, School of Civil Engineering
Leeds, United Kingdom
cnbm@leeds.ac.uk

Dr Giorgio Locatelli
University of Leeds, School of Civil Engineering
Leeds, United Kingdom
g.locatelli@leeds.ac.uk

Mahmoud Alaassar
University of Leeds, School of Civil Engineering
Leeds, United Kingdom
mahmoud.alaassar@hotmail.com

Diletta Colette Invernizzi
University of Leeds, School of Civil Engineering
Leeds, United Kingdom
cndci@leeds.ac.uk

ABSTRACT
The key characteristics of small modular reactors (SMRs), as their name emphasized, are their size and modularity. Since SMRs are a family of novel reactor designs, there is a gap of empirical knowledge about the cost/benefit analysis of modularization. Conversely, in other sectors (e.g. Oil & Gas) the empirical experience on modularization is much greater. This paper provides a structured knowledge transfer from the general literature (i.e. other major infrastructure) and the Oil & Gas sector to the nuclear power plant construction world. Indeed, in the project management literature, a number of references discuss the costs and benefits determined by the transition from the stick-built construction to modularization, and the main benefits presented in the literature are the reduction of the construction cost and the schedule compression. Additional costs might arise from an increased management hurdle and higher transportation expenses. The paper firstly provides a structured literature review of the benefits and costs of modularization divided into qualitative and quantitative references. In the second part, the paper presents the results of series of interviews with Oil & Gas project managers about the value of modularization in this sector.

1. THE VALUE PROPOSITION OF SMALL MODULAR REACTORS

The International Atomic Energy Agency [1] defines Small Modular Reactors (SMRs) as "*newer generation 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*" (Page 1). Several SMRs designs, detailed in [1–3], are currently at different stages of development. [4] provides a summary of the innovative feature of SMRs and describes SMRs as "*reactor designs that are deliberately small, i.e. designs that do not scale to large sizes but rather capitalize on their smallness to achieve specific performance characteristics.*"
Several papers discuss the competitiveness of SMRs vs Large Reactors (LRs) and how SMRs might balance the "diseconomy of scale" with the "economy of multiples"[5–11]. [12,13] analyse specific factors (such as grid characteristics, construction time, financial exposition, modularization, learning etc.) which distinguish SMRs from LRs in the evaluation of the capital cost. Once these factors are taken into account, the capital cost is comparable between the two technologies [5,7]. [14] discusses the effects of 'non-financial parameters', such as electric grid vulnerability, public acceptance, the risk associated with the project, licensing [15], during the evaluation of the best reactor size for investments in the nuclear sector. For many of these parameters, the authors explain how SMRs show an advantage with respect to LRs. Another key advantage of SMRs is the learning [16]. According to [16], the learning curve flattens out after 5-7 units, determining that the nth of a kind is reached with less MWe installed for SMRs respect to LRs [16]. SMRs, having the power fractionated are also ideal for cogeneration, as presented in [16–18]. Indeed, one of the key SMRs advantages is the possibility to split a large investment into smaller ones. The construction of a single LR is a risky investment [20]. The construction of SMRs is an investment decision with n degrees of freedom that allows hedging investment risks. The economic merit of flexibility can be calculated using the Real Options (ROs) approach [21].
However, despite the relatively large amount of literature published on SMRs, there is a gap in knowledge on the merit of having "small modular reactors" instead of just "small

reactors". In other words, one of the key challenges for the assessment of SMRs advantages and disadvantages is the lack of empirical information, as no SMRs have been built yet, but only "traditionally built small reactors". Therefore, it is necessary to explore the role of modularization in closely related fields, such as large infrastructures creation, and transpose the knowledge back to the nuclear and in particular the SMRs sector. Therefore, this paper addresses the following question: what SMRs in particular and the nuclear sector, in general, can learn about modularization from the infrastructure sector?

The rest of the paper is structured as follows: section 2 summarises the key references about modularization in large infrastructure to show how the transition from the stick-built construction to modularization impacts on the project schedule, budget and risk; section 3 presents the methodology used to collect and analyse data; section 4 shows and discusses the results of interviews with Oil & Gas project managers about the value of modularization in this sector; section 5 concludes the paper.

2. MODULARIZATION IN INFRASTRUCTURE: LESSON LEARNED

Several papers and reports, hereby described, deal with the costs and benefit of modularization. This section is divided into two subsections to show the qualitative and quantitative references. Qualitative references represent most of the studies.

2.1 Qualitative references

- **Schedule**

The impact of modularization on the project schedule is widely discussed in the literature. Understanding and planning the criticality of the project schedule is one of the decision-making factors that must be considered before the beginning of the modular construction [22]. Habibullah et al. [23] studied and compared modular design and Gravity Base Structure concepts to that of the traditional stick-built plant, in particular, the land-based large individual modules and the Liquefied Natural Gas (LNG) process facilities installed on a Gravity Base Structure. One of the main conclusions of the study is that the modularization reduces the construction schedule. Ikpe et al. [24] examined the modularization of projects in the Alberta Oil & Gas industry. The research methodology implemented was qualitative and involved interviews with seventeen industry practitioners. According to the authors, modularization has excellent potential to reduce the schedule overruns and improve the performance of the project. Moreover, in the construction of offshore Floating Production System, after the transition to modularization, most of the operators were able to reduce the schedule without delay from the start till the first oil extraction [25]. It is interesting the case of Yamal LNG Project, that is the construction of a liquefied natural gas plant for production, treatment, liquefaction, storage and export of LNG from South Tambey condensate gas field. It is the world's largest modularised LNG Project, and it respected the schedule [26,27]. Considering that an analysis of data from 318 industrial megaprojects [28] shows that the vast majority of megaprojects might be viewed as a failure when considering adherence to schedule and budget as well as benefits in operation, it wasn't trivial that Yamal LNG Project respected the schedule. There are several references [29–32] which define the schedule compression as one of the key characteristics of the modularization, but the critical point is to understand why. De La Torre [29] explains its causes and states: "*the reduced schedule is caused by:*
1) performing the design and procurement simultaneously,
2) working in parallel,
3) increasing the control of schedule (Wells, 1979),
4) higher productivity from the permanent workforce in fabrication shops,
5) the opportunity to train operators at fabrication shops rather than on-site (Wells,1979)".

- **Cost**

A considerable amount of literature has been published on the cost variations caused by the transition from the stick-built construction to modularization. The key point is to understand where the changes are, where the modularization determines a cost reduction and where a cost increase. According to Musa et al. [32], modularization can reduce the labour and material cost but can increase the transportation cost. Moreover, design and engineering phases require additional man hours and, consequently, a cost increase [29,33]. On the other hand, through high-quality materials and factory quality assessment (QA)/ quality control (QC) management and control, modularization determines a cost saving [32]. According to Jameson [30], modularization can reduce the labour cost but only if the off-site labour cost is less than the on-site one. This often happens for the following reasons:
- The cost of tools, supervision, training etc. is higher on-site than in a shop environment;
- Some areas have a labour cost higher than some yards located in a more economical environment.

The possibility to produce modules off-site increases the quantity and diversity of potential fabricators for a project and, consequently, the increase of competition that can determine a reduction cost [28]. Eftimie [34] states that a modular method is an alternative approach of doing engineering that aims to minimise the total installed cost and optimise the return on investment, sanctioning the standardisation for similar projects in the future. Standardisation is at the origin of a more efficient supply, construction and operations and it enables suppliers and utilities to more rapidly benefit from the learning economies [35]. Another essential characteristic of the modularization is the possibility to achieve economy of scale in production [36]. Moreover, one of the implications of the studies explained in the previous section is the reduction of the project cost [23,24]. De La Torre [29] concludes that despite the increased cost listed above, most modular construction projects show savings in installed costs over conventional construction.

- **Risk**

According to 5th Edition of the PMBOK® Guide [37] , project risk is "*uncertain event or condition that, if it occurs, has a positive or negative effect on one or more project objectives* *such as scope, schedule, cost, and quality. A risk may have one or more causes and, if it occurs, it may have one or more impacts*". According to De La Torre [29], the increased risk is one of the disadvantages of the modularization, and it is related to the necessity of expertise, the interdependency of activities, and the lack of adaptability to variations. Moreover, previous studies evaluating the modular construction in offshore Oil & Gas projects have highlighted that risks are mainly due to poor planning and poor detailed engineering [38,39]. The life cycle of Offshore Oil & Gas projects is characterised by eight phases, in which the risks are continuously assessed [40]. Cost and schedule estimates for Oil & Gas projects are commonly set up during Front End Engineering Design (FEED) and managed over the implementation phase [41]. Moreover, changes during the project may contribute to significant implications on the cost of the entire project cycle [42,43]. These changes are related to risk associated with modularised projects in Oil & Gas megaprojects [44,45]. On the other hand, Jameson [29] explains a characteristic of modularization which leads to a reduction in the safety risk: "*Shifting work into a controlled shop environment generally benefits the overall safety risks of a project. In addition, large vertical structures can be constructed in the horizontal by use of modularization. This limits the amount of vertical work at elevation and can decongest areas that, by their nature, possess a riskier work environment*". However, according to Shahtaheri et al. [46], several sectors of construction are shifting away from the stick-built method in the use of modularization due to its advantages, despite the constraints and risks that may impact its benefits.

2.2 Quantitative references

- **Schedule**

The Modular Building Institute is an association formed by manufacturers, contractors, and dealers working in the modular building sector. The organisation emphasises the benefit of modularization in the definition of modularization itself: "*a process in which a building is constructed off-site, under controlled plant conditions, using the same materials and designing to the same codes and standards as conventionally built facilities but in about half the time*" [47]. Also Shelley [48] indicates that modular construction can shorten construction time by 50%. Instead, Hesler [49] states that "*in-depth studies have shown that modular power plants show schedule savings approaching 40%* ". In the case study "High-rise Building in Wolverhampton", it was estimated a saving of 45% in the construction period [36]. Moreover, Choi & Song [38] estimated schedule for stick-built and modular method relative to the construction of an underground machine room for a high-rise residential building. This study concludes that the traditional approach takes about nine months and the modularization about seven months. Therefore, it is possible to estimate a schedule saving of 22.2%. Efrimie [34], instead, focused on offshore facilities. According to the data owned by the author:"*reduced schedule (up to 25-50%): yard fabrication allows early procurement of critical equipment and maximized parallel works (workshop vs field civil work/site preparation); yard work can start before obtaining a site permit. Short schedules are important when required to market products rapidly* [...]". Another example of an offshore project that adopted modularization is the Delta House FPS in the Gulf of Mexico [25,50]. The Delta House began the project well before the arrival of any data (such as volume, specific pressure, temperature, and production). Conversely, most of the FPS projects use the conventional developmental approach, wherein drilling tests the wells and the reservoir composition is analysed before the design and construction phase. With the use of standardisation and modularization, the Delta House was able to finish their project successfully in about three years after the construction of the facility started. Comparing to other platforms in the Gulf of Mexico, the Delta house project was roughly completed 2-3 years earlier [50,51]. Considering that the construction time of offshore FPS projects using the traditional development cycle is 5-7 years [25], it is possible to estimate a saving of at least 28.6% in the construction period. Another specific case study is the General Dynamics Electric Boat [52]. Electric Boat is the prime contractor and lead design yard for the U.S. Navy's Virginia-class attack submarines. According to the company "*Improvements in construction performance will reduce construction span from 84 months to 60 months. This is being achieved through greater use of modular construction, pushing as much work as possible into a manufacturing setting where it can be done more efficient.*". Therefore, it is possible to estimate a saving of 28.6% in the construction period. Most of the references analysed report a schedule saving between 40% and 50%. On the other hand, two case studies in two different sectors show the same value of schedule saving, 28.6%. Figure 1 summarises the quantitative information about the schedule.

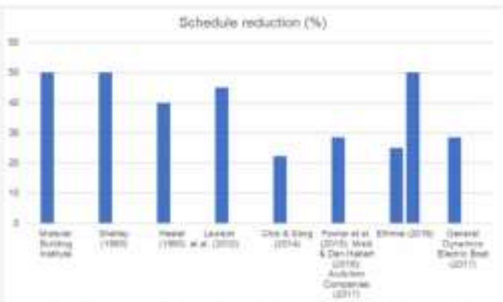


Figure 1: Schedule reduction determined by the transition from the stick-built method to modularization

- **Cost**

This section summarises the quantitative references about the cost variations determined by the transition from the stick-built method to modularization. Hesler [49] states that "*in-depth studies have shown that modular power plants show capital cost savings of 20 % or more*". He explains that the engineering costs involved in the first modular construction project are usually greater because of inexperience. In particular, the first modular design "*can be 50-60% more than conventional construction design, particularly if the job is done well. This, of course, is only 50-60% more (than conventional construction design) or 12% of the total installed cost.*". Shelley [48] shows that, in some cases, a reduction of capital costs by up to 20% is possible. Therefore, Shelley [48] and Hesler [49] agree on a capital cost saving of 20 % or more. Tatum et al. [53] evidence other significant benefits of the modularization. They state that it has been estimated that the modular engineering concept can save up to 10% of the total cost of a facility, cut on site labour by 25%, and reduce the plot [working] area by 10% to 50%. Parkingson & Short [54] show other examples of reduced costs through modular construction. In particular, they show that John Brown of John Brown Engineers & Constructors Inc. stated that savings of at least 7% of the total contract amount were obtained by using modular construction methods rather than conventional methods for over 40% of the process facilities for the Sullom Voe Oil Terminal in the Shetland Islands. Jameson [29] analysed a gasoil hydrotreater modular project located in North America. According to the author, modularization determined a cost saving of $ 12.5-million on an approximately $ 70-million project. Therefore, a cost saving of 17.8%. On the other hand, Glaser et al. [33] state that the additional man-hours required for design and engineering of a modular construction project increase the design and engineering cost by approximately 10%. Because of the effort needed to evaluate and select vendors, fabricators, and fabrication shops, and to administer contracts, the cost associated with procurement increases by 20% in modular construction projects, while the costs of the fabrication and transportation activities increase by approximately 17% and 13%, respectively. Instead, Kliewer [55] cites an engineering cost increase of 15%. Moreover, Shelley [48] shows that the transportation cost is about 1-2% of the value of the module. Figure 2 below summarises the quantitative information about the cost saving.

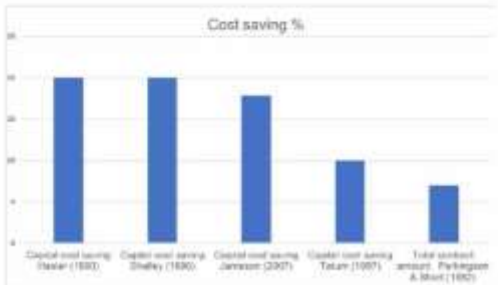


Figure 2: Cost saving determined by the transition from the stick-built method to modularization

2.3 Summary

Both qualitative and quantitative references show that the schedule reduction is one of the implications of the modularization. There are examples in several sectors, and the percentage can change from one to another one, but also within the same. Therefore, it should be assessed for each project individually. However, the references analysed show a maximum schedule reduction of 50%, a minimum of 22.2% and an average schedule reduction of 37.7%. At the same time, both qualitative and quantitative references show how modularization determines several cost variation. Design and engineering phase, procurement and transportation become more complicated than in the stick-built method, determining a cost increase. Nevertheless, the references analysed show a maximum capital cost saving of 20%, a minimum of 7% and an average cost saving of 15%.

3. RESEARCH METHODOLOGY

This section is concerned with the methodology used for the study explained above. Table 1 below provides a summary of the main research elements of this study.

Research Question	How modularization in offshore Oil & Gas projects impacts project cost and schedule?
Research Design	Inductive, exploratory study that implements a survey approach.
Sampling Strategy	Purposive and snowball sampling.
Data collection	Qualitative data collected through semi-structured interviews.
Data Analysis	Pilot-coding, content analysis through inductive coding.
Supplements	NVivo Pro

Table 1: research methodology, layout adapted from Bititci et al. [56]

3.1 Research Design and Research Method

The deductive approach and the inductive one are the primary research approaches. The deductive approach uses existing theory to develop a hypothesis and then tests it for validity. On the contrary, the inductive does not formulate a hypothesis at the beginning of the research [57]. The inductive approach has been selected, in consideration of the research question that aims to explore a phenomenon, identify the patterns and contribute to new generalisations [58,59]. Furthermore, this research design is categorised as an exploratory study. Based on Saunders et al. [60], qualitative research works in unity with interviews that consist of open-ended questions. Semi-structured interviews have been selected. This method allows open questions to be flexible in acquiring in-depth knowledge from the interviewees' responses [61].

3.2 Sampling strategy and Data Collection

The sampling strategy is based on the research design, access and representativeness of population [62]. For this research study, two sampling techniques are combined: the purposive sampling and the snowball sampling. The purposive sampling allows to be selective in choosing participants for the study. The participants targeted are senior project managers that worked on offshore Oil & Gas projects in Norway. The reason to choose this sample is that the concept of modularization in offshore Oil & Gas projects began to develop from around 40 years [63] and the Norwegian industry is one of the most advanced in the world in this sector. The snowball sampling is a technique in which the existing subject study propose other subjects who might become part of the sample. The advantage is the possibility to interview candidates that are hard to reach, mainly since the research focuses on a closed network industry. Data for this study were collected through interviews held in Norway, all being conducted face-to-face except for one phone-interview, with a total of 6 in-depth interviews with leading experts. Discussions focused on the participants roles and company background, experience from offshore projects, extent and view of modularization, further discussing related issues and examples. In all interviews, English was used to communicate. English is considered the second language in Norway, with participants in an industry that adopts it as its working language. Table 2 presents an overview with details of the six interviews, taking into consideration the anonymity of the interviewees.

No.	Date	Duration	Current position	Activity
1	6th June 17	35 mins	Engineering Manager	E & P
2	9th June 17	75 mins	Engineering Manager	EPC
3	12th June 17	70 mins	Engineering Manager	EPC
4	20th June17	60 mins	Director	Supplier
5	23th June 17	70 mins	Vice president	Supplier
6,7	6th July 17	60 mins	Discipline lead & Senior engineer	Concept & Design

Table 2: Overview of interview participants

Other data was collected in the process of setting up for interviews, such as phone calls and emails that discussed the research topic and its objectives. For instance, a conference call with both participants 1 and 2 occurred over a month before the face-to-face interview. It was initially arranged to brief participants more on the research question and discuss modularization before the formulation of the questions for the interview. Data collection is divided into two stages. In the first, the interview questions were put to the test by interviewing the first two participants, as pilot-test interviews. In the second stage, the other five participants were questioned based on the lessons learned from the previous ones. A key point is the engagement of the participants and several follow-up questions to attain elaborate answers and explore developing aspects relevant to the research question. This includes implementing the laddering technique to ask 'why' questions and ask participants for example [64].

3.3 Data analysis

A key point of research is the data analysis, which aims to finish the research work by drawing logical conclusions from obtained data [65]. Figure 3 below summarises the data analysis plan of this study.

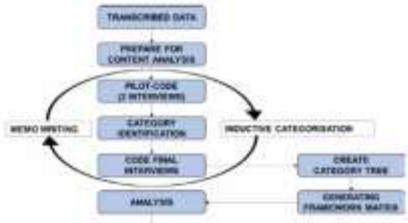


Figure 3: Data analysis plan

From the data collection stage, the interview transcripts were documented and each data content (six interviews transcript and notes) were thoroughly read and understood. NVivo Pro, a Computer-assisted Qualitative Data Analysis Software was employed to facilitate the analysis of data. Following the guideline set by Saldaña [66] in his coding manual, there are two cycles of coding. The first starts by reading the interview transcripts and summarising in a word or two each section of data into 'nodes' that represent different categories or themes. Further, the second cycle focuses on outlining the codes and reorganising the long initial list based on thematic similarity. Furthermore, the coding of the transcribed data is executed in two stages following a similar arrangement to the data collection. The initial phase includes pilot-coding the first two interviews using the cycles explained above. Following the second cycle of coding, a rough representation of the categories and sub-categories is formulated, and preliminary relationships were identified. The last stage proceeds to coding the final interviews using the initial stage categories for guidance. Throughout the process of coding, categories and sub-categories were rearranged, combined and titled appropriately based on the accumulated knowledge of the data. The following Figure 4 shows the final organising categories based on collected data.

Figure 4: Category tree

The root category, Modularization, gives a unique perception of the offshore Oil & Gas sector. The branching category, Project parameters, presents the identified interrelations between modularization and the primary project constraints. The last branching category, project life-cycle, is divided to show the determining offshore Oil & Gas phases.

4. FINDINGS AND DISCUSSION

This section summarises the findings and discusses the results of interviews in relation to the literature.

4.1 Modularization

This core category mainly focuses on defining modularization from the perspective of the participants. All of them agreed on its importance in the context of offshore projects. Most interviewees expressed modularization as the split of a project into various scopes or modules. As participant 3 articulated: *"…to take the complete project and split it into functional parts and split the scope. It could be internally… we prepare several modules that are fabricated as separate units, and then they are assembled on a later stage of the project. Or it could be split up into several scopes… other parties have other modules from the different parts of the whole project".* Participant 5 pointed out a key benefit of modularization as:

"the good thing about modularization of the equipment is that you can change out parts... then without having any downtime for the rig you can replace that... otherwise you have to do all retrofit work offshore". Furthermore, the phases that determine the modular approach were mentioned by participant 6: *"... we need to decide on the modularization as part of the concept, pre-FEED and FEED"*. Hence, these early phases represent the crucial stage which impacts the project most.

4.2 Schedule

- **Extract from the interviews**

Participants always acknowledge a direct relation between schedule and cost. Participant 2 explained: "*to compress a schedule that itself will have an extra cost due to overtime and additional personnel costs*". Participant 3 highlighted the importance of the control of the schedule: "*the schedule is very much controlled... it's one of the largest lifting vessels in the world ... therefore it's not an alternative to reschedule, so things need to be finished on that day*". Another aspect of having large modular offshore projects split and spread out is pointed out by Participant 2: "*the difficulty of managing site teams and communications is both time consuming and costly of course to have onsite follow-up of all these different sub-projects*"

- **Discussion**

A critical variable identified is the reduction of the project schedule. The shorter execution time influences the increase in costs since contractors, subcontractors and suppliers focus on delivering on time. These results support previous research that reflects on the impact of project duration on the cost performance [39,67,68]. Empirical evidence shows the constraints posed by the final transportation and lifting plan of these enormous modules are critical. Hence, the cost overruns can increase significantly for the EPC contractor as the schedule is very controlled. These results are in agreement with findings on the effect of scope delay on overall project commissioning [69]. On the other hand, it is interesting to note the excellent practice in the industry, where studies are performed on schedule performance issues upon project completion, providing lessons learned for similar future projects. The nuclear sector needs to familiarise with these lifting practices, particularly for SMRs built not on the coast.

4.3 Cost

- **Extract from the interviews**

As a result of the follow-up on modular parameters that impact cost, participant 6 made this statement: "*Weight is directly linked to cost... if you have an idea of the weight of steel you can just multiply the ratio number for cost and you get quite an accurate price range actually*". On the other hand, when asked about the impact of modular construction on the cost of procurement, participant 5 stated: "*you will have a more efficient and cost-effective procurement and fabrication, I think*". Other responses to this point included participant 2 statement: "*...you have more complex logistics... and typically you have misunderstandings of how and where various components are to be delivered, who shall purchase what. So, I would say ... procurement is more complicated and reduced in quality due to the modularization*". As for the cost of transporting modules compared to the overall project cost, participant 4 stated for small modules: "*when you come to big cranes ... it can be up to 10% of the cost of product*".

- **Discussion**

The empirical findings presented the direct relationship between weight, size, production capacity and cost. A similar relation and the importance of taking into account for the cost are documented in the literature [69]. However, the authors [69] don't consider design factors such as the met-ocean data required for the early design of floaters and semisubmersibles. The results presented that this design parameter influences the size of the hull which causes a definite increase in cost. Further, increase in weight affects fabrication costs due to additional steel, massive lift cranes, engineering costs and shipping costs. On the other hand, the relationship between risk of rework and increase in cost is reported in the literature [40,44]. The current study found that factors of rework risk impact cost due to lack of early involvement, the complexity of planning and interface handling. These results support the idea of developing interface management to better control risks [45]. A significant finding is that the modularization reduces in some instances the risk of rework. The results suggest, having smaller modules as units that can be removed or replaced would decrease the high costs of rework and enable cost savings. A key point for the nuclear sector would be to establish the exact size of the module(s), balancing the economies of scale with the learning process acquired by building a series of modules.

4.4 Risk

- **Extract from the interviews**

The participants illustrated several types of risk. Participant 2 stated: "*due to the extreme focus of let's say, turnover time. I think the risk of under engineering or poorly planned engineering... are the most critical*". Further, participant 3 presented an example related to modular parameters: "*there is a risk that maybe your assumption in the beginning was a module 20x20 meter and hopefully that will be enough space to house all the equipment and all the functionality you put in. But, if it turns out you cannot fulfil the requirements within the space, then you will have a very big problem*". Additionally, the schedule is linked to many risks. Participant 6 stated: "*Usually delay is a risk, for instance these topside modules built, even if it's on the same yard, it's still different locations and it needs to be timed correctly, needs to be finished at the right time because maybe you have one block that goes in before you have the outer one installed*". Moreover, participant 5 presented the risk of rework: "*...the equipment should be incorporated in the 3D model, when that fits together you start to do the construction... if the actual equipment isn't 100% identical with the drawings then... your assembling doesn't fit together. You have to do some rework... that should be in a small workshop not at a yard, an... you hold back maybe the whole fabrication*".

- **Discussion**

Previous studies evaluating the modular construction in offshore Oil & Gas projects have highlighted that risks are mainly due to poor planning and poor detailed engineering [38,39]. The empirical results presented the risk of not fulfilling the weight and capacity requirements due to poor detailed engineering and lack of communication among the parties in the EPC phase. On the other hand, findings present the risk of delays due to weather conditions to be critical for topside modules, since they require special large transport vessels. However, delays are not regarded for smaller modules that can be transported by commercial container ships for instance. Construction in the nuclear sector has often been affected by huge risks leading to overbudget and delay. If modularization will be able to offset some of these risks, it would be possible to have more investors confident to embark in nuclear projects. However, a key point will always be to properly allocate the different risks to the stakeholders better able to handle them. Novel solutions, like the usage of SPE, should be carefully investigated [70].

4.5 Project Life Cycle

- **Extract from the interviews**

➢ Concept Design

The relationship between the project characteristics of offshore Oil & Gas projects and modularization starts with the concept phase. Appropriate decisions made during the early design impact cost as stated by participant 7: "*To get robustness, to get a good start, if you do a lot of changes in the later phases it might be more expensive you have to redo a lot of things…*". Moreover, the decision made on lifting of modules may impact the modular design, participant 3 elaborated: "*you have to decide early for instance how to install this, shall this be an offshore installation with lifting or do you install the modules on the yard with skidding, that will affect the design of the modules*".

➢ Front End Engineering Development

When asked about complications that develop during the FEED phase, participant 6 related to module layout: "*for instance you add all the different sizes of piping and you will see that thing will increase in size… when you get to really do things in detail you will see the actual required space and not the assumption we made early on*". Participant 5 argued about FEED with an example: "*we had one project they have done FEED phase and the quality was not good enough, so the whole platform needed to be reinforced or increased in size and weight, that affects everything, the cost and schedule…*".

➢ Engineering, Procurement and Construction

Following the concept phase and FEED phase, the company developing the concept is usually not involved anymore. Participant 7 stated: "*we have done engineering up to a certain degree, and then the detailed contractors do the detailed engineering*". About the selection of EPC format, participant 1 said: "*normally the main hurdle is actually to have all the engineering in place before you start construction. I think that's actually where most companies or projects fail*". The reason behind this problem is illustrated by participant 3: "*all projects that we have been involved with have a very tough timeframe and…you are normally forced to start fabrication early, even when it's still a lot of remaining issues to be resolved in the engineering phase*".

➢ Transportation and Commissioning

The complete overview of transportation of different modules till the commissioning of the final offshore platform is presented from a project by Participant 3: "*to reduce offshore work that is very expensive… they assemble it as one unit… and transport it to the field… that is cost efficient*". On the other hand, transportation arrangements act as constraints that influence key milestones in the project. Participant 5 mentioned this remark: "*you might be building the hull at the yard and then you have the milestone to take the hull further for topside integration. Then you have a certain milestone … to just transport the vessel …*". Conversely, the delay may come from the transport or lifting vessel. Participant 1 stated: "*…we were two months delayed on the offshore installation of the module, that was actually due to harsh weather west of Africa…*". Most participants agreed on the impact of transportation, yet participant 4 stated: "*our equipment, it's smaller, it's not big structures, they are small and can maybe go into a container and they can go on fast going vessels, they maybe don't need special transport*".

➢ Interfaces

This matter was stressed upon by both participants from the EPC company, as participant 3 explained: "*Because you might have several engineering companies for systems engineering, you have several companies for fabrication, you can have several subcontractors … the number of interfaces are increasing your risk*". Moreover, the communication and integration between the various parties during the early project phases was acknowledged by participant 6: "*… the different disciplines have direct contact with the disciplines if we have a major client in UK or US … I need to have a contact person for my relevant discipline for the site*". Further, participant 7 followed with this statement: "*And in later phases, it might be required to work in integrated teams*". Participant 2 talked about an example to explain how to mitigate the impact of the interface: "*to handle all the interfaces …that was a modularised project, the demand for engineering phase was that all participants shall be co-located at a physical location…to counter the adverse effects…5 or 10 teams with separate scopes that should be integrated*".

A key problem for the nuclear industry has often been related to start the construction, still without a detailed design completed. For instance, in the case of Olkiluoto 3 the regulator said "*The schedule of Nuclear Island is now about four years behind the original plan. Main reasons for this delay are: […] – inadequate completion of design and engineering work prior to start of construction. – lack of experience of parties in managing a large construction*" [71]. Also "*making design as early as needed for smooth construction, & qualifying the new design features and technologies*" were key points raised by the regulator [71]. As clearly presented in the Oil & Gas sector, modularization would be a key driver here. It could exacerbate these aspects if not properly management (e.g. poor detailed design), but could also be the "silver bullet" if the designed is improved and optimised in the case of "series production". Again, SMRs would be an attractive proposition only if a multitude of identical units will be manufactured, commissioned and operated.

4.6 Key takeaways for the nuclear sector

A key result of the research reveals the actual importance of vendor selection, for the timely inclusion of modules, interface information and freezing critical modular parameters. Moreover, early engagement of suppliers and regulators during FEED phase is recommended to improve information sharing and decrease the impact of conceptual premises that affect the project life-cycle further. This is consistent with findings that show the impact of early decisions on modular construction projects [22,72]. Furthermore, empirical results presented the size and complexity of projects, which increases interdependence of interfaces among project scopes and increases risk. Under this perspective, SMRs might have a clear advantage respect to larger GWe scale reactors. Small projects are usually fast-paced and, in several instances, engineering and construction overlap causes an increase in requirements for interface handling. Failure to fulfil such requirements will impact installation and functionality of the whole module. Similar findings are documented in the literature. According to Love & Edwards [40], initiation of construction before engineering is completed causes risk of rework. Moreover, as the yard contractor subcontracts smaller modules as equipment packages to the supplier, further the supplier may subcontract the fabrication to distant sites to reduce costs. Although this particular notion is not specified in the presented literature, theory highlighted the crucial factors in EPC phase influencing the risk of rework due to the dispersion of the project team [40]. The literature on modularization of plants focuses on the impact of interfaces handling in terms of cost overruns, for instance, due to rework or other technical risks [38,40]. Nonetheless, as the empirical findings stated, if requirements for critical parameters such as weight and size exceed the specified range in the construction phase, then changes lead to extreme cost overruns for contractors causing, in certain case bankruptcy. In the nuclear sector, where the number of "qualified contractors" for a certain task is usually small, this might become a key risk.
The empirical findings show that contractors adopted concurrent planning and partnering with experienced subcontractors and suppliers. The theory recognises these as factors that enable the success of modular construction projects through the experience of contractors [43,72]. However, empirical findings present a limitation of these applied enablers, that is the discontinuity through projects phases due to the use of different contractors and consultants from one step to the next, or gap among the parties within one step. According to Olaniran et al. [73], implementation of integration teams would assist in improving the continuity and effective communication. An interesting empirical finding to point out is the recent measure taken by the main client in the Norwegian industry, that is the implementation of large integration teams at one location. This presents a development in client leadership in order to improve cost and schedule performance of modular projects, through the management of execution risks, delay avoidance and continuity through project phases. Otherwise, the repercussion according to empirical evidence has increased in costs for the topside contractor due to the interdependence of assembly on other modules, further increase of delay risk on schedule due to the critical transport and lift milestones for offshore delivery.

5. CONCLUSION

A keyword in "Small Modular Reactors" is "Modular". Despite many studies and papers discuss the economics of SMRs very few of them provide a sensible analysis of the modularization aspect. The key reason is that SMRs are a novel type of reactors, therefore historical data are not available. This paper addresses this gap in knowledge analysing modularization in other types of infrastructure. It describes, through a literature review analysis, how modularization in infrastructure impacts on the project schedule, cost and risk. Moreover, this paper summarises and discusses the results of interviews with Oil & Gas project managers about the value of modularization in this sector. Schedule reduction and cost saving can be considered as two of the key advantages of the transition from the stick-built method to modularization in infrastructure. On the other hand, the increased risk as one of the key disadvantages. Therefore, the aim of this paper is to show what we know about modularization in infrastructure on three key project parameters: schedule, cost, and risk.
The results of the literature review analysis and of the interviews suggest that the evaluation of the transition to modularization in infrastructure requires the consideration of several variables. However, the empirical evidence presented in this paper confirm the merit of modularization. This doesn't imply that the transition from the stick-built method to modularization in the nuclear sector will determine the same consequences. Future research might provide some cost comparison between the SMR with loop type PWRs.
However, SMRs in particular and the nuclear sector in general can learn from modularization in the infrastructure leveraging the experience accumulated over the year. "Learning the right way to do modularization" will be a key success factor for the deploy of SMRs.

REFERENCE

[1] IAEA. "Advances in Small Modular Reactor Technology Developments". 2016.

[2] Locatelli G, Mancini M, Todeschini N. "Generation IV nuclear reactors: Current status and future prospects". Energy Policy 2013, Vol. 61, pp. 1503–20.

[3] IAEA. "Advances in Small Modular Reactor Technology Developments. A Supplement to: IAEA Advanced Reactors Information System (ARIS)". Vienna, 2014.

[4] Ingersoll DT. "Deliberately small reactors and the second nuclear era". Prog Nucl Energy 2009, Vol.51, pp. 589–603.

[5] Carelli MD, Locatelli G, Mycoff CW, Garrone P, Mancini M, Ricotti ME, et al. "Competitiveness of

small-medium, new generation reactors: a comparative study on capital and O&M costs". 16th Int. Conf. Nucl. Eng., Vol. 4, Orlando, Florida, USA, May 11–15, 2008: ASME; 2008, pp. 1–8.

[6] Locatelli G, Mancini M. "A framework for the selection of the right nuclear power plant". Int J Prod Res 2012, Vol. 50 pp. 4753–66.

[7] Boarin S, Locatelli G, Mancini M, Ricottia ME. "Financial case studies on small- and medium-size modular reactors". Nucl Technol 2012, Vol. 178, pp. 218–32.

[8] Locatelli G, Bingham C, Mancini M. "Small modular reactors: A comprehensive overview of their economics and strategic aspects". Prog Nucl Energy 2014, Vol.73, pp. 75–85.

[9] Boarin S, Mancini M, Ricotti M, Locatelli G. "Economics and financing of small modular reactors (SMRs)". In: Carelli MD, Ingersoll DT, editors. Handb. Small Modul. Nucl. React., Elsevier; 2015, pp. 239–77.

[10] Trianni A, Locatelli G, Trucco P. "Competitiveness of small-medium reactors: A probabilistic study on the economy of scale factor". Int. Congr. Adv. Nucl. Power Plants 2009, ICAPP 2009, Vol. 1, 2009.

[11] Locatelli G. "Fusion: Go small to go fast". 25th Int. Conf. Nucl. Eng. ICONE 2017; Shanghai; China; 2 July 2017 through 6 July 2017; Code 131175, Vol. 5, American Society of Mechanical Engineers (ASME); 2017.

[12] Carelli MD, Petrovic B, Mycoff CW, Trucco P, Ricotti ME, Locatelli G. "Smaller sized reactors can be economically attractive". Soc. Fr. d'Energie Nucl. - Int. Congr. Adv. Nucl. Power Plants - ICAPP 2007, "The Nucl. Renaiss. Work., Vol. 5, 2007.

[13] Carelli M, Garrone P, Locatelli G, Mancini M, Mycoff C, Trucco P. "Economic features of integral, modular, small-to-medium size reactors". Prog Nucl Energy 2010, Vol. 52, pp. 403–14.

[14] 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, Vol. 53, pp. 212–22.

[15] Sainati T, Locatelli G, Brookes N. "Small Modular Reactors: Licensing constraints and the way forward". Energy 2015, Vol. 82, pp.1092–5.

[16] Carelli MD, Garrone P, Locatelli G, Mancini M, Mycoff C, Trucco P, et al. "Economic features of integral, modular, small-to-medium size reactors". Prog Nucl Energy 2010, Vol. 52, pp. 403–14.

[17] Locatelli G, Boarin S, Pellegrino F, Ricotti ME. "Load following with Small Modular Reactors (SMR): A real options analysis". Energy 2015, Vol. 80, pp. 41–54.

[18] Locatelli G, Boarin S, Fiordaliso A, Ricotti M. "Load following by cogeneration: Options for small modular reactors, gen IV reactor and traditional large plants". 25th Int. Conf. Nucl. Eng. ICONE 2017; Shanghai; China, vol. 3, American Society of Mechanical Engineers (ASME); 2017.

[19] Locatelli G, Fiordaliso A, Boarin S, Ricotti ME. "Cogeneration: An option to facilitate load following in Small Modular Reactors". Prog Nucl Energy 2017, Vol. 97, pp. 153–61.

[20] Brookes NJ, Locatelli G. "Power plants as megaprojects: Using empirics to shape policy, planning, and construction management". Util Policy 2015, Vol. 36, pp. 57–66.

[21] Locatelli G, Pecoraro M, Meroni G, Mancini M. "Appraisal of small modular nuclear reactors with "real options" valuation". Proc Inst Civ Eng - Energy 2017, Vol. 170, pp. 51–66.

[22] Azhar S, Lukkad MY, Ahmad I. "Modular v. Stick-Built Construction: Identification of Critical Decision-Making Factors". 48th ASC Annu. Int. Conf. Proc., United State: the Associated Schools of Construction; 2012.

[23] Habibullah A, Lardi P, Passmore M. "LNG Conceptual Design Strategies". WorleyParsons 2009.

[24] Ikpe E, Kumar J, Jergeas G. "Analysis of Modularization Compared to Total Project Cost in Alberta Oil and Gas Projects". Glob Adv Res J Manag Bus Stud 2015, Vol. 4, pp. 116-120.

[25] Misiti A, Dan Hebert P. "Modular Construction in the Oil and Gas Industry". GlobalSpec 2016.

[26] YOUR INDUSTRY NEWS, 2017, "Yamal LNG granted State permission to commission first LNG train". Available at: http://www.youroilandgasnews.com/yamal+lng+granted+state+permission+to+commission+first+lng+train_146567.html [Accessed [5-Dec-2017].

[27] LNG WORLD NEWS, 2014, "Technip Confirms Yamal LNG Deal". Available at: http://www.lngworldnews.com/technip-confirms-yamal-lng-deal/. [Accessed: 20-Nov-2017].

[28] Merrow EW. "Industrial Megaprojects: Concepts, Strategies and Practices for Success". John Wiley & Sons; 2011.

[29] De La Torre ML. "A review and analysis of modular construction practices". Lehigh University, 1994.

[30] Jameson PH. "Is modularization right for your project ?". Hydrocarbon Processing 2007, pp. 67-71.

[31] Musa MF, Yusof MR, Mohammad MF, Mahbub R. "Characteristics of Modular Construction : Meeting the Needs of Sustainability and Innovation". IEEE Colloq Humanit Sci Eng 2014, pp. 216–21.

[32] Musa MF, Yusof MR, Mohammad MF, Sahidah. "Towards the adoption of modular construction and prefabrication in the construction environment : a case study in Malaysia". ARPN Journal of Engineering and Applied Sciences 2016, Vol. 11, pp. 8122–31.

[33] Glaser L., Kramer J, Causey E. "Practical Aspects of Modular and BargeMounted Plants". Chem Eng Prog 1979, Vol. 75, pp. 49–55.

[34] Eftimie C. "How to Efficiently Engineer the Onshore Facilities: Standardized Modularization Drivers, challenges and perspectives in the Oil and Gas industry". Proj Value Deliv 2016.

[35] David PA, Rothwell GS. "Standardization, diversity and learning: Strategies for the coevolution of technology and industrial capacity. Int J Ind Organ 1996, Vol. 14, pp. 181–201.

[36] Lawson RM, Ogden RG, Bergin R. "Application of Modular Construction in HighRise Buildings". J Arc hit Eng 2012, Vol.18, pp.148–54.
[37] PMBOK, 2013. A Guide to the Project Management Body of Knowledge - Fifth Edition.
[38] Choi J, Song H. "Evaluation of the modular method for industrial plant construction projects".Int J Constr Manag 2017, Vol. 14, pp. 171–80.
[39] Zidane YJT, Stordal KB, Johansen A, Van Raalte S. "Barriers and challenges in employing of concurrent engineering within the Norwegian construction proje cts". Procedia Econ Financ 2015, Vol. 21, pp. 494–501.
[40] Love PED, Edwards DJ. "Curbing rework in offshore projects: systemic classification of risks with dialogu e and narratives". Struct Infrastruct Eng 2013, Vol. 9, pp. 1118–35.
[41] Burke R. "Project management: planning and control techniques". New Jersey, USA 2013.
[42] De Meyer A, Loch CH, Pich MT. "Managing project uncertainty: from variation to chaos". MIT Sloan Ma nag Rev 2002, Vol. 43, p. 60.
[43] Choi JO, O'Connor JT, Kim TW. "Recipes for Cost and Schedule Successes in Industrial Modular Projects: Qualitative Comparative Analysis". J Const r Eng Manag 2016, Vol.142, p. 4016055.
[44] Olaniran OJ, Love PED, Edwards DJ, Olatunji O, Matthews J. Chaos Theory: Implications for Cost Overrun Research in Hydrocarbon Megaprojects. J Constr Eng Manag 2017, Vol. 143, p. 5016020.
[45] Shokri S, Haas CT, G. Haas RC, Lee SH. "Interface-management process for managing risks in complex c apital projects". J Constr Eng Manag 2015, Vol. 142, p. 4015069.
[46] Shahtaheri Y, Rausch C, West J, Haas C, Mohamma d N. "Risk Mitigation through Tolerance Strategies f or Design in Modularization". 1st Int. Conf. Ind. Con str., 2015.
[47] MODULAR BUILDING INSTITUTE, 2013. "Why Build Modular". Available at: http://www.modular.or g/HtmlPage.aspx?name=why_modular [Accessed 28-Nov-2017].
[48] Shelley S. "Making inroads with modular construction". Chem Eng 1990, pp. 30–5.
[49] Hesler W. "Modular Design - Where It Fits". Chem Eng Process 1990, pp. 76–80.
[50] Audubon Companies. "Fast-Track Platform Success: The Story Behind Delta House Fps". Audubon Co 2017.
[51] Fowler RL, Zimmermann EC, Leimkuhler JM, Mullett C, Cooley B, Paternostro B, et al. "Delta House Project Overview". Offshore Technol. Conf., Offshore Technology Conference; 2015.
[52] General Dynamics Electric Boat. General Dynamics Electric Boat | Business Centers 2017.
[53] Tatum C, Vanegas J, Williams J. "Constructability improvement using prefabrication, preassembly, and modularization". 1987.
[54] Parkingson G, Short H. For more plant projects the word is: go modular. Chem Eng 1982, pp. 66–9.
[55] Kliewer VD. "Benefits of Modular Plant Design". Chem Eng Prog 1983, Vol. 79, pp. 58–62.
[56] Bititci U, Cocca P, Ates A. "Impact of visual performance management systems on the performance management practices of organisations". Int J Prod Res 2016, Vol. 54, pp. 1571–93.
[57] Thomas RM. "Blending qualitative and quantitative research methods in theses and dissertations". Corwin Press 2003.
[58] Saunders MNK. Research methods for business students. Pearson Education India, 2011.
[59] Bryman A, Bell E. Business research methods. Oxford University Press, USA, 2015.
[60] Saunders M, Lewis P, Thornhill A. Research Methods for Business Students. 6th ed. Harlow: Pearson Education Limited, 2012.
[61] Rubin HJ, Rubin IS. Qualitative interviewing: The art of hearing data. Sage 2011.
[62] Bryman A. Social Research Methods. 4th ed. New York: Oxford University Press 2012.
[63] Bjørnstad S. "Shipshaped: Kongsberg industry and in novations in deepwater technology". BI Norwegian School of Management, 2009.
[64] Easterby-Smith M, Thorpe R, Jackson PR. Management and business research. Sage 2015.
[65] Merriam SB. Qualitative research and case study application in educations. San Fransisco: Jossey-Bass Publishers, 1998.
[66] Saldaña J. The coding manual for qualitative researchers. Sage, 2015.
[67] Olaniran OJ, Love PED, Edwards D, Olatunji OA, Matthews J. "Cost Overruns in Hydrocarbon Megaprojects: A Critical Review and Implications for Research". Proj Manag J 2015, Vol. 46, pp. 126–38.
[68] Yun S, Choi J, de Oliveira DP, Mulva SP. "Developm ent of performance metrics for phase-based capital project benchmarking". Int J Proj Manag 2016, Vol. 34, pp. 389–402.
[69] Rui Z, Li C, Peng F, Ling K, Chen G, Zhou X, et al. " Development of industry performance metrics for off shore oil and gas project". J Nat Gas Sci Eng 2017, Vol. 39, pp. 44–53.
[70] Sainati T, Locatelli G, Brookes N. "Special Purpose Entities in Megaprojects: empty boxes or real companies?" Proj Manag J 2017, Vol. 48.
[71] Symposium US. "Lessons for the next NPP projects, as learned from the Olkiluoto 3 construction experi ences". Radiation and Nuclear Safety Authority - STUK 2011.
[72] O'Connor JT, O'Brien WJ, Choi JO. "Critical Success Factors and Enablers for Optimum and Maximum Industrial Modularization". J Constr Eng Manag 2014, Vol.140, p. 4014012.
[73] Olaniran OJ, Love PED, Edwards D, Olatunji OA, Matthews J. "Cost Overruns in Hydrocarbon Megaprojects: A Critical Review and Implications for Research. Proj Manag J 2015. Vol. 46, pp. 126–38.

II.

D.2 Publication VI

Mignacca, B., Alawneh, A.H., Locatelli, G., 2019. Transportation of small modular reactor modules: What do the experts say? The proceedings of the 27th International Conference on Nuclear Engineering, Ibaraki (Japan) - **Scopus indexed proceedings**.

Proceedings of ICONE-27
27th International Conference on Nuclear Engineering
May 19-24, 2019, Ibaraki, Japan

ICONE27-1235

TRANSPORTATION OF SMALL MODULAR REACTOR MODULES: WHAT DO THE EXPERTS SAY?

Benito Mignacca
University of Leeds, School of Civil Engineering
Leeds, United Kingdom

Ahmad Hasan Alawneh
University of Leeds, School of Civil Engineering
Leeds, United Kingdom

Dr Giorgio Locatelli
University of Leeds, School of Civil Engineering
Leeds, United Kingdom

Keywords: Small Modular Reactor, Modularization, Transportation, Construction, Factory Fabrication

ABSTRACT
One of the key characteristics of small modular reactors (SMRs), as their name emphasised, is the modularization. Modularization implies factory production, which in turn implies transportation of large, heavy, complex and fragile modules from the factory to the site. Various vendors and organisations are developing several SMR concepts and designs, but there are extremely limited information about the crucial element of modules transportation. Conversely, in other industries (e.g. Oil & Gas), the experience on modules transportation is much greater. This paper provides a structured analysis for the knowledge transfer from the general literature (i.e. other major infrastructure) to the SMR world. Firstly, the paper provides a summary of the literature about transporting large modules. In the second part, the paper presents and discusses the results of a series of interviews with transport industry experts about large modules transportation. The third part provides a summary of the findings and the key takeaways.

1 INTRODUCTION

The International Atomic Energy Agency (IAEA, 2016) defines Small Modular Reactors (SMRs) as "*newer generation 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*". Several SMR designs, detailed in (Locatelli, *et al.*, 2013; IAEA, 2014, 2016, 2018), are currently at different stages of development. (Ingersoll, 2009) provides a summary of the innovative features of SMRs and describes SMRs as "*reactor designs that are deliberately small, i.e. designs that do not scale to large sizes but rather capitalize on their smallness to achieve specific performance characteristics*". Several papers discuss the competitiveness of SMRs vs Large Reactors (LRs) and how SMRs might balance the "diseconomy of scale" with the "economy of multiples" (Carelli, *et al.*, 2008; Trianni, *et al.*, 2009; Boarin, *et al.*, 2012, 2015, Locatelli, *et al.*, 2012, 2014; Locatelli, 2017). (Carelli, *et al.*, 2007, 2010) analyse specific factors (such as grid characteristics, construction time, financial exposition, modularization, learning etc.) which distinguish SMRs from LRs in the evaluation of the capital cost. Once these factors are taken into account, the capital cost is comparable between the two technologies (Carelli, 2008; Boarin, 2012). (Locatelli, *et al.*, 2011) discuss the effects of 'non-financial parameters', such as electric grid vulnerability, public acceptance, the risk associated with the project, licensing (Sainati, *et al.*, 2015), during the evaluation of the best reactor size for investments in the nuclear sector. For many of these parameters, the authors explain how SMRs show an advantage with respect to LRs. Another key advantage of SMRs is the learning (Carelli, 2010). According to (Carelli, 2010), the learning curve flattens out after 5-7 units, determining that the n^{th} of a kind is reached with less MWe installed for SMRs with respect to LRs (Carelli, 2010). SMRs, having the power fractionated are also ideal for cogeneration, as presented in (Carelli, 2010; Locatelli, *et al.*, 2015; Locatelli, Boarin, *et al.*, 2017). Indeed, one of the key SMR advantages is the possibility to split a large investment into smaller ones. The construction of a single LR is a risky investment (Brookes, *et al.*, 2015). The construction of SMRs is an investment decision with n degrees of freedom that allows hedging investment risks. The economic merit of flexibility can be calculated using the Real Options approach (Locatelli, Pecoraro, *et al.*, 2017). SMR components and systems are designed to be factory manufactured and transported to the site as modules. Therefore, SMR modules transportation is one of the three main steps: factory manufacturing, modules transportation and installation on-site. However, despite the relatively large amount of literature published on SMRs and despite several concepts and designs being developed by various countries, there are extremely limited information about the crucial element of SMR modules transportation. Therefore, it is necessary to explore modules transportation in closely related fields (e.g. Oil & Gas) and transpose the knowledge back to the SMR sector. As later discussed, modules transportation is strictly related to the country. This paper investigates how SMR modules can be transported in the United Kingdom (UK) and what can be learned from previous experiences. The rest of the paper is structured as follows: section 2 summarises the key references about transporting large modules; section 3 presents the methodology used to collect and analyse data; section 4 shows and discusses the results of interviews with transport industry experts about modules transportation. The last part provides guidelines about SMR modules transportation and the key takeaways.

2 TRANSPORTATION IN MODULAR INFRASTRUCTURES

2.1 Modularization: what it is and its implications

Modularization is the process of converting the design and construction of a monolithic plant into a plant that facilitates factory fabrication of modules for shipment and installation in the field as complete assemblies (GIF/EMWG, 2007). Several papers deal with the costs and benefit of modularization (De La Torre, 1994; Azhar, *et al.*, 2012; Bondi, *et al.*, 2016; Upadhyay, *et al.*, 2016). Most of these references are qualitative, like the recent review of modularization in the nuclear industry (Upadhyay, 2016). Factory fabrication is usually cheaper than site fabrication, but the costs associated with shipping of modules to the site must also be considered. Smaller plants can take better advantage of modularization since it is possible to have a greater percentage of factory-made components. Although there are a number of works in the literature describing the qualitative advantages of modularization, only a few of them are able to quantify the underlying advantages. (Mignacca, *et al.*, 2018) provide a summary of the quantitative information about two key implications of modularization in infrastructure: schedule reduction and cost saving. Therefore, modularization implies factory production, which in turn implies transportation of large, complex and fragile modules from the factory to the site. According to (Vegel, *et al.*, 2017), SMRs will be in the factory for the first two years (build time and testing), and in the last year will be transported and installed on site. However, the literature about SMR modules transportation is almost inexistent. Conversely, in other sectors (e.g. Oil & Gas), the experience on modules transportation is much greater.

2.2 Transporting large and heavy modules

This section summarises the key concepts about transporting large and heavy modules. According to (De La Colina, *et al.*, 2016), heavy lift impacted successfully on the construction industry, opening the doors to new construction alternatives, methods, and strategies. Modularization is one of them. However, modularization presents significant logistical challenges (Mammoet, 2018b). Once prefabricated modules are ready, they must be lifted, transported, and installed in the right sequence (Mammoet, 2018b). Modules transportation is recognised as one of the main disadvantages of modularization. According to (Musa, *et al.*, 2016), modularization can reduce the labour and material cost, but can increase the transportation cost. One of the reason is the additional material needed for proper transportation and the structural requirements of the modules (De La Torre, 1994; Choi, *et al.*, 2014). (De La Torre, 1994) also includes modules loss and modules transport damage in the main risks of modularization, and points out how the interdependence of planning, design, fabrication, transportation, handling, and erection determines more planning and communication than the stick-built method. Furthermore, (De La Colina, 2016) states that modules are usually fabricated in different locations respect to their final position. These locations are usually specialised yards away from the site and sometimes even different countries, determining the increase of the transportation cost and making logistics even more complex. Furthermore, modules and equipment have grown in size and complexity, causing new challenges for the transport industry, requiring custom-made techniques depending on the load and dimensions of the module (Mammoet, 2018b). However, (Wrigley, *et al.*, 2018) point out as the recent technology development such as driverless electric transport might reduce the transportation cost. Currently, there is a large range of heavy transport equipment used in the industry, ranging from conventional trailers and barges to skidding system and Self-Propelled Modular Transporters (SPMTs). As common in the transportation industry, the main heavy transport and lifting techniques are here categorized by road, barge, and rail transport methods.

2.2.1 Road transport

There are two main methods to transport large and heavy modules by road: conventional trailers and SPMTs. (Fagioli, 2018c) defines SPMTs as: *"multi-axel trailers designed for the transportation of heavy and large objects"*. They are characterised by 4-8 axel lines that have a maximum load capacity ranging from 44 tons up to 60 tons per axle line and are controlled through a remote operation console with several steering programs. SPMTs consist of a strong metallic framework which also acts as a load carrying platform. It is supported by hydraulic rams which act as the suspension of the SPTM and provides lifting ability. They are mainly used for short distances (Fagioli, 2018c; Mammoet, 2018d). On the other hand, the conventional ones are heavy load trailers characterised by numerous axel lines and high bearing capacity (36 tons per axle line). They are often connected with beams to create a larger trailer. The external propulsion is often generated by truck, and in some cases by several trucks (Mammoet, 2018d). Furthermore, (Smith, 2010) states that "Container Shipping" and "Dimensional Shipping" are the two main methods used to transport heavy modules into containers by road. Container shipping consists of trailers that have standardized size and lifting methods. Conversely, dimensional shipping requires custom dimensions.

2.2.2 Barge transport

"*The river transport is another important activity […] especially with the size of the items getting bigger and bigger and the new infrastructures do not always supply for these large items to be transported by convoy*" (Fagioli, 2018a). More in general transportation by barge is usually used when module dimensions don't allow using land transport method. This transport method provides an alternative both when the roads are extremely busy and to avoid restrictions such as bridges. The module is usually loaded onto the barge by using a gantry crane. The main advantage of this method is that a standard barge has a capacity 50 times more than a normal trailer, determining a significant cost saving (Fagioli, 2018a). (Devgun, 2013) also states that transport by barge is usually the favoured method for very heavy modules.

2.2.3 Rail transport

Transportation by rail consists of railcars having a carrying capacity ranging from 200 to 1200 tons (Mammoet, 2018a). The heavy-duty railcars have 8-44 axel lines which can be shifted horizontally and vertically allowing the transportation of the over-sized load. (Fagiloli, 2018; Mammoet, 2018a). Rail transport and road transport tend to have a similar cost, but rail transport tends to have lower lead time, frequency, and service flexibility (Larsson, 2009).

2.2.4 Cranes and special equipment

(Devgun, 2013) states that heavy and large modules would require the use of Very High Lift (VHL) cranes, but they are very expensive. Some less expensive alternatives to the VHL cranes are (Fagioli, 2018b; Mammoet, 2018c):

Crawler Cranes: It is a crane that is attached to an undercarriage with a pair of caterpillar's tracks to provide steadiness and mobility. It is commonly used at power stations and refinery projects and offers lifting capabilities up to 3000 tons and a total lifting height up to 200 meters.

Strand Jack System: It consists of a jack pulling a bundle of wires called strand. It has an upper and bottom clamp which are connected to a hydraulic cylinder that moves up and down. This system has a capacity of 15-750 tons (depending on the number of strands).

Skidding System: This system is used to move extremely heavy loads such as offshore platforms and complete buildings. It is simple and can only be fitted in a straight line which uses a skidding track to allow large loads to be moved with a limited force.

Gantry Lifting System: This system is a combination of 2 or more legs and overhead beam. There are usually four jacking units supported on wheels having one vertical lift cylinder and a vertical lift on top. The legs are hydraulic, which enable the system to lift loads up to 800 tons.

3 RESEARCH METHODOLOGY

This section is concerned with the methodology used for the study explained above. Table 1 provides a summary of the main research elements of this study.

Research question	How can SMR modules be transported in the UK?
Research design	Inductive, exploratory study
Sampling strategy	Purposive sampling
Data collection	Semi-structured interviews and secondary data
Data analysis	Content analysis (inductive coding)
Supplements	NVivo 11

Table 1: Research methodology - Layout adapted from (Bititci, *et al.*, 2016)

3.1 Research design and method

For this kind of research there are two main research approaches: deductive and inductive (Saunders, *et al.*, 2007). The deductive approach generates hypothesis starting from the existing theory, and then move towards specific observations testing the validity. On the contrary, the inductive does not formulate hypothesis at the beginning of the research but starts from data (Dudovskiy, 2018). In summary, a deductive approach tends to test the theory, while an inductive generates theory. The inductive approach has been selected, in consideration of the research question that aims to explore a phenomenon, identify the patterns and contribute to new generalisations (Saunders, 2011; Bryman, *et al.*, 2015). Furthermore, this research design is categorised as an exploratory study. Secondly, based on (Saunders, *et al.*, 2012), qualitative research works in unity with interviews that consist of open-ended questions. Semi-structured interviews have been selected. This method allows open questions to be flexible in acquiring in-depth knowledge from the experts' responses (Rubin, *et al.*, 2011).

3.2 Sampling strategy and data collection

(Kumar, 2011) states that in qualitative research, the researcher should be guided by his/her judgement on who might be able to provide the "best" information. A purposive sampling technique has been selected for this study, which allows being selective in choosing experts in heavy-lifting and transporting modular projects. The reason to choose this sample is that the most critical SMR modules are heavy and large objects. The authors created an interview questionnaire to investigate how SMRs modules can be transported and what can be learned from previous modules transportation experiences. The main data collected were primary data from the interviews, but secondary data were also provided by some of the experts in form of internal company handbook, project drawing, etc. In summary, nine interviews were conducted: four by phone, four by Skype, and one questionnaire was answered through email. In all interviews, English was used to communicate, except for some terminologies in Arabic in two interviews. Table 2 presents an overview with details of the nine interviews, giving consideration the anonymity of the experts.

	Date (2018)	Duration (minutes)	Position	Experience (years)
TC1	04/04	15	Engineering Manager	10-15
HL1	12/04	60	Site Operations Manager	5-10
TC2	13/04	30	Transport Manager	30+
HL2	18/04	50	Project Engineer	5-10
TC3	01/05	20	Transport Manager	10-15
TC4	04/05	30	Director	30+
HL3	11/06	50	Project Engineer	5-10
TP	22/06	email	Consultant	10-15
HL4	21/07	40	Project Operations Manager	5-10

Table 2: Overview of the experts. TC=Transportation company, HL=Heavy lifting and transportation company, TP=Transportation professional

3.3 Data Analysis

A key point of research is the data analysis, which aims to draw logical conclusions from obtained data (Merriam, 1998). Following the guidelines of (Bailey, 2008), the first step to conduct qualitative data analysis was the transcription, which is the process of converting recorded interviews data into text. Subsequently, following the guidelines of (Hesse-Biber, 2010; Saldaña, 2015), the interview transcripts were formatted in a common layout, and thoroughly read and understood to identify themes and specific sections of information related to the research question. NVivo 11, a Computer-assisted Qualitative Data Analysis Software, was employed to facilitate and speed up the analysis of data. The data was then coded to organise the collected data, assessing which category they would be relevant to. The main purpose of this research is to investigate the pre-conditions, enabling factors, and barriers to transporting SMR modules. Therefore, they were the three main categories. Based on data collected, an additional category called "transportation method" was created to explain which transportation method was preferred based on the background of the experts. Figure 1 and Figure 2 show the main categories with their coded subcategories and codes.

4 FINDINGS AND DISCUSSION

This section summarises the findings and discusses the results of the interviews.

4.1 Pre-conditions

- **Evidence from the experts' interviews**

Experts acknowledged the heavy bureaucratic process including several permits and procedures that must be prepared before transport. TC3 stated: "*First of all we try to get all approvals from the consultant in the factory before we start shifting the module as this avoids any rejection or correction which might lead us to return the module back to the factory. Then you should make sure that the site is ready to receive the module. And all authorities permits.*" Regarding the licenses TC2 stated: "*I have a special licence for that, and that's called a stig, S-T-I-G-two. That allows me to transport over sixty-five ton on the road*". Conversely, HL4 stated: "*special licence no because since it is very specialised work there is no one which can certify you about your abilities*".

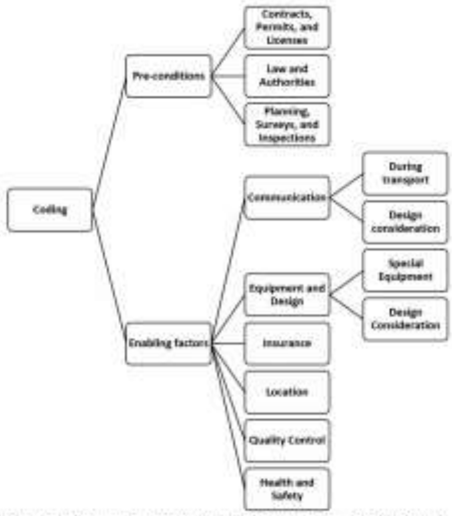


Figure 1: Summary of categories, sub-categories and codes (part 1)

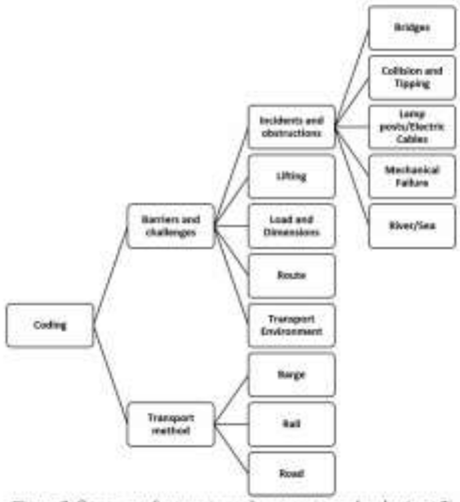


Figure 2: Summary of categories, sub-categories and codes (part 2)

Furthermore, TC1 highlighted the role of law and authorities: "*I mean like the size of the transported object to be matching with the maximum height allowed to be passing under the existing bridges and the weight of the object to be matching with the maximum axle weight permitted by the road authorities*". Another key aspect about pre-conditions is pointed out by HL2: "*The preliminary works that we have to before the bid phase is going to see all the path the module have to do in the future*".

- **Discussion**

Experts highlighted that several relevant permits and procedures must be prepared before transport, respecting local regulations (e.g. load, size, delivery time, storage area). The common documents mentioned are: method statements, risk assessments, permits, drawings, communication plan, and contingency plan. (ESTA, 2009) also highlights that these documents should be accepted by all parties involved, as they state the method, risks, mitigating actions, and liability of each task. Regarding the licence, experts pointed out the need of a licence (STIG 2) to transport heavy loads (>65 tons) on the road. However, there is a controversial statement about this point. A key point highlighted is that every transport requires a preliminary route survey to be conducted and documented. The transported SMR modules would require the route conditions to be checked and assessed to whether public infrastructure such as roads, bridges, etc. can be used. The route survey would also be used to assess whether any obstructions will be in the way of the transporter or load. Examples of these obstructions could be trees, power lines, pipelines, etc. Furthermore, other route settings such as slopes, ground surface, maximum ground bearing pressure, and permitted axle load would need to be analysed to ensure the module can be transported appropriately. An internal document also states that work preparations such as ground reinforcement would be the responsibility of the client or the operating company depending on the contractual agreement between the stakeholders. Furthermore, heavy and/or large modules are usually required to satisfy special requirements. For example, the transported module must match the maximum eight allowed under a bridge, and the weight must match the maximum axle weight. Prior the transport, the authorities will also need to approve any solutions for constraints such as building a new path or disconnecting overhead electricity. It is also stated that the usual working hours permitted are early morning or late night and that the authority is a key factor to start the transport process. Furthermore, internal documents supplied by the experts point out the importance of communication and contingency plan which tackle unanticipated events, describe the responsibilities of various stakeholders involved, and the communication method agreed.

4.2 Enabling factors

- **Evidence from the experts' interviews**

A critical enabling factor identified is the communication. TC2 highlighted a type of communication: "*The driver especially needs to know what he is doing, he will probably also be on a walkie-talkie. Ok, so normally we have got walkie-talkies so we always make sure that everybody is communicating with everybody. It does not matter how small it is, whether not there is a small problem to a large problem. Everybody needs to know communication*". TC4 also highlighted the importance of communication, but focusing on another aspect: "*communication between the transport company and manufacturer would be very helpful. Like in certain cases they build the module and face many problems due to it being very heavy or for example requiring more expensive lifting methods*". Several equipment were also suggested by the experts. In particular, HL1 stated: "*for example I can help you if the path will not be so long. I can suggest to use SPMT, it is a kind of trailer… it is a hydraulic trailer that is driven (sic) by remote control and is very versatile. I mean there is a lot of kind of steering option, it is very easy to use, and this is used especially in a small area where you do not have so much space to manoeuvre*". Furthermore, HL3 stated: *"One thing either for transportation and especially the lifting… the vendor that is designing the equipment he should also involve or he should know how the equipment will be installed so if it will be installed by crane or by strand jack he should know it so he can prepare a lifting point or whatever the way we will transport it"*. Another key element to consider is the insurance, as highlighted by HL3: "*But when you're transporting a cargo for example from Germany to the Middle East then it should have insurance to transport it there inland transport from the factory to the port also will have another insurance for the sea transportation then another insurance when it reaches the middle east. And at each stage there is one contractor which having insurance for the equipment they transport with*". Furthermore, HL4 pointed how the final location can influence the transportation: "*if you go to some bigger big port they have the capabilities to handle. If you go to smaller port they don't have the capabilities*". The quality control is also considered fundamental in this kind of transportation, as highlighted by HL2: "*there is a surveyor but there is a team of surveyors around the transport. Because you need to check...ok all the movement*". Furthermore, TC4 pointed out the importance of a proper equipment, stating: "I *think safety is an important thing to consider. So use proper equipment*".

- **Discussion**

Communication

The experts presented the importance of communication in ensuring the success of the transportation process. In particular, two types of communication have been pointed out: "Design communication" and "Communication during Transport". Regarding the first, the transport company should be involved in the design phase, because specific design requirements such as lifting points must be implemented. This might improve the overall cost. The need of involving transport company in design phase is also pointed out by (Naqvi, *et al.*, 2014) in the literature, who states that modules transportation becomes challenging because it is finalized late in a project. Regarding the second, it is an enabling factor that helps reducing errors such as tipping. For instance, the truck driver and convoy vehicle should be in constant contact to be aware if something irregular is happening.

Equipment and design

The experts pointed out the following special equipment and design consideration which would allow SMR modules to be transported and lifted:

SPMTs: When using this equipment, it is suggested to have the module at least 1.3 meters high. The SPMT is equipped with suspension and is used to jack up the structure. With the aid of a transport beam and building the module at that height, the module would not need lifting determining a lifting cost reduction. More than one SPMT can be used to transport an item. The difference between conventional trailers and SPMTs is that they require trucks to pull it and have mechanical steering. SPMTs are also stated to have better manoeuvring than conventional trailers.

Gantry Crane: This equipment is used to lift the module from the SPMT. It can be used in the fabrication yard and on-site and is stated to be cheaper and faster than using a crane due to it requiring less space. It can also be prepared faster than normal lifting cranes and is used to install items at low positions.

Strand Jack: It is a very strong tool used to lift heavy objects. They are sometimes combined with a gantry crane, and is also considered a faster method to install very heavy items than cranes. Usually, this combination is used when the module needs to be installed at a higher height or underground. If strand jacks will be used, the design of the module must have 'lifting lugs' to be connected to the strand jacks.

Saddles: They are like stools shaped to take the module on the SPMT or trailer. The saddle should be wider than the module and the trailer to make it easier when switching from SPMT to the conventional trailer. The saddles must be designed well to accommodate the module and lashed well to have a good connection between the module, saddle, and the trailer.

Cranes: For small modules which can be transported in containers, it would be cheap to lift them with cranes but would mainly depend on the port cranes lifting capability. Crawler cranes are also mentioned but are considered expensive compared to other lifting solutions.

Overall the experts stated that the transport equipment used would depend on the module's size, weight, and the location of its final position. It is fundamental for the design of a module to know how it will be lifted and transported, as it will require design requirements such as lifting lugs, span and height requirements, etc.

Insurance

The experts highlighted how the transported module's insurance is based on the agreement between the client and the transport company. It is usually insured by the manufacturer; however, the insurance company asks for documents from both parties to make sure documents such as the method statement and drawings are signed off and assessed properly prior the transportation. There are also several insurances dependent on the country you are transporting the item in and the transport method selected. Contractors transporting the module would need their own insurance for their equipment such as SPMTs, trucks, etc. However, the experts stated that sometimes the client includes them in their insurance policy. If the item was to be lightly damaged during transport such as a scratch, the client usually fixes it; however, if there are big damages, the insurance party comes in. In summary, the insurance is dependent on the responsibility and risk allocation agreement between the stakeholders involved.

Final location

One of the key enabling factors pointed out is the final location of the modules. Experts stated that if the final location is accessible by river/sea or by rail, then that may be an advantage. However, this is dependent on the availability of equipment and capability of the location. For example, there might be a nearby port to the final location but the available crane there is not strong enough to lift the module and thus would require a special crane leading to a higher cost. The final location also influences the safety measures and quality control required. Furthermore, according to the experts, if the fabrication yard and final location of the modules are in the same country, the transport process is easier and cheaper, since the country's capability and government requirements would be recognised easily by local transport companies.

Quality control

The experts also showed the importance of the quality control, usually through a visual check before and after the transport. However, it depends on the agreement with the client and their internal requirements. A surveying team may also be assigned to check when the module is being lifted onto a barge or when being transported near bends and obstacles to ensure it does not collide or get damaged. Additionally, qualified personnel are with the transport and keep monitoring that they are on track while regularly updating the risk assessment. One expert mentioned a new technology called 'Point Cloud' improving the quality of the pre-surveys and planning of transport, and is usually implemented when the engineering of the transport is very busy. 'Point Cloud' is similar to a google car but instead of an image it creates points on a software of the original path and its surroundings such as lamp posts and trees. Nonetheless, another expert mentioned that this method is usually expensive and that the experience of the staff and transport company is more effective.

Health and Safety

The experts stated that transport by rail and barge would be the safest options as interaction with the public is limited. Safety of the transported module must also be prepared. For example, in sea transport, the module must be fastened properly to avoid damage from oscillations. It is also mentioned that when dealing with large and heavy items, safety consideration must be taken for the route to make sure nobody is injured or harmed and not to cause damage to any property. Safety must also be maintained when lifting the item onto a transporter, to a barge, or at the final position.

4.3 Barriers and challenges

- **Evidence from the experts' interviews**

Several barriers and challenges related to module transportation have been pointed out by the experts. The experts pointed out several typical incidents and obstructions faced during modules transportation. For instance, HL4 stated: "*some transport being bent...let's say can happen tipping...then during the transport you hit something with the module you are transporting so usually small damages. With of course tipping you have a big consequence*". Regarding modules lifting, TC1 stated: "*During our shifting of a pre-cast* *unit, we couldn't unload it in the proper place with the available crane there due to the big distance between our truck and the final location. So we had to wait and change the crane to a bigger size, to cover the big span*". HL4 also stated: "*Yes but the problem that in any case you have to deal with the infrastructure actually existing so usually for example in a port the ship to shore crane are designed for a range between twenty to sixty ton*". Furthermore, expert HL1 pointed out two key challenges of modules transportation: "*the main challenging (sic) is for sure the load. The load and the size of the module*". Expert HL1 also highlighted this point focusing on possible solution: "*This is the main issue yes, that is why in that case as I said, if you have possibility to use barge… the only other option would be barge, otherwise you have to consider to reinforce the road if it is not enough and to reinforce the bridge if they are not strong enough*". Another challenge related to modules transportation is the route, as pointed out by HL3: "*mainly the ground preparation like when you have a two thousand ton equipment you need to maintain certain ground preparation and many cases ground not capable to do this so you have to prepare either…sometimes you have to prepare bridges, sometimes you have to prepare new roads, sometimes you need to level the ground and compact it with some special material*". Another challenge is related to the transport environment, as stated by HL3: "*Yes yes for sure the high tide especially when the tide going up then they can make either loadout or load in. If the tide is going low then this will be issue as they start putting equipment inside the barge or taking the equipment out of the barge and the water level going down then the load can tip over*".

- **Discussion**

Incidents and obstructions

Despite careful planning, unexpected incidents can happen. Based on the experiences of the interviewed sample, one typical incident is the tipping of the module or transporter. It is due to road failure, load capacity, passing over an underground pipe not highlighted in the drawings, mechanical failure due to overloading, etc. When a module is tipped and gets damaged, there would be relevant consequences for the project. If the module gets damaged and cannot be repaired, then a new module needs to be fabricated. This will determine schedule and cost overruns. The lack of adaptability to changes is also mentioned in the literature as one of the main disadvantages of modularization (De La Torre, 1994). According to (Shelley, 1990), it is very important to avoid changes during construction of a modular project because the cost could increase significantly. According to the experts, there have also been incidents where the design of the module was not calculated well and caused issues when transporting/lifting. Sometimes transporting modules over infrastructure such as bridges can cause issues due to its size and weight. Possible solutions mentioned are: building a new bridge specifically for the transport, using an alternative route if available, or for example, if faced with a height constraint sometimes the transport equipment/tires may be slightly adjusted to pass over or under the obstacle.

Module lifting

The experts have identified several barriers regarding module lifting. The main barrier is usually related to sea transport. Several issues are related to the dislocation of the dock and ship as well as the lifting capability of sea/river ports. Some ports may not have the lifting limit required and would require more expensive lifting methods. Another barrier is the availability of cranes and special lifting such as strand jacks. Train terminals and normal seaport usually have lifting capabilities of 20-60 tons, anything larger would require large cranes. The common suggestion for lifting larger SMR modules is a combination of Gantry Crane and Strand Jacks, which are stated to be cheaper and faster than large cranes. Strand jacks would definitely be used as they would allow the SMRs to be vertically installed underground.

Load and dimension

One of the biggest challenges is the load and dimensions of the module being transported. These measurements affect the calculations such as how the load will be spread and determining how many axels are required for the SPMT/conventional trailer. The number of axel lines is determined from the ground pressure caused by the module, the trailer, saddles, and all equipment used to transport it on the road. For road transport, the load capacity is usually 10 ton/sq., and anything higher would require reinforcing the road and infrastructure such as bridges, determining a big cost impact and causing serious delays.

Route

According to the experts, the route has always to be planned before transport. If the route encounters problems such as holes or weak soil, then the ground would need to be reinforced. Additionally, experts who worked on projects in Europe, Asia, and the Middle East state that temporary roads or bridges made with steel stools may need to be built to overcome route barriers. However, one expert states that in the UK it is not a common solution. Often with heavy loads, if the load does not match the ground bearing capacity of a certain road, then an alternative route or transport method would be made. An example of a normal route was 244 kilometres covered in 45 days. An example of a challenging route was around 1300 kilometres covered in 10 months.

Environment

Another challenging aspect which often causes delay is the weather condition. Weather conditions such as fog and snow cause a lot of delays and losses. Additionally, if sea transport is used, rough sea conditions may damage the module through internal and external vibrations.

4.4 Transport method

- **Evidence from the experts' interviews**

Regarding the best modules transportation method in the UK, TC4 stated: "*But I think best is barge then rail if possible since the UK has the facilities*". On the other hand, other experts stated that rail transport is the quickest one, as TC2: "*The quickest…the quickest method would be by train*". Furthermore, regarding the road transport, HL3 stated: "*Ok* *for short distance I believe it will be the best to do it either with conventional or SPMT we can consider it the same. Conventional or SPMT this is for short distance*".

- **Discussion**

The majority of the experts thought that barge would be the best transport method for SMR modules in the UK. It is common in Europe and is considered safer and faster than other methods. However, some experts stated that it is a riskier method especially if the module's design is weak externally and internally. It is usually considered an option when the module's weight or dimensions do not match the road capability. It is also faster than road transport but is restricted to the availability of sea or river. On the other hand, some experts stated that rail transport would be the quickest method and the least vulnerable to have an accident. However, this would depend if the final site is near/will use the normal rail routes available in the UK. Empirical findings highlighted how the most common method currently used is road transport. It might not be the fastest or safest, but it is found to be the most flexible. For short distances (10-15 kilometres) SPMTs and conventional trailers would be a preferred transport method. Nevertheless, there are instances where they have been used to transport modules up to 900 km. The main issues related to this transport method is that it is slow and dependent on road capability.

5 Key takeaways for SMR modules transportation

Modules transportation is a very complex process requiring the consideration of several factors and (after the module has been fabricated) the participation of two main stakeholders: transportation company and client. One key takeaway from previous experiences of modules transportation is the division of the responsibilities between the transportation company and client. Table 3, developed from a document supplied by one of the experts, provides the division of responsibilities adopted by several transport companies. The SMR sector needs to familiarise with the division of the responsibilities during the SMR modules transportation process. Table 3 also mentions most of the main categories and subcategories come out from the analysis of primary data. In particular, a key result of the research reveals the importance of communication both during the design phase and during the transportation process. Transportation companies should be involved in the design phase, providing cost analysis of different transport options. Furthermore, the involvement of transportation companies in the design phase would allow avoiding the possible incompatibility of module designs with transport method and local regulation. Considering this aspect might be a key advantages for the SMR sector. In particular, it might allow knowing route and site restrictions before the arrival of the heavy/oversized SMR modules to the final location, avoiding any related project delays. Furthermore, it would allow obtaining earlier permits from local authorities if needed, and SMR designs would be developed according to the transport and lifting requirements.

Task	Company	Client
The load of the module		
Design to be transportable	S	P
Engineering		
Load properties	-	P
Route situation	P-Offsite	P-Onsite
Threshold engineering values	P	S
Perform adequate engineering	P	-
Preparation		
Route survey	P-Offsite	P-Onsite
Civil work	P-Offsite	P-Onsite
Permits	P (Mutual agreement)	
Risk assessment	P	S
Method statement	P	S
Toolbox talk	P	S
Operation		
Employees	P	-
Communication	P	-
Performing final checks	P	S
Monitoring weather conditions	P	-

Table 3: Responsibility matrix. P= Primary, S = Secondary
Adapted from (ESTA, 2009)

It is also recommended a preliminary route survey before transport. The transported SMR modules would require the route conditions to be checked and assessed to whether public infrastructure such as roads, bridges, etc. can be used. Furthermore, the following special equipment should allow SMR modules to be transported and lifted: SPMT, Gantry Crane, Strand Jack, Saddles, and Cranes. However, the use of one rather than another one depends on module characteristics. The SMR sector needs to familiarise with these practices. Regarding the best transport method for SMR modules in the UK, there are controversial opinions from the experts. There are several factors to consider such as availability of infrastructure, weight and height of the module, safety and speed of the transport method. However, the choice is strictly dependent on the SMR modules final location. A "*condicio sine qua non*" pointed out by the experts is the attaining of the necessary documentation such as contracts, permits, and licences (in particular the STIG-2 licence to transport more than 65 tons). The SMR sector needs to be aware of the needed licences, contracts and permits to transport SMR modules in the UK. In particular, SMR should be developed considering the UK transport limitations reported in Table 4.

Category	Weight	Length	Width	Height
Normal	44 tons	18.65 m	2.9 m	4.9 m
Abnormal	150 tons	30 m	6.1 m	4.9 m
Special	>150 tons	>30 m	>6.1 m	4.9 m

Table 4: UK transport limitations
Data from (Driver & Vehicle, *et al.*, 2018; Harrison, 2018)

Proper contracts, permits and licences characterise each category. SMR sector needs to consider these information in the design stage. Table 5 provides three examples of RPV (Reactor Pressure Vessel) specifications in order to allow a comparison with the UK transport limitations. Regarding the three SMRs in Table 5, there are no information about weight specifications, except for the NuScale SMR. (NuScale, 2018) reports the following information about SMR weight *"~700 tons in total are shipped from the factory in three segments"*.

	Westinghouse-SMR (>225 MWe)	NuScale (50 MWe)	SMR-160 (160 MWe)
RPV height	28 m	17.8 m	15.0 m
RPV diameter	3.7 m	3.0 m	3.0 m

Table 5: SMR specifications. Data from (IAEA, 2018)

Furthermore, other main factors to consider are: transported module's insurance (based on the agreement between transportation company and client, but usually insured by the manufacturer), quality control (usually through a visual check before and after the transport, but it depends on the agreement between transportation company and client), weather conditions (often cause of delays and losses, they have to be kept under control).

6 CONCLUSION

"SMR" differ from "small reactors" of just one word: "modular". Modular refers to modularization. Modularization is a construction technique which implies factory manufacturing. Indeed, SMR components and system are designed to be "factory manufactured" and "transported" to the site as modules. However, despite the relatively large amount of literature published on SMRs, there are extremely limited information about SMR modules transportation. This paper address the gap in knowledge analysing modules transportation in other sectors. It summarises, through a literature review analysis, the main heavy transport and lifting techniques: road transport, barge transport, and rail transport. It also provides a summary of the main cranes and special equipment used to transport and to lift heavy and large modules. Furthermore, this paper summarises and discusses the results of a series of interviews with transport industry experts about transporting large modules. Therefore, this paper aims to summarise the main aspects of modules transportation, in order to allow the SMR sector to avoid mistakes learning from previous experiences. The results of the literature review analysis and the interviews suggest that modules transportation is a very complex process requiring the consideration of several factors. Communication is a relevant factor both in the design stage and during the modules transportation. A right communication and the engagement of transportation companies in the design stage would allow the reduction of cost and schedule overruns. Furthermore, the choice of the "best transport method" for SMR modules is strictly dependent on the final location of SMR modules. There, the complex project of module transportation and the evaluation of several factors (insurance, special equipment, licences, quality control, possible incidents and obstructions, environment, etc.) start after the definition of the final location of the SMR modules. However, SMR sector can learn about modules transportation from the experience accumulated over the years in other sectors.

ACKNOWLEDGEMENTS

This work was supported by the UK Engineering and Physical Sciences Research Council (EPSRC) grant EP/N509681/1. Furthemore, this work is partially supported by Major Project Association (MPA). The authors are immensely grateful to the MPA members for their support. 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 any other organisation involved.

7 REFERENCES

Azhar, S. *et al.* (2012) 'Modular v. Stick-Built Construction: Identification of Critical Decision-Making Factors', in *48th ASC Annual International Conference Proceedings*.

Bailey, J. (2008) 'First steps in qualitative data analysis: transcribing.', *Family Practice*, 25(2), pp. 127–131.

Bititci, U. *et al.* (2016) 'Impact of visual performance management systems on the performance management practices of organisations', *International Journal of Production Research*. Taylor & Francis, 54(6), pp. 1571–1593.

Boarin, S. *et al.* (2012) 'Financial case studies on small- and medium-size modular reactors', *Nuclear Technology*, 178(2), pp. 218–232.

Boarin, S. *et al.* (2015) '10 – Economics and financing of small modular reactors (SMRs)', in Carelli, M. D. and Ingersoll, D. T. (eds) *Handbook of Small Modular Nuclear Reactors*. Elsevier, pp. 239–277.

Bondi, A. *et al.* (2016) 'Supporting Decisions on Industrial Plant Modularization : A Case Study Approach in the Oil and Gas Sector', in *International Conference on Industrial Engineering and Operations Management*. Kuala Lumpur, pp. 742–753.

Brookes, N. J. *et al.* (2015) 'Power plants as megaprojects: Using empirics to shape policy, planning, and construction management', *Utilities Policy*, 36, pp. 57–66.

Bryman, A. *et al.* (2015) *Business research methods*. Oxford University Press, USA.

Carelli, M. *et al.* (2010) 'Economic features of integral, modular, small-to-medium size reactors', *Progress in Nuclear Energy*, 52(4), pp. 403–414.

Carelli, M. D. *et al.* (2007) 'Smaller sized reactors can be economically attractive', in *Societe Francaise d'Energie Nucleaire - International Congress on Advances in Nuclear Power Plants - ICAPP 2007, 'The Nuclear Renaissance at Work'*.

Carelli, M. D. *et al.* (2008) 'Competitiveness of small-medium, new generation reactors: a comparative study on capital and O&M costs', in *16th International Conference on Nuclear Engineering*. Orlando, Florida, USA, May 11–15, 2008: ASME, pp. 1–8.

Choi, J. *et al.* (2014) 'Evaluation of the modular method for industrial plant construction projects', *International Journal of Construction Management*. Taylor & Francis, 14(3), pp. 171–180.

Devgun, J. (2013) *Managing Nuclear Projects*. Edited by Cambridge: Woodhead Publishing Limited.

Driver & Vehicle *et al.* (2018) *Special types enforcement guide*. Available at: https://www.gov.uk/government/publications/special-types-enforcement-guide/special-types-enforcement-guide (Accessed: 15 August 2018).

Dudovskiy, J. (2018) *The Ultimate Guide to Writing a Dissertation in Business Studies: A Step-by-Step Assistance*. Available at: https://research-methodology.net/research-methodology/ (Accessed: 4 August 2018).

ESTA (2009) *Best Practice Guide for Self-Propelled Modular Transporters*. Available at: http://estaeurope.eu/media/downloads/ESTA_A4versie_DEFdigitalHR-pages.pdf.
Fagiloli (2018) *Rail Wagons*. Available at: https://www.fagioli.com/en/equipment/transport/rail-wagons (Accessed: 2 July 2018).
Fagioli (2018a) *Barges*. Available at: https://www.fagioli.com/en/equipment/transport/barges (Accessed: 2 July 2018).
Fagioli (2018b) *Heavy Lifting*. Available at: https://www.fagioli.com/en/equipment/heavy-lifting (Accessed: 2 July 2018).
Fagioli (2018c) *SPMTs*. Available at: https://www.fagioli.com/en/equipment/transport/transport-spmts (Accessed: 2 July 2018).
GIF/EMWG (2007) *Cost estimating guidelines for generation IV nuclear energy systems - revision 4.2*.
Harrison, L. (2018) *Wide Loads on UK Roads – What is the Maximum Size/Weight Allowed?* Available at: https://blog.ntex.co.uk/wide-loads-on-uk-roads-what-is-the-maximum-size-weight-allowed (Accessed: 14 August 2018).
Hesse-Biber, S. (2010) 'Analyzing Qualitative Data: With or without software'. Available at: https://www.bumc.bu.edu/crro/files/2010/07/Hesse-Bieber-4-10.pdf.
IAEA (2014) *Advances in Small Modular Reactor Technology Developments. A Supplement to: IAEA Advanced Reactors Information System (ARIS)*. Vienna.
IAEA (2016) *Advances in Small Modular Reactor Technology Developments*. Available at: https://aris.iaea.org/Publications/SMR-Book_2016.pdf.
IAEA (2018) *Advances in Small Modular Reactor Technology Developments*.
Ingersoll, D. T. (2009) 'Deliberately small reactors and the second nuclear era', *Progress in Nuclear Energy*. Elsevier Ltd, 51(4–5), pp. 589–603.
Kumar, R. (2011) *Research Methodology: A step-by-step guide for beginners*. 3rd edn. Edited by SAGE Publications Ltd.
De La Colina, M. F. *et al.* (2016) 'Handling Heavier Loads in Construction', in *Procedia Engineering*.
De La Torre, M. L. (1994) *A review and analysis of modular construction practices*. Lehigh University.
Larsson, S. (2009) 'Weight and dimensions of heavy commercial vehicles as established by Directive 96/53/EC and the European Modular System (EMS)'. Brussels, Belgium.
Locatelli, G. *et al.* (2015) 'Load following with Small Modular Reactors (SMR): A real options analysis', *Energy*, 80, pp. 41–54.
Locatelli, G., Pecoraro, M., *et al.* (2017) 'Appraisal of small modular nuclear reactors with "real options" valuation', *Proceedings of the Institution of Civil Engineers - Energy*. Thomas Telford Ltd, 170(2), pp. 51–66.
Locatelli, G. (2017) 'Fusion: Go small to go fast', in *Proceedings of the 2017 25th International Conference on Nuclear Engineering*, pp. 1–10.
Locatelli, G., Boarin, S., *et al.* (2017) 'Load following by cogeneration: Options for small modular reactors, gen IV reactor and traditional large plants', in *25th International Conference on Nuclear Engineering, ICONE 2017; Shanghai; China*. American Society of Mechanical Engineers (ASME).
Locatelli, G. *et al.* (2014) 'Small modular reactors: A comprehensive overview of their economics and strategic aspects', *Progress in Nuclear Energy*, 73, pp. 75–85.
Locatelli, G. *et al.* (2011) 'The role of the reactor size for an investment in the nuclear sector: An evaluation of not-financial parameters', *Progress in Nuclear Energy*, 53(2), pp. 212–222.
Locatelli, G. *et al.* (2012) 'A framework for the selection of the right nuclear power plant', *International Journal of Production Research*, 50(17), pp. 4753–4766.
Locatelli, G. *et al.* (2013) 'Generation IV nuclear reactors: Current status and future prospects', *Energy Policy*, 61, pp. 1503–1520.
Mammoet (2018a) *Heavy-Duty Rail Cars*. Available at: https://www.mammoet.com/equipment/transport/heavy-duty-rail-cars/heavy-duty-rail-cars/ (Accessed: 2 July 2018).
Mammoet (2018b) *Heavy Transport*. Available at: https://www.mammoet.com/heavy-transport/ (Accessed: 2 July 2018).
Mammoet (2018c) *Special Equipment*. Available at: https://www.mammoet.com/equipment/?filters=j10bV6x%2FGh%2B8OujWbD%2F6dQ%3D%3D (Accessed: 2 July 2018).
Mammoet (2018d) *SPMT*. Available at: https://www.mammoet.com/equipment/transport/self-propelled-modular-transporter/spmt/ (Accessed: 2 July 2018).
Merriam, S. B. (1998) *Qualitative research and case study application in educations*. San Fransisco: Jossey-Bass Publishers.
Mignacca, B. *et al.* (2018) 'We never built small modular reactors (SMRs), but what do we know about modularization in construction?', in *International Conference on Nuclear Engineering (ICONE26)*.
Musa, M. F. *et al.* (2016) 'Towards the adoption of modular construction and prefabrication in the construction environment: A case study in Malaysia', *ARPN Journal of Engineering and Applied Sciences*, 11(13), pp. 8122–8131.
Naqvi, D. *et al.* (2014) 'Transportation considerations in module design', *Structures Congress 2014*, pp. 1771–1781.
NuScale (2018) *How the NuScale Module Works*. Available at: https://www.nuscalepower.com/technology/technology-overview (Accessed: 25 November 2018).
Rubin, H. J. *et al.* (2011) *Qualitative interviewing: The art of hearing data*. Sage.
Sainati, T. *et al.* (2015) 'Small Modular Reactors: Licensing constraints and the way forward', *Energy*, pp. 1092–1095..
Saldaña, J. (2015) *The coding manual for qualitative researchers*. Sage.
Saunders, M. *et al.* (2007) *Research Methods for Business Students*. Edited by E. P. E. Ltd.
Saunders, M. *et al.* (2012) *Research Methods for Business Students*. 6th edn. Harlow: Pearson Education Limited.
Saunders, M. N. K. (2011) *Research methods for business students, 5/e*. Pearson Education India.
Smith, R. E. (2010) *Prefab Architecture: A Guide to Modular Design and Construction*. Edited by New Jersey: John Wiley & Sons Inc.
Trianni, A. *et al.* (2009) 'Competitiveness of small-medium reactors: A probabilistic study on the economy of scale factor', in *International Congress on Advances in Nuclear Power Plants 2009, ICAPP 2009*.
Upadhyay, A. K. *et al.* (2016) 'Modularity in nuclear power plants: a review', *Journal of Engineering, Design and Technology*, 14(3).
Vegel, B. *et al.* (2017) 'Economic evaluation of small modular nuclear reactors and the complications of regulatory fee structures', *Energy Policy*, 104, pp. 395–403.
Wrigley, P. *et al.* (2018) 'Design for Plant Modularisation: Nuclear and SMR', in *Proceedings of the 2018 26th International Conference on Nuclear Engineering (ICONE 26), 22-26 July, London*.

III.

D.3 Publication VII

Locatelli, G., Mignacca, B., 2020. Small Modular Nuclear Reactors. Book chapter in Future Energy: Improved, Sustainable and Clean Options for Our Planet, pp. 151-169, **Scopus indexed chapter**.

8

Small Modular Nuclear Reactors

Giorgio Locatelli, Benito Mignacca
UNIVERSITY OF LEEDS, SCHOOL OF CIVIL ENGINEERING, LEEDS, YORKSHIRE, UNITED KINGDOM

8.1 Introduction

The International Atomic Energy Agency (IAEA) defines small modular reactors (SMRs) as "*newer generation 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*" [1]. IAEA also defines medium-sized reactors as "*reactors with an equivalent electric power between 300 and 700 MW*" [2]. Large reactors (LRs) are generally considered reactors with an equivalent electric power higher than 700 MWe. Regarding SMRs, which is the main topic of this chapter, Ref. [3] provides a summary of the innovative features and describes SMRs as "*reactor designs that are deliberately small*, i.e., *designs that do not scale to large sizes but rather capitalize on their smallness to achieve specific performance characteristics.*" Furthermore, Ref. [4] explains the meaning of "small" and "modular" as follows:

> *Small refers to the reactor power rating. While no definitive range exists, a power rating from approximately 10 to 300 MWe has generally been adopted [...] Modular refers to the unit assembly of the nuclear steam supply system (NSSS) which, when coupled to a power conversion system or process heat supply system, delivers the desired energy product. The unit assembly can be assembled from one or severe submodules [...]*

SMRs encompass a large number of technologies such as "pressurized water reactors," the most common technology used for LRs in operation and under construction, to more revolutionary designs based on Gen IV reactors that are mostly unproven [5]. Ref. [6] provides an overview of the different types of SMRs. SMRs, by their nature, are designed to be factory manufactured, transportable, and, for few designs, even relocatable. The term "modular" in this context refers to (1) a single reactor that can be grouped with others to form a large nuclear plant and (2) whose design incorporates mainly pre-fabricated modules assembled on site. While current LRs also incorporate factory-fabricated components or modules, a substantial amount of fieldwork is required to assemble components into an operational plant. SMRs are envisaged to require less work

Future Energy. https://doi.org/10.1016/B978-0-08-102886-5.00008-6

on site, and some extreme designs are expected to be almost "plug and play" when arriving from the factory.

One of the key challenges for the assessment of SMR advantages and disadvantages is the lack of empirical information, as no modern SMRs have been built yet, but only "traditionally built small reactors" such as the CNP-300 (300 MWe) and the PHWR-220 (220 MWe) [7]. However, a key discussion about the competitiveness of SMRs versus LRs regards how SMRs might balance the "diseconomy of scale" with the "economy of multiples". [8–16] analyze specific factors (such as grid characteristics, construction time, financial exposition, modularization, learning, etc.), which distinguish SMRs from LRs in the evaluation of the capital cost. Once these factors are taken into account, the capital cost is comparable between the two technologies [10,17]. Furthermore, Ref. [18] discusses the effects of "non-financial parameters," such as electric grid vulnerability, public acceptance, the risk associated with the project, and licensing [19]. For many of these parameters, the authors explain how SMRs show an advantage with respect to LRs.

Another advantage of SMRs is the possibility to accelerate the learning curve [16]. According to Ref. [16], the learning curve flattens out after 5–7 units, determining that the nth of a kind is reached with less MWe installed for SMRs with respect to LRs [16]. Another key feature of SMRs is the possibility to split a large investment into smaller ones. The construction of a single LR is a risky investment [20]. The construction of SMRs is an investment decision with n degrees of freedom that allows hedging investment risks. The economic merit of flexibility can be calculated using the real option approach (ROA) [21]. SMRs, having the power fractionated, are also ideal for cogeneration, as presented in Refs. [20,22,23].

The rest of the chapter is structured as follows: Section 8.2 provides an overview of economics and financing of SMRs; Section 8.3 summarizes the "external factors" that have been identified from the literature about the differential characteristics of SMRs with respect to LRs; Section 8.4 concludes the chapter providing a brief explanation about why no-one SMR has been built so far.

8.2 Economics and financing of SMRs

8.2.1 Introduction to the economic evaluation of nuclear power plants

The nuclear industry commonly clusters nuclear power plant (NPP) life-cycle costs as capital cost, operating and maintenance, fuel, and decommissioning. Two broad cost estimation approaches can be used to calculate these, known as top-down and bottom-up approach [24]. Following the top-down cost estimation approach, a new project is compared with similar projects already completed (called "project analogs"). Cost and time needed in "project analogs" are adapted and used as predictors for the new power plant or parts of it (e.g., a turbine). In the bottom-up cost estimation approach, the power plant is divided into activities, and, subsequently, the cost of each activity is estimated. According to Ref. [25], the bottom-up approach is most suitable for projects near construction, where the design has been almost totally developed. On the contrary, in the early stages, when there is a lack of information, a top-down approach is preferred.

Furthermore, in the power plant cost estimation, it is fundamental to consider that "power plants do not exist in isolation," but plants are interconnected with a wider system both from a technical and economic point of view. Ref. [26] focuses on this key point, highlighting how each electricity generation power plant is characterized by three cost levels:

1) Plant-level costs: the direct costs to build/operate/decommission a power plant;
2) Grid-level costs: the costs incurred to enhance transport and distribution grids, to connect new capacity to the grid, and to maintain the long-term and short-term electricity supply;
3) Total system costs: this represents a broader set of costs, including effects difficult to monetize and beyond the power reactor itself, e.g., CO_2 emission, impact on the security of energy supply, country's strategic position, etc. [18].

The following Fig. 8.1 summarizes these concepts.

Several indicators are used to investigate the profitability of investing in an NPP for utilities. One of the most important economic indicators for policymakers is the levelized cost of the electricity produced by the NPP. This indicator, generally termed "levelised unit electricity cost (LUEC)" or "levelised cost of electricity," accounts for all the life-cycle costs and is expressed in terms of energy currency, typically ($\$ \ (KWh)^{-1}$). Net present value (NPV) and the internal rate of return (IRR) are other two key indicators of financial performance. NPV measures absolute profitability ($) and depends by the discount value, i.e., the factor used to weight "present cost" versus "future revenue." The discount value usually depends on the source of financing and for many practical

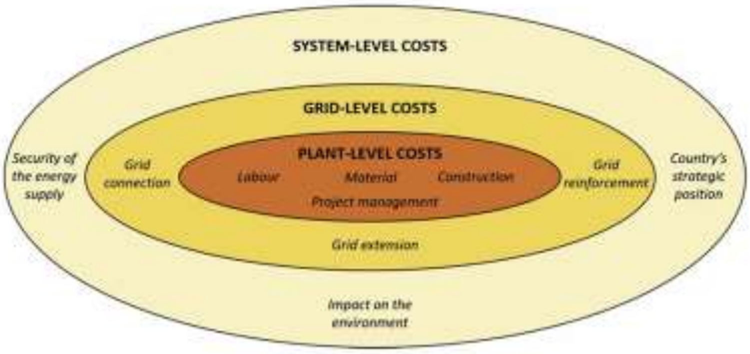


FIGURE 8.1 Plant-, grid-, and system-level costs. *Adapted from OECD, Nuclear Energy and Renewables: System Effects in Low-Carbon Electricity Systems, 2012.*

applications can be intended as the weighted average cost of capital (WACC). A low WACC gives the same weighting to present cost and future revenue (promoting capital-intensive plants such as nuclear power stations), while a high WACC is weighted more toward the present cost with respect to future revenues (promoting low capital cost solutions, such as gas-fired power plant). The IRR is a dimensionless indicator, i.e., the value of WACC that brings the NPV to zero. The greater the value, the higher the profit for the utility.

The NPP cost (both construction and operation) depends on how many identical (or at least very similar) units are planning to be built both globally, in the country and, most important, in the site. When the same identical plant is delivered more than one time (ideally several times), the economy of multiples is achieved and therefore, a cost reduction. Economy of multiples in the construction of NPPs is somehow rooted in the idea of "mass production", a concept born in the automotive industry and later adopted in other fields, such as aerospace (e.g., the production of aircraft), IT (e.g., the production of computers and smartphones), or even the food industry (e.g., the production of ready meals). For NPPs, the economy of multiples is achieved because of two key factors: learning process and co-siting economy. On the other hand, techno-economic analyses show that the average investment and operating costs per unit of electricity are decreasing with respect to increasing plant size (i.e., "economy of scale" principle).

Regarding SMRs, several papers discuss the competitiveness of SMRs versus LRs and how SMRs might balance the "diseconomy of scale" with the "economy of multiples" [8–14]. The "economy of scale principle" cannot be directly transferred into the investment analyses of SMRs versus LRs because it relies on the clause "other things being equal." Effectively, this presumes that SMRs are the same as LRs except for the size. If the designs of large and small units are very similar, the unitary capital cost of a larger unit is significantly cheaper than for a smaller version. By contrast, SMRs exhibit several benefits that are uniquely available to smaller innovative reactors and can only be replicated by LRs to a very limited extent. The most important are modularization, co-siting economies, learning, and construction time.

8.2.2 Modularization

One of the key characteristics of SMRs, as their name emphasized, is the modularization. Ref. [25] defines modularization as the "*process of converting the design and construction of a monolithic or stick-built plant to facilitate factory fabrication of modules for shipment and installation in the field as complete assemblies.*" Several papers and reports explain the costs and benefits of modularization. Most of these references are qualitative, like the review of modularization in the nuclear industry [27]. Factory fabrication is usually cheaper than site fabrication (see Section 8.2.5 for a more detailed explanation on the reasons), but the costs associated with shipping of modules to the site must also be considered. Smaller plants can take a better advantage of modularity as it is possible to have a greater percentage of factory-made components. In the nuclear sector, Hayns and Shepherd [28] were the first authors to illustrate why the technical solutions that are embodied by the small plant design might reduce the investment cost for a given plant. The most relevant elements of the small plant concept are the standardization of components and a broader safety by design approach. Standardization is at the origin of a more efficient supply, construction, and operation (see Ref. [29] for a general discussion of the effects of standardization through design modularity), and it enables suppliers and utilities to more rapidly benefit the learning economies [30]. Although there are a number of works in the literature describing the qualitative advantages of modularization, only a few of them are able to quantify the underlying advantages. Ref. [31] focuses on the impact of modularization on cost and schedule in infrastructure, reporting quantitative information about schedule and capital cost saving determined by the transition from the stick-built construction to modularization. In particular, Ref. [31] reports a range of schedule saving between 7% and 20% and a range of cost saving between 22% and 50%. Furthermore, Ref. [32] shows a methodology to evaluate the impact of modularization in the construction of an NPP, applying this methodology to Westinghouse SMR. In particular, Ref. [32] evaluates the TCIC (total capital investment cost) for three different construction strategies with different degrees of modularization. The authors include in the definition of TCIC the cost of activities and components during construction and the time value of capital. The Westinghouse SMR design is characterized by 12 supermodules that are assembled in five assembly areas on site. Three construction strategies are evaluated:

- Complete modularization: modules fabricated in factory, supermodules in the assembly area, and then installed creating the nuclear island.
- Lesser degree of modularization: modules fabricated in the assembly area, supermodules in the assembly area, and then installed creating the nuclear island.
- Stick-built construction: no supermodules.

The analysis shows a TCIC saving for the first and the second strategy, respectively, of 39% and 21% with respect to the stick-built strategy. Therefore, the analysis shows the positive impact of modularization.

8.2.3 Co-siting economies

Co-siting economies result from the cost saving of the setup activities related to siting (e.g., acquisition of land rights, connection to the transmission network), which have been already carried out and, by certain fixed indivisible costs, which can be saved when installing the second and subsequent units [14]. Therefore, the larger the number of NPP co-sited units, the smaller the total investment cost for each unit [16,17,33]. Operational costs would also be reduced because of the sharing of personnel and spare parts across multiple units [8] or the possibility to share the cost of upgrades on multiple units, e.g., the cost of upgrading software. In the literature, there are many statements about cositing economies. For example, Ref. [34] suggests that "*the average cost for identical* *units on the same site can be about 15% lower than the cost of a single unit, with savings coming mostly in siting and licensing costs, site labor and common facilities. The 58 PWR in France built as multiple units at 19 sites are good examples.*"

8.2.4 Learning and construction schedule

For the same power installed, SMRs can exploit two strong synergic advantages with respect to LRs: learning and construction time.

Regarding the first advantage, there are two key aspects [16]:

Modularity—learning economies

Ref. [35] explains what a learning rate is: "*A progressive increase in efficiency and effectiveness can be achieved by building experience and learning how to perform a process and use tools to deliver a product. The learning rate is the cost reduction realised in this way, for every cumulative doubling of production.*" Learning rate increases through [35]: modularization and factory fabrication, high production rates, standardization of design, and a consistent delivery chain, in a stable regulatory environment. SMRs rely on the supply of standardized components and their assembly and maintenance within the plant site, with a reduction of investment and operating costs. The standardization of SMR design and components is a necessary condition for suppliers, along with the smaller size of units, to replicate in a factory the production of SMR units and to reap the learning economies. SMRs are characterized by an expected learning rate higher than LRs. The nuclear sector has always been characterized by a lower learning rate than the other industries, between 1% and 3% [35]. According to Ref. [35], the expected rate of SMR industry ranges between 5% and 10% (with a proportion of factory fabrication of 45%–60%). Fig. 8.2 summarizes these information, providing also a learning rate comparison between different industries and between SMRs and LRs.

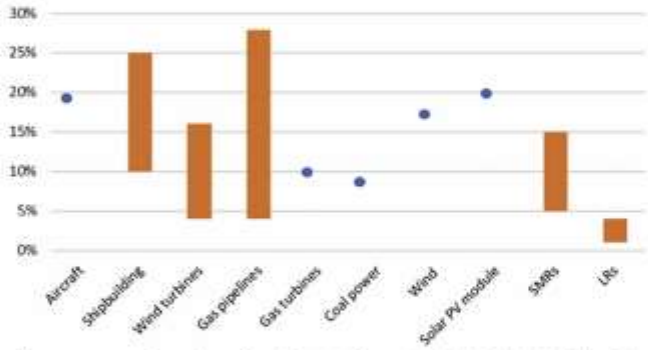


FIGURE 8.2 Learning rate comparison. *Data from Ernst & Young Global Limited, Small modular reactors - Can building nuclear power become more cost-effective?, 2016; Tony Roulstone, Nuclear's Economy of Scale vs Volume, 2015. Available: https://www.youtube.com/watch?v=A2XpllbopnU.*

Mass production economies

For a certain installed power, many more SMRs than LRs are required as the power provided by an SMR is a fraction of the power provided by an LR. Therefore, it is possible to have a large bulk ordering process of components, like valves, that are specifically developed for a certain reactor design. This aspect allows SMRs to exploit the economies of mass production and a more standardized procurement process.

Regarding the second advantage, construction time represents a critical aspect in NPP for two reasons.

Fixed daily cost

On an NPP construction site, there are thousands of people working and the utilization of expensive equipment (e.g., cranes). Consequently, each working day has high fixed costs.

The postponing of cash inflow

Because of the postponing of cash inflow, there are two negative effects. First, each year of construction delays the time when cash is expected to flow into the utility increasing the interest to be paid on the debt. Second, the present value of future cash flow decreases exponentially with time.

SMRs have an expected shorter construction schedule than LRs [16,21,35,37]. The projected schedule is 4/5 years for the first-of-a-kind SMR and 3/4 years for the nth-of-a-kind SMR [35,38], instead of the 6 years of LRs [38]. The SMR characteristics, which determine the shorter construction schedule, are [16,37–39] smaller size, simpler design, increased modularization, a large fraction of components produced in a factory, serial fabrication of components, and standardization.

Three key consequences of schedule reduction are

1) Reduction of the time to market [3,21];
2) Reduction of the interest during construction [16,40];
3) Possibility to match the demand growth [3].

8.2.5 Life-cycle costs

8.2.5.1 Capital cost

Firstly, it is worth clarifying the difference between capital cost and CAPEX (capital expenditure, also called overnight cost). Capital cost is the sum of the "overnight capital cost" and the "interest during construction (IDC)" [41]. Ref. [25] defines the "overnight capital cost" as "*the base construction cost plus applicable owner's cost, contingency, and first core costs. It is referred to as an overnight cost in the sense that time value costs (IDC) are not included.*" Examples of owner's cost are land, site works, switchyards, project management, administration, and associated buildings [42]. The capital cost is also defined as TCIC. Ref. [35] highlights that SMR CAPEX can be reduced up to 20% by way of (1) modularization and factory fabrication, (2) advanced manufacturing, (3) BIM (building information modelling), (4) advanced construction methods, and (5) co-siting of multiple reactors. Regarding BIM, it is defined as a "*combination of Computer Aided Design (CAD) tools and additional functionality, which gives a digital representation of the physical and functional characteristics of a facility. This can be used to collect and share facility information in order to improve decision making over the course of the life cycle*" [35]. The use of BIM might determine a CAPEX reduction for SMRs by 4%–10% (consistently with saving in other industries) [43]. The same percentage of CAPEX reduction is also envisaged for LRs [35]. Regarding the advanced construction method, open-top construction can determine a CAPEX saving of up to 2%. Parallel construction and crane optimization can further increase the CAPEX reduction. These methods have to be considered early in the design phase. Considering the limited maturity of SMR designs, the possibility to achieve a CAPEX reduction is higher for SMRs than LRs [35]. Regarding the last point, the reasons because of SMRs can benefit from the co-siting economies are summarized in Section 8.2.3. However, Ref. [35] points out a CAPEX cost saving of 5%–14% for SMRs (considering between 2 and 12 reactors on the same site).

Ref. [17] compares the 335 MWe IRIS reactor (SMR representative) and a 1340 MWe Generation III+ PWR (LR representative) evaluating six factors: size, multiple units at a single site, learning, construction time, match of construction schedule to demand, and design-related characteristics. The comparison shows how the economy of scale is a big disadvantage for SMRs if the two plants are comparable in design and characteristics. Indeed, by considering only the factor "size," IRIS reactor has an average cost (€/kWe) 70% greater than a 1340 MWe Generation III+ PWR. This percentage changes if other factors are considered. Ref. [17] considers the following factors and the corresponding cost reductions (%) in the case of 4 versus 1 plant comparison: multiple units at a single site (14%), learning (8%), construction schedule (6%), and design-related characteristics (17%). When these factors are considered and combined, four 335 MWe SMRs have a capital cost ($\$(MWh)^{-1}$) 5% higher than a 1340 MWe LRs [17].

Ref. [40] considers four plant sizes (1600 MWe, 1200 MWe, 300 MWe, 150 MWe) to compare the "economy of scale" and the "economy of multiples" paradigms and two scenarios: NPPs deployed by a big utility and two minors and NPPs deployed by a single utility. The main results are

- By considering only the "economy of scale," the overnight cost ($€(kWe)^{-1}$) of the first SMR (300 MWe) would be 89% higher than a single LR (1600 MWe);
- By considering not only the "economy of scale" but the "economy of replication" too, the gap reduces to 13%.
- If the "IDC" is considered, the gap between SMRs (300 MWe) and LR (1600 MWe) reduces to 7%–10%.

8.2.5.2 Operating expenditure

Firstly, it is worth clarifying the meaning of operating expenditure (OPEX) and O&M (operation and maintenance). Ref. [35] defines OPEX as "*the cost of maintaining a plant, including both the cost of keeping the plant available to generate (fixed opex) and the incremental cost of generation (variable Opex). Variable costs of operation include fuel, output related repair and maintenance, residue disposal and the incurring of charges that will fund the decommissioning costs after the operating life of the asset.*" Furthermore, Ref. [35] defines O&M as "*all actions which have the objective of retaining or restoring an item in or to a state in which it can perform its required function these include the combination of all technical and corresponding administrative, managerial and supervision actions.*"

The OPEX breakdown for LRs is usually characterized in this way: 50% fixed O&M, 25% fuel, 15% variable O&M, and 10% decommissioning [35]. O&M costs are the "*most addressable areas*" of the OPEX [35]. SMR fuel cost is expected to be higher than the LR one, in particular with the single-batch fuel strategy adoption. SMR decommissioning cost is also expected to be higher than the LR one. Regarding the "*most addressable areas*", Ernst & Young Global Limited [35] highlights that they are expected to be higher for SMRs with respect to LRs. The main reasons are the expected higher workforce costs per unit of output (considering the lack of the economy of scale) and the expected higher manning costs. SMRs might reduce the expected higher OPEX through co-siting of multiple reactors, operational learning, and shared control. In particular, cositing of SMRs might reduce the fixed O&M costs by 10%−20% (7%−14% of the OPEX). The operational learning (determined through familiarity with the designs and a consistency of operations) might improve the capacity factor (potential increase by 5%−10%) and reduce the variable O&M costs (potential saving of 5%). The shared control (single control for several reactors) can reduce the staffing cost [35].

In another study, Carelli et al. [17] compare the O&M costs of four 335 MWe SMRs (IRIS) with a 1340 MWe LR using a multiple regression analysis. According to the analysis carried out by Carelli et al. [17], the O&M costs of four 335 MWe SMRs (IRIS) are 51% greater than a 1340 MWe LRs, if only the "economy of scale" factor is considered. This percentage becomes equal to 19% if the following factors and corresponding cost reductions are considered in the comparison: multiple units at single sites (15%), additional outage cost (3%), and outage duration (4%).

Furthermore, Refs. [44,45] highlight another two factors that might reduce the SMR O&M costs: the higher quality determined by factory fabrication and the fewer components with respect to LRs.

8.2.5.3 Decommissioning cost

NPP decommissioning is complex, long, and expensive [46,47]. However, SMR decommissioning cost is the least life-cycle cost component analyzed in both scientific and industrial literature. According to Refs. [48,49], SMR decommissioning stage appears technically easier for full factory-assembled reactors, as they can be transported back to the factory in an assembled form. The dismantling and recycling of components of a decommissioned NPP at a centralized factory is expected to be cheaper compared with the on-site activity, in particular due to the economies of scale associated with the centralized factory. However, estimates of decommissioning costs vary between authors. Locatelli and Mancini [50] compared one or two LRs (1340 MWe) versus four or eight SMRs (IRIS reactor, 335 MWe), both in the case of immediate and deferred decommissioning. The analysis shows that, if the economy of scale is considered as the only driver, the specific decommissioning cost ($\$(\mathrm{MWe})^{-1}$) of SMRs is three times higher, but if other factors are considered (site sharing and different technological solutions), the gap will be reduced.

8.2.6 Small modular reactor financing

Reduction of the investment risk with respect to the LRs is a key advantage of SMRs. SMRs are characterized by lower up-front investment, lower capital at risk during construction, and lower financial distress than LRs, allowing the reduction of the investment risk [40,51]. SMRs can be a solution to reduce the financial risk of NPPs (that are often taken by national government utilities or companies that already have several NPPs), and, therefore, the possibility to attract investment increases with respect to LRs [52,53]. SMRs are also characterized by the successive addition of multiple units at the same site, determining that the revenue from completed units can help finance the construction of successive units and build investor confidence [51].

However, considering that some aspects of the technology feasibility have to be proven, and the commercial deployment might be long and complicated, few investors are inclined to take these early stage risks [53].

Ref. [13] evaluates the competitiveness of SMRs versus LRs from many points of views with the support of a simulation software. The main results of the analysis are as follows:

- The NPV of the LR option is higher than that for SMRs ($\$752 \times 10^6$ vs. $\$110 \times 10^6$) (752 million US dollars vs. 110 million US dollars), with an uncertainty range that may influence the profitability of the investment;
- SMRs are characterized by an average debt lower than LR ($\$825 \times 10^6$ vs. $\$1342{,}825 \times 10^6$), but by a duration higher (9 vs. 13.3);

SMRs are characterized by an equity capital required lower than the LR. This happens because SMR's capital cost is higher than SMR's benefits of the margin generated by the previous units in operation.

Furthermore, Ref. [54] compares the investment in LR with SMRs (4 SMRs of 335 MWe each and an LR of 1340 MWe) on the same site using ROA, evaluating how the profitability of SMRs changes if ROA approach is applied instead of a DCF (discounted cash flow) approach. According to Ref. [54], the ROA permits to consider management's flexibility to adapt later decision. On the contrary, DCF ignores the management's flexibility, then resulting inappropriate in valuing the flexibility given to managers by the

SMRs. Furthermore, Locatelli et al. [54] chose the following "state variables," which are the variable influencing the investor strategy: electricity price, equipment cost, licensing time, and cost. The profitability is evaluated in terms of FCFO (free cash flow from operation) both with an ROA and with a DCF methodology. The results show that the managerial flexibility has a value, and it is higher in a modular project (more options to take advantage) than in one LR project. However, the profitability is higher for an LR project.

Furthermore, Locatelli and Mancini [55] point out that in energy-generating portfolios, small plants (therefore also SMRs) might provide a lower investment risk than LR (2 GWe). The reason is that with SMRs, it is possible to increase the diversification in a portfolio, particularly in case of 2–3 GWe.

8.3 External factors

In the energy and nuclear field, most of the researches about the profitability of electrical power plants are focused on the generation cost (using indicators such as the LUEC) and the financial performance of the investment (using indicators such as IRR, NPV, etc.). Beside these important indicators, private or public investors must include in the analysis the so-called "external factors." These factors are called external because they are not always monetary factors under the control of the investor, but they strongly influence the economic performance and the feasibility of the project itself. This section, elaborating the work of [18], provides an overview of several external factors that have been identified from the literature about the differential characteristics of SMRs respect to LRs.

8.3.1 Regulation

The licensing process (LP) is a key issue for the deployment of SMRs. Sainati et al. [19] discuss SMR specific aspects of the LP, highlighting the following key topics.

Regulatory harmonization and international certification

One of the key debates concerning licensing SMR is the regulatory harmonization. In the nuclear industry, there are few major reactor vendors, contractors, and "nuclear manufacturer suppliers". However, the nuclear industry operates internationally (several countries are interested in SMRs), and the LP and nuclear regulations are country-specific [56]. Consequently, reactor vendors cannot "produce a standard plant" and simply ship/build identical units all over the world. A necessary precondition for the deployment of nearly identical/standard units in more than one country is the harmonization of law and LP. It is extremely difficult to make significant progress in this direction in the short–medium term because of the heterogeneity of [57]: legal systems and jurisprudence, institutional systems, and LP structures and underlying principles. Because each government has power over only its country, a short-term harmonization is unlikely.

Duration and predictability of the licensing process

The existing LP has been designed for LRs that are characterized by long construction periods. LRs require various assessments that take time and are performed in parallel with their construction. SMRs are designed for a shorter construction, and consequently, the "parallel" LP time could be longer than the SMR construction schedule time, preventing the expected time saving. Furthermore, Sainati et al. [19] state that the SMR LP could be longer than the SMR construction time because of *"novelty of the design technology, issuance of different safety principles with respect the conventional Nuclear power plants, lack of experienced and specific regulatory framework, the multitude of institutions involved, and the various bureaucratic passages."*

Manufacturing license

The manufacturing license was introduced by the US Nuclear Regulatory Commission for certifying the processes of critical nuclear suppliers. The manufacturing license does not substitute the LP, but it speeds up the LP because the manufacturers are known and certified by the regulatory body. Indeed, the plant must be certified onsite at the end of the construction because "*the reactor owner cannot get rid in any way of the nuclear operator liability, it is the ultimate and sole responsible for the nuclear safety*" [19]. Even if all the "mechanical components" would be certified in the factory, the LP applies to another unit of analysis: the system installed at the site; the LP relies on the NPP in a specific site and not on its parts. Even if the components are certified, the LP requires the appraisal of the specific context, i.e., the site, the NPP, the interaction between the operator and the NPP, etc.

The need for a new and regulatory framework

Another issue is the need for the development of specific laws, regulations, and LP for SMRs. This approach is already common for small nuclear research facilities. Three main challenges make difficult to develop a new legal and regulatory framework. Firstly, it requires a significant review of legal and regulatory frameworks. Secondly, it implies a complete rethink of LPs that in turn implies a redefinition of the institutional framework. Thirdly, it implies a reduction of licensing protections in institutional and democratic terms (e.g., exemption from public inquiry processes).

8.3.2 Electric grid characteristics/market dimension

This factor refers to the adaptability of the reactor size to the grid extension. Typical markets that will take advantage from SMR deployment are countries with a population requiring electricity in remote locations. A site for an LR must have an appropriate grid; however, on the opposite, the SMR can fit where an extension of the current electric grid for LR is not feasible or the extension is very expensive. Two of the key purposes of SMR technology are the construction of NPPs in developing countries (with limited grid capability) and in isolated areas (as power or multipurpose energy) [58]. According to

Ref. [59], the capacity of a single-power plant should be lower than 10% of the grid's total capacity. Therefore, for instance, in countries such as Jordan, which has about 3400 MW of installed electricity capacity, SMRs are regarded as an option. Furthermore, the large vessels used in LRs limit the siting of the NPPs to coastal area or along major rivers [3]. Conversely, SMRs use smaller vessel size leading to the opportunity for inland and remote sites [3]. Ref. [3] highlights another two SMRs features determining flexibility in plant location and the increased possibility of NPP construction. The first is the reduction of radionuclides produced by the fission process (the radionuclides produced are roughly proportional to the power level), determining a reduction of the site boundary leading to flexibility in plant siting. The second is the reduction of the water needed for the rejection of the waste heat. Smaller plants produce less power and, consequently, reject less power leading to the possibility of NPP construction in countries where only small or low flow rate rivers are available.

8.3.3 Public acceptance

The public acceptance of nuclear power is the attitude of the public toward the deployment of this technology.

Regarding SMRs, there are two different main points of view about public acceptance of SMRs:

- According to Refs. [60,61], public acceptance 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.
- Vuji et al. and Canadian Nuclear Laboratories [45,62] consider the public acceptance of new concepts as one of the disadvantages of SMRs that must be overcome to develop SMRs in the near future.

8.3.4 Safety and security

Increased safety and security are two key advantages of SMRs with respect to LRs. Several papers highlight the increased safety as one of the advantages of SMRs with respect to the LRs [3,45,51]. The reduction of the type and number of the safety components and simplification of the remaining ones determine a dramatic increase in safety [16]. Furthermore, some SMR designs are characterized by an improved separation of systems and functions [51], determining a lower probability of compromising safety functions. Ref. [3] highlights three main reasons determining the enhanced safety as follows: (1) "*the reduced inventory of radionuclides produced from the fission process,*" (2) "*the potential to eliminate design features that introduce accident vulnerabilities,*" and (3) "*the opportunities to passively respond to unexpected transients.*" Furthermore, considering that SMRs are characterized by a smaller area of skyline than LRs leading to a reduction of terrorist air attack probability, NPPs security is improved [16,40]. SMR security is further improved in the case of SMR designs characterized by an underground siting [51].

8.3.5 Emergency planning zone

The emergency planning zone (EPZ) is the area surrounding a nuclear facility where special regulatory requirements apply (e.g., specific emergency preparedness procedures need to be available, the demographic density needs to be lower than a specific limit, etc.). Each country prescribes the regulatory requirements associated to their EPZ. The IAEA [63] suggests an EPZ radius between 5 and 25 km (for reactors having a power higher than 100 MWth). Many SMR reactor vendors advocate a smaller radius because of the improved safety concepts of SMRs (compared with LRs) and because of the limited radioactive material they store. Ref. [64] points out that the Nuclear Regulatory Commission agrees SMRs need scalable EPZs.

8.3.6 Cogeneration

Locatelli et al. [65] provide an overview of the main challenges and opportunities related to the use of cogeneration for the load following of NPPs and highlight three most relevant technologies for the load following (particularly with SMRs): district heating, desalination, and hydrogen. SMRs are more suitable for cogeneration than LRs because it is possible to switch some of the SMR fleet for the cogeneration, and, consequently, SMRs can run at the full nominal power and maximum conversion efficiency [23]. Furthermore, a specific requirement for the cogeneration is the siting of the heat or desalination plant near the end-user areas [3,16].

In particular, Locatelli et al. [66] analyze the load following of SMRs by cogeneration of hydrogen, providing an assessment of the technical and economic feasibility of coupling hydrogen production facilities with SMRs, investigating three different hydrogen production electrolysis technologies: alkaline water electrolysis, high-temperature steam electrolysis, and sulfur–iodine thermochemical. Alkaline water electrolysis is technically feasible, and the investment can be profitable depending on the hydrogen and electricity price (hydrogen price ≥ 0.40 €$(Nm^3)^{-1}$ and the electricity price relatively low). For high-temperature steam electrolysis, the coupling with an LWR SMR might be challenging because of the different temperature between the steam produced and the cogeneration process requirements. This coupling becomes profitable when the hydrogen price is in the range of 0.30–0.45 €$(Nm^3)^{-1}$ or above. For sulfur–iodine thermochemical, the coupling with an HTGR SMR is possible, but the coupling with an LWR SMR it is not feasible. This coupling results very profitably as far the hydrogen price reaches 0.30 €$(Nm^3)^{-1}$. Locatelli and Ingersoll et al. [22,67] analyze the coupling of a NuScale SMR plant with different desalination technologies. The analysis shows how the coupling is easy and effective.

8.4 Why has nobody built SMRs in the last two decades? And the way forward

Most SMRs have attractive characteristics of simplicity and enhanced safety and require fewer financial resources than LRs. However, they are usually not considered as economically competitive with respect to LRs because of the accepted axiom of "bigger is better", i.e., a misguided application of the economy of scale principle. The economy of scale principle applies if and only if the comparison is 1 large versus one small and the reactors are of a similar design, as this has largely been the case in the past. This is no longer true today, however, where smaller, modular reactors have very different designs and characteristics from large-scale counterparts. Thus, assuming by definition that because of the economy of scale principle the capital cost of a smaller size reactor is higher than for a large size reactor is simplistic and not wholly applicable, and assuming that SMRs presents several advantages with respect to LRs (suitability for cogeneration, enhanced safety and security, increased possibility of NPP construction, reduction of the time to market, etc.), a reasonable retort is "why has nobody built SMR in the last two decades?" There are a number of reasons, the most important being:

- In the nuclear industry, there is a strong belief in the economy of scale. However, this is not supported by the data. An example is analyzed by Grubler [68] for the French case. In this instance, the author showed that with increasing the size came increased construction time without the economy of scale.
- In general, in the last two decades, relatively few reactors have been built globally, with most investors (mainly in South Korea, Japan, and China) using "proven designs", i.e., the large GEN II reactors further developed in large GEN III reactors.
- To be fully competitive, the SMR needs to balance size reduction with technical solutions that can only be enabled by a reduction in size; a typical example of which is an integral vessel, incorporating the heat exchangers, able to rely on natural circulation. Solutions like these are impossible to be fully implemented on LRs. It was not possible to implement these solutions in the 1970s because (quoting a senior engineer from an important nuclear vendor) "*to properly exploit passive solutions like natural circulation you need a great deal of computer simulations and codes. Twenty to thirty years ago those tools were not available, so the only option was to use a pump (plus the backup pumps). From an engineering perspective it is much easier to control fluids using several pipes and pumps than to rely and make sophisticated simulations with computer codes*".
- One of the enabling factors to build cost competitive SMRs is the modularization (again expensive to implement in terms of software resources) and the availability of advanced technology and software (e.g., BIM), which have emerged only in recent years.

Very recently, the UK government commissioned several studies about SMR economics and financing, as [35,53]. The reports are publicly available and the authors encourage the reader to read them.

The authors also want to close the chapter echoing the wise words from Admiral Hyman G. Rickover, delivered in 1953: "*An academic reactor or reactor plant almost always has the following basic characteristics: (1) It is simple. (2) It is small. (3) It is cheap. (4) It is light. (5) It can be built very quickly. (6) It is very flexible in purpose. (7) Very little* *development will be required. It will use off-the-shelf components. (8) The reactor is in the study phase. It is not being built now. On the other hand a practical reactor can be distinguished by the following characteristics: (1) It is being built now. (2) It is behind schedule. (3) It requires an immense amount of development on apparently trivial items. (4) It is very expensive. (5) It takes a long time to build because of its engineering development problems. (6) It is large. (7) It is heavy. (8) It is complicated."*

References

[1] IAEA, Advances in Small Modular Reactor Technology Developments, 2016.

[2] IAEA, Approaches for Assessing the Economic Competitiveness of Small and Medium Sized Reactors, 2013.

[3] D.T. Ingersoll, Deliberately small reactors and the second nuclear era, Progress in Nuclear Energy 51 (4–5) (2009) 589–603.

[4] M.D. Carelli, D.T. Ingersoll, Handbook of Small Modular Nuclear Reactors, 2014.

[5] G. Locatelli, M. Mancini, N. Todeschini, Generation IV nuclear reactors: current status and future prospects, Energy Policy 61 (November) (2013) 1503–1520.

[6] IAEA, Advances in Small Modular Reactor Technology Developments, 2018.

[7] World Nuclear Association, Small Nuclear Power Reactor, 2018. Available: http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx.

[8] M.D. Carelli, C.W. Mycoff, P. Garrone, G. Locatelli, M. Mancini, M.E. Ricotti, A. Trianni, P. Trucco, Competitiveness of small-medium, new generation reactors: a comparative study on capital and O&M costs, in: 16th International Conference on Nuclear Engineering, vol. 4, 2008, pp. 499–506.

[9] G. Locatelli, M. Mancini, A framework for the selection of the right nuclear power plant, International Journal of Production Research 50 (17) (2012) 4753–4766.

[10] S. Boarin, G. Locatelli, M. Mancini, M.E. Ricottia, Financial case studies on small- and medium-size modular reactors, Nuclear Technology 178 (2) (2012) 218–232.

[11] G. Locatelli, C. Bingham, M. Mancini, Small modular reactors: a comprehensive overview of their economics and strategic aspects, Progress in Nuclear Energy 73 (2014) 75–85.

[12] S. Boarin, M. Mancini, M. Ricotti, G. Locatelli, 10 – economics and financing of small modular reactors (SMRs), in: M.D. Carelli, D.T. Ingersoll (Eds.), Handbook of Small Modular Nuclear Reactors, No. ii, Elsevier, 2015, pp. 239–277.

[13] A. Trianni, G. Locatelli, P. Trucco, Competitiveness of small-medium reactors: a probabilistic study on the economy of scale factor, in: International Congress on Advances in Nuclear Power Plants 2009, ICAPP 2009, vol. 1, 2009.

[14] G. Locatelli, Fusion: go small to go fast, in: 25th International Conference on Nuclear Engineering, ICONE 2017; Shanghai; China; 2 July 2017 through 6 July 2017; Code 131175, vol. 5, 2017.

[15] M.D. Carelli, B. Petrovic, C.W. Mycoff, P. Trucco, M.E. Ricotti, G. Locatelli, Smaller sized reactors can be economically attractive, in: Societe Francaise d'Energie Nucleaire - International Congress on Advances in Nuclear Power Plants - ICAPP 2007, vol. 5, The Nuclear Renaissance at Work, 2007.

[16] M. Carelli, P. Garrone, G. Locatelli, M. Mancini, C. Mycoff, P. Trucco, Economic features of integral, modular, small-to-medium size reactors, Progress in Nuclear Energy 52 (4) (2010) 403–414.

[17] M.D. Carelli, G. Locatelli, C.W. Mycoff, P. Garrone, M. Mancini, M.E. Ricotti, A. Trianni, P. Trucco, Competitiveness of small-medium, new generation reactors: a comparative study on capital and O&M costs, in: 16th International Conference on Nuclear Engineering, 4, 2008, pp. 1–8.

[18] G. Locatelli, M. Mancini, The role of the reactor size for an investment in the nuclear sector: an evaluation of not-financial parameters, Progress in Nuclear Energy 53 (2) (2011) 212–222.

[19] T. Sainati, G. Locatelli, N. Brookes, Small modular reactors: licensing constraints and the way forward, Energy 82 (2015) 1092–1095.

[20] N.J. Brookes, G. Locatelli, Power plants as megaprojects: using empirics to shape policy, planning, and construction management, Utilities Policy 36 (2015) 57–66.

[21] G. Locatelli, M. Pecoraro, G. Meroni, M. Mancini, Appraisal of small modular nuclear reactors with 'real options' valuation, Proceedings of the Institution of Civil Engineers - Energy 170 (2) (2017) 51–66.

[22] G. Locatelli, S. Boarin, F. Pellegrino, M.E. Ricotti, Load following with Small Modular Reactors (SMR): a real options analysis, Energy 80 (2015) 41–54.

[23] G. Locatelli, S. Boarin, A. Fiordaliso, M. Ricotti, Load following by cogeneration: options for small modular reactors, gen IV reactor and traditional large plants, in: 25th International Conference on Nuclear Engineering, ICONE 2017; Shanghai; China, vol. 3, 2017.

[24] A. Trendowicz, R. Jeffery, Software Project Effort Estimation, 2014, pp. 125–152.

[25] GIF/EMWG, Cost Estimating Guidelines for Generation IV Nuclear Energy Systems - Revision 4.2, 2007.

[26] OECD, Nuclear Energy and Renewables: System Effects in Low-carbon Electricity Systems, 2012.

[27] A.K. Upadhyay, K. Jain, Modularity in nuclear power plants: a review, Journal of Engineering, Design and Technology 14 (3) (2016).

[28] M.R. Hayns, J. Shepherd, SIR - reducing size can reduce cost, Nuclear Energy 30 (2) (1991) 85–93.

[29] R.N. Langlois, Modularity in technology and organization, Journal of Economic Behavior and Organization 49 (1) (2002) 19–37.

[30] P.A. David, G.S. Rothwell, Standardization, diversity and learning: strategies for the coevolution of technology and industrial capacity, International Journal of Industrial Organization 14 (2) (1996) 181–201.

[31] B. Mignacca, G. Locatelli, M. Alaassar, D.C. Invernizzi, We never built small modular reactors (SMRs), but what do we know about modularization in construction?, in: International Conference on Nuclear Engineering (ICONE26), 2018.

[32] G. Maronati, B. Petrovic, J.W. Banner, C.C. White, M.H. Kelley, J. Van Wyk, Total capital investment cost evaluation of SMR modular construction designs, in: International Congress on Advances in Nuclear Power Plants, ICAPP 2016, vol. 2, 2016, pp. 943–948.

[33] M.D. Carelli, B. Petrovic, C.W. Mycoff, Economic comparison of different size nuclear reactors, in: Simposio LAS/ANS 2007/2007 LAS/ANS Symposium, 2007, pp. 653–662.

[34] IAEA, Country Nuclear Power Profiles 2004 Edition, 2005.

[35] Ernst & Young Global Limited, Small Modular Reactors - Can Building Nuclear Power Become More Cost-Effective?, 2016.

[36] T. Roulstone, Nuclear's Economy of Scale vs Volume, 2015. Available: https://www.youtube.com/watch?v=A2XpilbopnU.

[37] I.N. Kessides, V. Kuznetsov, Small modular reactors for enhancing energy security in developing countries, Sustainability 4 (8) (2012) 1806–1832.

[38] B. Vegel, J.C. Quinn, Economic evaluation of small modular nuclear reactors and the complications of regulatory fee structures, Energy Policy 104 (2017) 395–403.

[39] I. Playbell, Economy, safety and applicability of small modular reactors, in: Proceedings of the Institution of Civil Engineers, 2016.

[40] S. Boarin, G. Locatelli, M. Mancini, M.E. Ricotti, Italy Re-opening the nuclear option: are SMR a suitable choice? An application of the INCAS model, in: ASME 2011 Small Modular Reactors Symposium, SMR 2011, 2011.

[41] MIT, The Future of Nuclear Energy in a Carbon-Constrained World, 2018.

[42] World Nuclear Association, The Economics of Nuclear Power, 2008.

[43] G.V.R. Holness, BIM Gaining Momentum, 2008.

[44] T.S. Carless, W.M. Griffin, P.S. Fischbeck, The environmental competitiveness of small modular reactors: a life cycle study, Energy 114 (2016) 84–99.

[45] J. Vuji, R.M. Bergmann, R. Skoda, M. Mileti, Small modular reactors: simpler, safer, cheaper? Energy 45 (2012) 288–295.

[46] D.C. Invernizzi, G. Locatelli, N.J. Brookes, An exploration of the relationship between nuclear decommissioning projects characteristics and cost performance, Progress in Nuclear Energy 110 (March 2018) (2019) 129–141.

[47] D.C. Invernizzi, G. Locatelli, N.J. Brookes, Managing social challenges in the nuclear decommissioning industry: a responsible approach towards better performance, International Journal of Project Management In press (2017).

[48] OECD/NEA, Current status, technical feasibility, and economics of small nuclear reactors, Nuclear Development (June) (2011).

[49] IAEA, Status of Small Reactor Designs Without On-site Refuelling, 2007.

[50] G. Locatelli, M. Mancini, Competitiveness of small-medium, new generation reactors: a comparative study on decommissioning, Journal of Engineering for Gas Turbines and Power 132 (10) (2010).

[51] R.J. Budnitz, H.H. Rogner, A. Shihab-Eldin, Expansion of nuclear power technology to new countries – SMRs, safety culture issues, and the need for an improved international safety regime, Energy Policy 119 (April) (2018) 535–544.

[52] G. Alonso, S. Bilbao, E. Del Valle, Economic competitiveness of small modular reactors versus coal and combined cycle plants, Energy 116 (2016) 867–879.

[53] EFWG, Market Framework for Financing Small Nuclear, 2018.

[54] G. Locatelli, M. Mancini, F. Ruiz, P. Solana, Using real options to evaluate the flexibility in the deployment of SMR, in: International Congress on Advances in Nuclear Power Plants 2012, ICAPP 2012, vol. 4, 2012.

[55] G. Locatelli, M. Mancini, Large and small baseload power plants: drivers to define the optimal portfolios, Energy Policy 39 (12) (2011) 7762–7775.

[56] M. Tronea, European quest for standardisation of nuclear power reactors, Progress in Nuclear Energy 52 (2) (2010) 159–163.

[57] IAEA, Governmental, Legal and Regulatory Framework for Safety, 2010.

[58] IAEA, International Status and Prospects of Nuclear Power, 2010.

[59] M. V Ramana, A. Ahmad, Wishful thinking and real problems: small modular reactors, planning constraints, and nuclear power in Jordan, Energy Policy 93 (2016) 236–245.

[60] Nea, Small Modular Reactors: Nuclear Energy Market Potential for Near-term Deployment, 2017.

[61] S.T.M. Mancini, G. Locatelli, 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, 2009.

[62] Canadian Nuclear Laboratories, Perspectives on Canada'S SMR Opportunity, 2017.

[63] IAEA, Method for Developing Arrangements for Response to a Nuclear or Radiological Emergency, 2003.

[64] NEI, NRC Staff Agrees Small Modular Reactors Won't Need Large-Scale Emergency Zones, 2018. Available: https://www.nei.org/news/2018/nrc-staff-agrees-smrs-wont-need-large-epzs.

[65] G. Locatelli, A. Fiordaliso, S. Boarin, M.E. Ricotti, Cogeneration: an option to facilitate load following in Small Modular Reactors, Progress in Nuclear Energy 97 (2017) 153−161.

[66] G. Locatelli, S. Boarin, A. Fiordaliso, M.E. Ricotti, Load following of Small Modular Reactors (SMR) by cogeneration of hydrogen: a techno-economic analysis, Energy 148 (2018) 494−505.

[67] D.T. Ingersoll, Z.J. Houghton, R. Bromm, C. Desportes, NuScale small modular reactor for Co-generation of electricity and water, Desalination 340 (1) (2014) 84−93.

[68] A. Grubler, The costs of the French nuclear scale-up: a case of negative learning by doing, Energy Policy 38 (9) (2010) 5174−5188.

D.4 Publication VIII

Mignacca, B., Locatelli, G., 2020. Economics and finance of Molten Salt Reactors. Progress in Nuclear Energy – **Scopus indexed journal, Impact Factor: 1.508**. **Most downloaded article of the journal at the time of writing (May 2021)**.

Progress in Nuclear Energy 129 (2020) 103503

Contents lists available at ScienceDirect

Progress in Nuclear Energy

journal homepage: http://www.elsevier.com/locate/pnucene

Economics and finance of Molten Salt Reactors

Benito Mignacca, Giorgio Locatelli*

University of Leeds, School of Civil Engineering, Leeds, United Kingdom

ARTICLE INFO

Keywords:
Molten salt reactor
Economics
Finance
LCOE
Modularisation
GEN IV reactor

ABSTRACT

There is a long-standing and growing interest in Molten Salt Reactors (MSRs) mainly because of their potential advantages in terms of safety, sustainable fuel cycle, and the high melting and boiling points of salt which allow operations at high temperatures and atmospheric pressure with potential merits in terms of cost. A key objective of MSRs is to have a life-cycle cost advantage over other energy sources. Leveraging a systematic literature review, this paper firstly provides an overview of "*what we know*" about MSR economics and finance following two main streams: scientific and industrial literature. Secondly, this paper highlights "*what we should know*" about the economics and finance of MSRs, suggesting a research agenda. The literature is very scarce and focuses on MSR overnight capital cost estimations and the comparison between MSR cost of electricity and other energy sources. Cost estimations need to be more transparent and independently assessed. Furthermore, there is no peer-reviewed literature on MSR financing, only claims from vendors.

1. Introduction

The evolution of Nuclear Power Plants (NPPs) is usually divided into four generations (GIF, 2014):

- I generation (1950–1970): early prototypes to test different technologies[1];
- II generation (1970–1995): medium-large commercial NPPs, mostly Light Water Reactors (LWRs), conceived to be reliable and economically competitive;
- III/III + generation (1995–2030): mostly an evolution of the II generation LWR;
- IV generation (2030+): designs called "revolutionaries" because of their discontinuity with the III/III + generation NPPs.
  The Generation IV International Forum (GIF) lists six GEN IV technologies (GIF, 2014):
- VHTR (Very-High-Temperature Reactor) is a thermal reactor technology cooled by helium in the gaseous phase and moderated by graphite in the solid phase;
- SFR (Sodium-cooled Fast Reactor) is a fast reactor technology cooled by sodium in the liquid phase. It is the most investigated fast reactor;
- SCWR (Supercritical-Water-cooled Reactor) is a thermal/fast reactor technology cooled by supercritical water. It is considered as an evolution of the actual boiling water reactor because of its comparable plant layout and size, same coolant and identical main application, i.e. electricity production;
- GFR (Gas-cooled Fast Reactor) is a fast reactor technology cooled by helium in the gaseous phase. This technology aims to put together a high-temperature reactor with a fast spectrum core;
- LFR (Lead-cooled Fast Reactor) is a fast reactor technology cooled by lead or lead-bismuth eutectic. It is a liquid metal reactor (similar to SFR) for electricity production and actinides management;
- MSR (Molten Salt Reactor) is a fast or thermal reactor technology cooled by molten salts in the liquid phase and moderated, in most cases, by the graphite. In this technology, the fuel can be in either liquid or solid form (Zheng et al., 2018).

Currently, there is an increasing interest in MSRs both from industry and academia. (Zheng et al., 2018) summarise the advantages of MSRs. The high melting and boiling points of salt allow operating at high temperatures (increasing the efficiency in electricity generation) and atmospheric pressure (lowering the risk of a significant break and loss of coolant because of an accident). In addition, the opportunity to dissolve

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

[1] It is worth clarifying the difference between technology, design, and project right at the start of the paper with an example. An example of technology is the Pressurised Water Reactors (PWR), which has several designs. An example of PWR design is the AP1000. A project implementing the AP1000 is the HAIYANG 1 in China. Therefore, for each technology there are several designs, and for each design there could be different projects around the world.

https://doi.org/10.1016/j.pnucene.2020.103503
Received 18 February 2020; Received in revised form 17 August 2020; Accepted 1 September 2020
Available online 19 September 2020

fuel materials in the salt eliminates the fabrication and disposal of solid fuel. Furthermore, the opportunity to constantly remove fission products from the liquid fuel allows a higher fuel burnup and less decay heat is generated after reactor shutdown. MSRs are also characterised by a passive shutdown ability, low-pressure piping, negative void reactivity coefficient and chemically stable coolant (Saraf et al., 2018; Zheng et al., 2018). MSRs can be designed as nuclear waste "burners" or "breeders". In the case of "burners", MSRs have the potential to reduce nuclear waste. In the case of "breeders", MSRs could greatly extend nuclear fuel resources (IAEA, 2020a; Zhou et al., 2020).

Given their attractive features, the interest in MSRs is not new. Indeed, from the 1950s to 2020, many MSR concepts and designs have been proposed using different fission fuels (i.e. Uranium, Plutonium or Thorium) and salt compositions (e.g. chlorides, fluorides) (IAEA, 2020a; Serp et al., 2014). In the 1960s and 1970s, the Oak Ridge National Laboratory (ORNL) demonstrated many aspects of the MSR technology with the MSR Experiment, where the MSR ran for a relatively long period of time (15 months), and maintenance was carried out safely and without substantial issues (Macpherson, 1985; Oak Ridge National Laboratory, 2010; Serp et al., 2014).

However, although there is a long-standing and growing interest in MSRs, there are no MSRs in commercial operation, under construction or planned for near term commercial operation (IAEA, 2019). Therefore, while the vast majority of MSRs literature focuses on technical aspects, there is little historical data about the economics or financing of MSR projects (Serp et al., 2014; Wang et al., 2020; Wooten and Fratoni, 2020; Zeng et al., 2020; Zhou et al., 2020; Zhuang et al., 2020).

Information about MSR economics and finance is scattered between a few academic papers, not peer-reviewed publications and vendor websites. This paper aims to provide, through a Systematic Literature Review (SLR), a summary of "*what we know*" and "*what we should know*" about the economics and finance of MSRs. Instead of a traditional narrative review, an SLR has been performed to provide a holistic perspective and allow repeatability. The research objective is "to critically summarise the state-of-the-art about MSR economics and finance and the most relevant gaps in knowledge".

The rest of the paper is structured as follows. Section 2 introduces key economic and financial concepts; Section 3 presents the methodology used to conduct the SLR; Section 4 summarises "*what we know*" about MSR economics and finance; Section 5 summarises "*what we should know*" suggesting a research agenda; Section 6 concludes the paper.

2. Economic and financial concepts

Considering this paper deals with the economics and finance of MSRs, it is worth clarifying the difference between economics and finance. Economics is the study of the management of goods and services, comprising production, consumption, and the elements affecting them (Ehrhardt, 2011; Investopedia, 2019a). Economic studies deal with cost estimations (e.g. construction cost, decommissioning cost), identification of cost drivers (e.g. size, construction technique), etc. Usually, economic models do not consider the payment of taxes, remuneration of debt or equity, or debt amortisation captured by financial analysis (Ehrhardt, 2011). Finance focuses on cash flows or equivalent means. For instance, asking "how much is the construction cost of an MSR?" is an economic question, while asking "who will pay to build an MSR?" is a financial question. The next sections provide an overview of the main economic and financial concepts enabling the reader to understand the following sections of the paper.

2.1. Cost vs price

Commonly misunderstood are the terms cost and price. The cost is the sum of the expenses for a company to manufacture a product (e.g. an MSR) or to provide a service (e.g. maintenance). The price is the amount the customer (e.g. the utility) pays for a product or service, and it is usually market-driven. Therefore, the cost is an endogenous measure (dependent on technology, design, etc.), while the price is an exogenous measure (dependent on the market, policy decisions, etc.). Price can be less than cost if, for example, the vendors aim to build a reference plant to gain experience (and not directly profiting from it) or to make a profit from selling additional services (e.g. maintenance) or products (e.g. fuel).

2.2. Top-down vs bottom-up approach

There are two main cost estimation approaches: top-down and bottom-up. Following the top-down approach, a new project is compared to similar projects already completed (Trendowicz and Jeffery, 2014), and the cost of a project is estimated by increasing or decreasing the cost items (e.g. material, equipment, systems) of similar projects. The top-down approach is preferred when there is a lack of information (GIF/EMWG, 2007). Conversely, following the bottom-up approach, the cost of a project is estimated as the sum of the costs of each element (e.g. a pump), material (e.g. kg of concrete), labour (e.g. the number of hours worked by certain type of workers), service (e.g. site security), etc. The bottom-up approach is most suitable for projects with a detailed design, a specific site for the construction and availability of detailed data (GIF/EMWG, 2007). (GIF/EMWG, 2007) provides guidelines on both top-down and bottom-up cost estimation approaches for Gen IV reactors.

2.3. General cost items

- Direct costs: All costs to build an NPP apart from support services (e.g. field indirect costs, construction supervision) and other indirect costs (e.g. design services) (GIF/EMWG, 2007). For instance, (MIT, 2018) includes, among others, the following direct costs in the MSR cost estimation (summarised in Section 4.1): costs for reactor and turbine plant equipment; labour costs for installation; and civil work costs to prepare the site.
- Indirect costs: Design services, construction supervision, and all the costs not directly associated with the construction of an NPP (GIF/EMWG, 2007). For instance, (MIT, 2018) includes, among others, the following indirect costs in the MSR cost estimation (summarised in Section 4.1): costs for construction management; procurement; quality inspections; project fees; and taxes.
- Base costs: The initial NPP cost estimation before validation and any cost adjustments (GIF/EMWG, 2007).
- Base construction cost: The most likely NPP construction cost, considering only direct and indirect costs (GIF/EMWG, 2007).
- Contingency: An addition to account for uncertainty in NPP cost estimation (GIF/EMWG, 2007).

2.4. Generation costs of a nuclear power plant

In the nuclear sector, the generation costs (or life-cycle costs) are commonly divided into four groups: capital cost; operation and maintenance costs; fuel cost; and decommissioning cost.

- Capital cost is the sum of the "overnight capital cost" and Interest During Construction (IDC) (MIT, 2018). (GIF/EMWG, 2007) defines the "overnight capital cost" as "*the base construction cost plus applicable owner's cost, contingency, and first core costs*" (Page 25). Therefore, the time value costs (e.g. Interest During Construction) are not included. Examples of owner's costs are land, site works, switchyards, project management, administration and associated buildings (World Nuclear Association, 2009). The "overnight capital cost" is also defined as "overnight cost".
- Operation and Maintenance (O&M) costs are the costs to maintain and operate an NPP, i.e. all the non-fuel costs, such as plant staffing, purchased services, replaceable operating materials (e.g. worn

parts), and equipment. O&M costs can be divided into fixed and variable. Fixed O&M costs do not depend on the power generation level, e.g. plant staffing. Variable O&M costs depend on electricity production, e.g. non-fuel consumables (GIF/EMWG, 2007). The fixed costs represent by far the biggest percentage of O&M costs.

- Fuel cost is the sum of all activities related to the nuclear fuel cycle, from mining the uranium ore to the final high-level waste disposal (NEA, 1994). Enrichment of uranium, manufacture of nuclear fuel, reprocessing of spent fuel, and any associated research are examples of activities related to the nuclear fuel cycle (IAEA, 2006).
- Decommissioning cost includes all the costs from the planning for decommissioning until the final remediation of the site. Therefore, the costs in the transition phase from the shutdown to decommissioning and the costs to perform the decontamination, dismantling and management of the waste are included (IAEA, 2013; Invernizzi et al., 2020b, 2019a; 2017; Locatelli and Mancini, 2010).

2.5. *Indicators of the economic and financial performance of a power plant*

- Levelised Cost of Electricity and Levelised Avoided Cost of Electricity

One of the most relevant indicators for policy-makers is the levelised cost of the electricity produced by the power plant. This indicator, usually termed "Levelised Unit Electricity Cost" (LUEC) or "Levelised Cost Of Electricity" (LCOE) accounts for all the life cycle costs, and it is expressed in terms of energy currency, usually as [$/kWh] (IAEA, 2018). In the nuclear sector, the main component of the LCOE is the capital cost (50–75%), followed by O&M and fuel cost (Carelli and Ingersoll, 2014). From a policy perspective, a power plant is considered economically attractive when its projected LCOE is lower than its projected Levelised Avoided Cost of Electricity (LACE). LACE is the power plant's value to the grid (EIA, 2019). In other words, according to (EIA, 2015), LACE "*reflects the cost that would be incurred to provide the same supply to the system if new capacity using that specific technology was not added*". LACE is usually expressed as [$/kWh]. LCOE and LACE are extremely relevant for policy-makers and the appraisal of the design in its early stages. However, coming close to construction, the following parameters are also relevant.

- Net Present Value and Internal Rate of Return

Two of the most relevant indicators for utility companies (or investors in general) to assess the profitability of investing in a power plant are the Net Present Value (NPV) and the Internal Rate of Return (IRR) (Locatelli et al., 2014; Locatelli and Mancini, 2011; Mignacca and Locatelli, 2020). The NPV uses a discount factor to weight "present cost" versus the "future revenue" and measures the absolute profitability in terms of currency (Investopedia, 2019b). The discount factor depends on the source of financing and applied in practice as the Weighted Average Cost of Capital (WACC). A high WACC gives more weight to present cost with respect to future revenue (promoting low capital technologies such as gas plants). A low WACC gives similar weighting to present cost and future revenues (promoting capital-intensive technologies such as NPPs). The IRR is a specific dimensionless indicator, i.e. the value of WACC that brings the NPV to zero. The greater the IRR, the higher is the profitability of the investment as a percentage on the money invested (Investopedia, 2019c; Locatelli et al., 2014).

2.6. *Potential approaches for cost reduction*

This section provides an overview of three key approaches to reduce the costs of NPPs.

2.6.1. *The economy of scale*

Historically, the size of NPPs has increased from a few hundred MWe to 1500 MWe and more. The reason behind increasing the size of NPPs is the economy of scale principle, i.e. 'bigger is cheaper'. According to the economy of scale principle, the capital cost [currency/kWe] and LCOE [currency/MWh] of an NPP decreases when size increases. The capital cost reduction is due to several factors such as: the rate reduction of unique set-up costs (e.g. siting activities, work to access the transmission network); the higher performance of larger equipment (e.g. steam generator, pumps); and the more efficient use of raw material (Locatelli et al., 2014). However, the implementation of the economy of scale principle can present drawbacks. For instance, other things being equal, the larger the reactor size, the higher is the up-front investment and problems of affordability for the utility companies. Furthermore, grid connection could struggle to reliably handle increased power (Black et al., 2015; OECD/NEA, 2011). These and other factors, such as economy of multiples and enhanced modularisation, are driving the growing interest in Small Modular nuclear Reactors (SMRs) (Mignacca and Locatelli, 2020).

2.6.2. *The economy of multiples*

NPP life-cycle costs (construction, operations, decommissioning) depend on how many identical (or at least very similar) units are built in the same site, country or globally. When the same identical plant is delivered more than once (ideally several times by the same organisations), the economy of multiples is achieved reducing, other things being equal, the unitary investment cost (Boarin et al., 2012; Locatelli and Mancini, 2012a; Mignacca and Locatelli, 2020). The economy of multiples in the construction of NPPs is related to the idea of "mass production", firstly adopted in the automotive industry and later in other fields (e.g. aerospace, production of computers and smartphone). The economy of multiples is achieved because of two key factors: the learning process and the co-siting economies (Locatelli, 2018).

- Learning process

The replicated supply of plant components and the replicated construction and operation of the plant determine the learning economies. The learning process reduces the cost of equipment, material and work (Locatelli, 2018) and reduces the construction schedule (EY, 2016; Mignacca and Locatelli, 2020). As shown in (Locatelli et al., 2014), the construction schedule is a critical economic and financial aspect of an NPP for two main reasons:

1. Fixed daily cost. On an NPP construction site, there are thousands of people working, often utilising expensive equipment. Consequently, each working day has relevant fixed costs.
2. The postponing of cash in-flow. Postponing the cash in-flow has two main negative effects. First, each extra-year of construction increases the interest to be paid on the debt. Second, the present value of future cash flow decreases exponentially with time.

Therefore, the unit cost of a First-of-A-Kind (FOAK) MSR is expected to be higher than the unit cost of an Nth-of-A-Kind (NOAK) MSR. The consequences of the learning process should be considered at two levels:

1) World-level – After the FOAK MSR for commercial operation in the world, a cost reduction for the NOAK MSR is expected even if they are built in different countries.
2) Country-level – If a country plans to build a series of MSRs for commercial operation, there is a learning process from the FOAK to the NOAK MSR stronger than the "world-level" because of the same regulatory regime and similar (or identical) supply chain.

- Co-siting economies

Co-siting economies result from the set-up activities related to siting (e.g. acquisition of land rights, connection to the transmission network) which have already been carried out, and by certain fixed indivisible costs which can be saved when installing the second and subsequent units (Locatelli, 2017). Therefore, the larger the number of co-sited units, the lower the total investment cost for each unit (Carelli et al., 2008, 2007). Operational costs across MSRs would also be reduced because of sharing of personnel and spare parts across multiple units (Carelli et al., 2007) or the possibility to share the cost of upgrades, e.g. the cost of upgrading software (Locatelli, 2018). (IAEA, 2005) suggests that identical units at the same site cost on average 15% less than a single unit. Siting and licensing costs, site labour and common facilities mostly drive such cost reduction. Therefore, two identical MSRs at the same site are envisaged to cost less than doubling the cost of a single MSR.

2.6.3. Modularisation

Modularisation is a construction strategy characterised by the factory fabrication of modules for shipment and installation on-site as complete assemblies (GIF/EMWG, 2007). Fabrication in controlled factory environments: increases the quality of the components (e.g. reducing mistakes in construction and reworks); reduces construction schedules; reduces maintenance cost because of a reduction of the probability of failure of components; and supports safer construction processes (Boldon et al., 2014; Carelli and Ingersoll, 2014; Maronati et al., 2017). Furthermore, factory fabrication could determine a cost-saving in labour and construction. By contrast, the supply chain start-up cost is expected to be high (UxC Consulting, 2013). The expected higher cost of transportation activities is a further disadvantage of modularisation (Carelli and Ingersoll, 2014; Mignacca et al., 2019; UxC Consulting, 2013). (Mignacca et al., 2018) review the cost reduction (an average of 15%) and schedule saving (an average of 37.7%) resulting from the transition from stick-built construction to modularisation in infrastructure projects. Therefore, by implication, modular MSRs might have a lower cost and a shorter schedule than stick-built MSRs. However, challenges and costs typically associated with modularisation such as setting up a supply chain and module transportation, need to be carefully considered.

3. Methodology

This paper provides an SLR combining the methodologies presented by (Di Maddaloni and Davis, 2017; Mignacca and Locatelli, 2020; Sainati et al., 2017). Starting from the research objective "to critically summarise the state-of-the-art about MSR economics and finance and the most relevant gaps in knowledge", the selection process of the documents includes two sections. Section A deals with academic documents extracted from the search engine Scopus, and Section B deals with the industrial literature (e.g. documents mostly provided from reactor vendors) and reports published by relevant organisations (e.g. International Atomic Energy Agency).

Section A has three main stages. The first stage is the identification of relevant keywords related to the research objective. Discussions with experts and several iterations led to the following list:

- MSR: "*Molten salt reactor*" and "*MSR*";
- Economics: "*Economic*" and "*Cost*";
- Finance: "*Finance*" and "*Financing*".

In the second stage, the following search string was developed with the Boolean operator "AND"/"OR" and introduced in Scopus to search the relevant literature:

- "*Molten Salt Reactor*" OR "*MSR*" AND "*Economic*" OR "*Cost*" OR "*Finance*" OR "*Financing*" (search date: 05/06/2020).

Scopus was chosen because of its international coverage from major scientific peer-reviewed journals, conference papers, and books. A timeframe was not selected a priori (therefore it is 1966–2020). The selection step retrieved 476 documents by using the aforementioned string (applied to title, abstract or keywords), excluding 52 non-English documents (not related to the research objective).

The third filtering stage is characterised by the following two steps:

1) Carefully reading the title and abstract of each document, screening out documents not related to the research objective or duplication. After the first step, 461 documents were screened out.
2) Carefully reading the introduction and conclusion of each document retrieved after the first step, screening out documents not related to the research objective. After the second step, 11 documents were screened out, leaving 4 documents to be analysed: (Moir, 2002), (Moir, 2008), (Samalova et al., 2017), and (Richards et al., 2017).

Fig. 1 summarises the selection process for Section A.

Furthermore, following discussions with experts, (MIT, 2018) which provides relevant information about MSR economics was added.

In section B of the selection process, documents were firstly searched on reactor vendor websites with the aim to retrieve information about economics and finance of MSRs. Vendor websites often provide links to external sources. External sources reporting information about economics and finance of MSRs were therefore consulted. Secondly, documents were searched on the IAEA (International Atomic Energy Agency) and NEA (Nuclear Energy Agency) websites (section: publications). IAEA and NEA were selected because they are leading organisations in the nuclear field and publish high-quality reports. Two keywords related to MSRs were used to search documents on the IAEA and NEA websites: "Molten Salt Reactor" and "MSR" (search date: 05/06/2020). However, there are no publications focusing on economics and finance of MSRs. After discussions with experts, the Advanced Information Reactor System (ARIS) was consulted. ARIS is an IAEA reactor database reporting several MSR designs and related documents providing information about MSR economics and finance.

4. What we know about the economics and finance of MSRs

This section gives an account of the state of the literature about economics and finance of MSRs following two main streams: scientific and industrial literature. For the sake of transparency and reproducibility, quantitative data from the retrieved documents are reported in section 4.1 and 4.2 and scaled to 2020 prices ($) in section 4.3 (summary and comparison).

4.1. Scientific literature

The scientific literature about the economics of MSRs is very scarce and almost non-existent in terms of their financing. Four scientific papers were retrieved from the SLR [(Moir, 2002),[2] (Moir, 2008),[2] (Samalova et al., 2017), (Richards et al., 2017)], and (MIT, 2018) was added after discussions with experts.

(Moir, 2002) estimates the MSR LCOE and benchmarks this value with comparable PWR and coal plant estimates, based on the evaluations of the ORNL in 1978 (Engel et al., 1980, 1978). According to (Moir, 2002), a cost breakdown and description of a 1000 MWe MSR, an equal size PWR and coal plant were presented in the ORNL report; all of them NOAK plants. Starting from this report and other sources (Moir, 2002), reaches the following two main results:

- LCOE of a 1000 MWe MSR (20% enriched): $36.5/MWh;
- LCOE of a 1000 MWe MSR is 7% lower than an equal size PWR and 9% lower than an equal size coal plant.

[2] (Moir, 2008, 2002) seem to calculate the LCOE in a simplified manner without considering time-dependent aspects such as cash flow discounting.

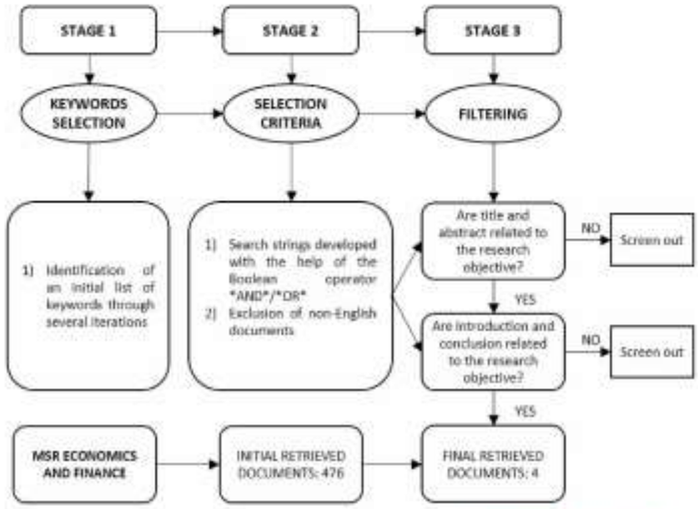


Fig. 1. Section A of the selection process – Layout adapted from (Di Maddaloni and Davis, 2017).

However, the analysis does not consider the impact on the cost of several items such as safety, licensing, and environmental standard.

(Moir, 2008) also compares the LCOE of a 1000 MWe MSR (20% enriched), a 1000 MWe MSR (100% enriched), a 1000 MWe PWR and a 1000 MWe coal plant. Table 1 summarises the comparison; it is worthy of highlight that the enrichment has to be lower than the non-weapon grade for industrial and commercial plants (<20% ^{235}U or <12% ^{233}U) (Moir, 2008; Siemer, 2019). The difference between the LCOE of the two analyses [(Moir, 2002) and (Moir, 2008)] is due to a different capacity factor (95% vs 90%).

(Samalova et al., 2017) compare cost estimations of three different Integral Molten Salt Reactors (IMSRs) (IMSR600, IMSR300, and IMSR80) and an Advanced Passive PWR (AP1000), using the methodology developed by the GIF Economic Modelling Working Group (GIF/EMWG, 2007). (Samalova et al., 2017) follows a top-down approach, because of the lack of data precluding a bottom-up approach.

Table 2 shows the calculated total Overnight Cost (OC) [M$] and the OC [$/kWe] for the AP1000 and three different IMSRs.

Table 2 highlights how the IMSR's total OC is about one-quarter of AP1000's total OC. However, considering that the IMSR's power output is one-third of AP1000's one, the OC per kWe is comparable. The IMSR80 is characterised by a significantly higher OC per kWe, but also by a significantly lower total OC. (Samalova et al., 2017) also calculate and compare the AP1000's LCOE and IMSRs' LCOE (Table 3) and the relative share of LCOE components for AP1000, IMSR600, IMSR300 and IMSR80 (Fig. 2).

(Samalova et al., 2017) highlight that the AP1000 presents a capital cost share slightly higher than the IMSR600. Considering that the AP1000 has about three times higher power output, it is expected that the IMSR600 capital cost share would be lower if IMSR600 and AP1000 are compared with the same power output (Samalova et al., 2017). Furthermore, (Samalova et al., 2017) carry out an LCOE sensitivity analysis to the discount rate (3% low scenario, 5% base scenario, 10% high scenario). Fig. 3 summarises the results. In another study, (Richards et al., 2017) calculate the MSR's LCOE under different OCs ranging from $2000/kWe to $7000/kWe ($2000/kWe is the lower manufacturers estimation, $7000/kWe is a reasonable high end). Fig. 4 summarises the results.

(Richards et al., 2017) compares the cost of various electric grid scenarios introducing MSRs, considering the following costs of nuclear power:

- MSR OC: $3000/kWe;
- Light water SMR OC: $5028.58/kWe;
- Large scale LWR OC: $5451.86/kWe;
- Variable MSR O&M costs assumed the same as large scale LWRs;
- Fixed MSR O&M costs assumed to be similar to light water SMRs.

Table 1
LCOE [$/MWh] MSR - PWR – coal. Adapted from (Moir, 2008).

Components	MSR (20% enriched)	MSR (100% enriched)	PWR	Coal
Capital	20.1	20.1	20.7	15.8
O&M	5.8	5.8	11.3	8.0
Fuel	11.1	4.0	7.4	17.2
Waste disposal	1.0	1.0	1.0	0.9
Decomposition	0.4	0.4	0.7	–
Total	38.4	31.3	41.1	41.9

Table 2
AP1000 and IMSRs total overnight cost - Adapted from (Samalova et al., 2017).

Case	MWe	Total Overnight Cost [M$]	Overnight Cost [$/kWe]
AP1000	1000	3249.105	2972.57
IMSR600	291	829.456	2850.37
IMSR300	141	524.450	3719.51
IMSR80	32.5	297.840	9164.31

Table 3
AP1000 and IMSRs LCOE (Discount rate: 5%) - Adapted from (Samalova et al., 2017).

Components [$/MWh]	AP1000	IMRS600	IMSR300	IMSR80
Capital cost	20.79	21.92	28.60	70.48
Operational cost	9.23	13.85	17.15	44.73
Fuel cycle – Front End	7.95	7.01	7.44	9.25
Fuel cycle – Back End	1.24	1.20	1.21	1.24
D&D Sinking Fund	0.16	0.15	0.17	0.35
Total [$/MWh]	**39.38**	**44.13**	**54.58**	**126.05**

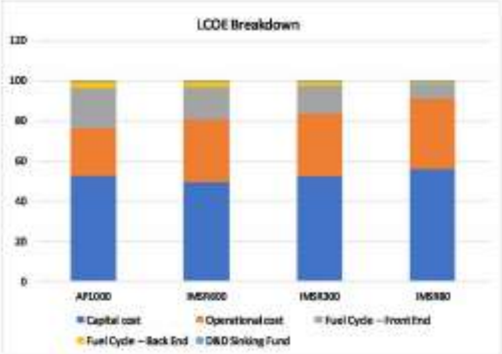


Fig. 2. LCOE breakdown [%] for AP1000, IMSR600, IMSR300, IMSR80 - Data from (Samalova et al., 2017).

In order to compare several scenarios, the authors start from the following base case using the US electricity generation mix: coal (33%), natural gas - combined cycle (32%), LWR (20%), hydropower (6%), wind (4.7%), natural gas – combustion turbine (1.7%), biopower (1.6%), solar - photovoltaic (0.6%), and geothermal (0.4%). (Richards et al., 2017) analyse several scenarios, but those focusing on MSRs are:

- Replacing coal with light water SMRs and MSRs (16.5% each); this replacement determines an overall cost reduction of 8.3%;
- Replacing LWRs with MSRs; this replacement determines an overall cost reduction of 10% (mostly due to the lower OC).

In another study, (MIT, 2018) provides a detailed capital cost estimation of the ORNL 1000 MWe MSR scaled to 2014, as summarised in Table 4. Furthermore, (MIT, 2018) provides a capital cost comparison between several NOAK advanced reactors: High-Temperature Gas-cooled Reactor (HTGR), SFR, Fluoride salt-cooled High-temperature Reactor (FHR) (Large), FHR (Small), and MSR (summary in Fig. 5).

(MIT, 2018) cost estimation is based on stick-built construction in the US for a NOAK plant. NOAK plant is considered identical to the FOAK, except for some site-specific characteristics. MSR direct costs have been calculated from an early-1980s pre-conceptual design escalating them to 2014$. Indirect costs have been considered as a percentage of the direct costs because of the lack of information. Furthermore, a contingency based on the design maturity, related technology development and supply chain considerations has been considered (20% for HTGR and SFR, and 30% for FHR and MSR). The key hypotheses are a construction time of 60 months and an interest rate of 8% (50% debt and 50% equity financing, 30 years as the economic life of the plant). Furthermore, (MIT, 2018) reports an LCOE estimation of the ORNL 1000 MWe scaled to 2014 of $119.25/MWh.

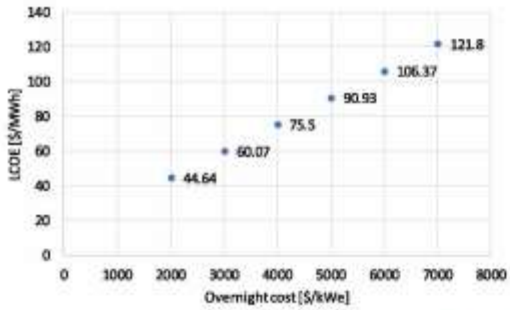


Fig. 4. MSR overnight cost sensitivity analysis - Data from (Richards et al., 2017).

4.2. Industrial literature

This section summarises the information retrieved from Section B of the SLR. Some MSR designs have not been included in this section because, at the time of writing, there is no public information about their economics and finance. For each design, firstly economic information from vendor websites are briefly presented (where available). Secondly, economic information from external industrial documents/websites are summarised (where available). Lastly, financial information from both vendor websites and external sources are summarised (where publicly available).

4.2.1. Terrestrial Energy's integral Molten Salt Reactor

Terrestrial Energy's 195 MWe IMSR uses graphite as moderator and molten salts as coolant (Terrestrial Energy, 2017a). Terrestrial Energy's

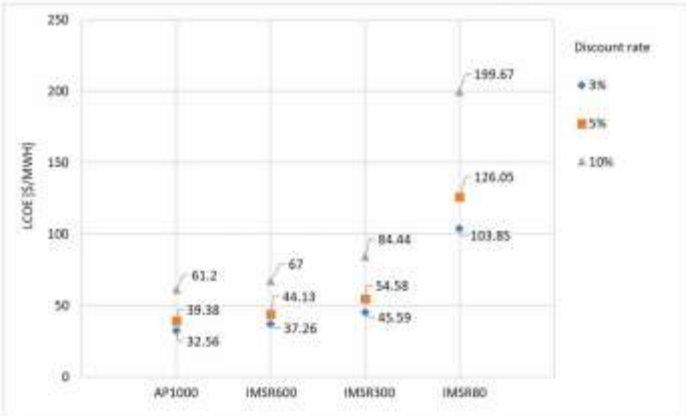


Fig. 3. LCOE sensitivity analysis to the discount rate – Data from (Samalova et al., 2017).

Table 4
ORNL 1000 MWe MSR - MIT Cost estimation Adapted from (MIT, 2018).

Cost items	[$/kWe]	Total [$/kWe]
Direct costs		
Structures and improvements	659	
Reactor plant equipment	870	
Turbine plant equipment	440	
Electrical plant equipment	266	
Miscellaneous plant equipment	159	
Main Cond heat reject system	61	2455
Indirect Costs		
Owner's costs	% Direct	
Construction services	% Direct	
Home Office Engine & Service	% Direct	
Field Office Engine & Service	% Direct	1669 (68%)
Base cost		4125
Contingency		1237 (30%)
Total overnight cost		5362
Interest during construction		751 (20%)
Total [$/kWe]		6113

IMSR is envisaged to adopt modularisation as a construction strategy. The modular approach would allow the 195 MWe IMSR power plant to be built in 4 years, requiring an upfront investment of less than 1 B$ (Terrestrial Energy, 2017b). According to (Terrestrial Energy, 2017b), IMSRs can dispatch power at under $50/MWh.

ARIS reports the IMSR-400, characterised by an electrical capacity of 194 MWe per module (IAEA, 2016a). However, according to (WNA, 2018), there are three proposed sizes of the Terrestrial Energy's IMSRs: 80 MWt (32.5 MWe), 300 MWt (141 MWe), and 600 MWt (291 MWe). These three sizes are equivalent to those presented in the scientific literature on IMSRs (i.e. (Samalova et al., 2017)). (Terrestrial Energy, 2015) states that IMSR600 and IMSR300 levelised cost is estimated respectively $43 and $59 per MWh. Furthermore, (NEI, 2016a) reports an interview with the Terrestrial Energy CEO, stating that the levelised cost of the plant for a 300 MWe IMSR is projected at $40-$50/MWh.

Regarding IMSR financing, Terrestrial Energy website reports several links to external sources. The retrieved information are categorised by year and presented in chronological order.

In 2016, Terrestrial Energy raised:

- 7.1 M$ in venture capital for IMSR technology developement (NEI, 2016b);
- 4.4 M$ from Sustainable Development Technology Canada for IMSR pre-commercial activities (Nuclear Street News, 2016);
- 4 M$ (unspecified how), leading to 17.2 M$ received from its inception (Cantech letter, 2016).

Furthermore, in 2016, the US Department of Energy (DOE) invited Terrestrial Energy to submit the second part of its application for a US federal loan guarantee. Terrestrial Energy applied for a loan guarantee of between 800 M$ and 1.2 B$ (World Nuclear News, 2016).

In 2018, Terrestrial Energy received a technology development voucher of 0.5 M$ from the US DOE (DOE, 2018).

4.2.2. MSR-FUJI

MSR-FUJI is a size-flexible (100 MWe–1000 MWe) MSR which uses graphite as moderator and fluoride salt as coolant. It has been developed since the 1980s by a Japanese group (now, International Thorium Molten-Salt Forum: Japanese, Russian and US consortium) based on the ORNL results (IAEA, 2016b; International Thorium Molten-Salt Forum, 2017; WNA, 2018). The developer's website (International Thorium Molten-Salt Forum, 2017) does not provide economic or financial information.

According to (IAEA, 2016b), the typical MSR-FUJI design is 200 MWe and can be considered an SMR (IAEA, 2016b). The estimated construction cost of the 1000 MWe MSR-FUJI is less than $2000/kWe

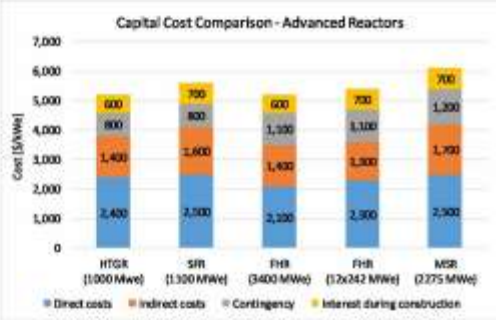


Fig. 5. Capital cost comparison - Advanced reactors - Adapted from (MIT, 2018).

and the total electricity generation cost is about $30/MWh (IAEA, 2016b).

4.2.3. ThorCon MSR

The ThorCon is a 250 MWe scaled-up Oak Ridge MSR Experiment, designed by Martingale in the US, which uses graphite as moderator and a mixture of sodium and beryllium fluoride salts as coolant. Thorcon NPP drawing presents two 250 MWe power modules (ThorCon, 2018). (ThorCon, 2019) reports a capital cost estimation of $800–1000/kWe and an electricity generation cost of $30/MWh for a 500 MWe ThorCon NPP.

ARIS reports the 250 MWe per module (IAEA, 2020b). According to (WNA, 2018), the company claims generation costs of $30–50/MWh (depending on scale).

4.2.4. Moltex Energy's stable salt reactor (SSR)

Moltex Energy's SSRs are modular with a size flexible from 150 MWe to 1200 MWe. Moltex Energy commissioned a cost estimation from Atkins Ltd (nuclear engineering company), which estimated a cost to build a NOAK 1 GWe SSR of $2063/kWe, putting the cost range at $1339-3703/kWe (Energy Economist, 2015). (NEI, 2016c) reports an interview with the Moltex' Energy Chief Operating Officer, stating that the capital cost of 1 GWe SRR is estimated at $1950/kWe and the LCOE at $44.64/MWh.

Regarding its financing, Moltex Energy website (www.moltexenergy.com) provides information about its financing in the period 2018–2020, also providing links to external sources.

Moltex Energy received in 2018:

- a £300k contract by the UK Government in order to develop a feasibility study for SSR deployment in the UK (Moltex Energy, 2018a); and
- 5 M$ of financial support from New Brunswick Energy Solutions Corporation and New Brunswick Power to continue the development of the SSR-Wasteburner technology in New Brunswick (Moltex Energy, 2018b).

In 2019:

- 2.5 M$ from IDOM Consulting, Engineering, Architecture SAU in order to accelerate the SSR pre-licensing progress through Vendor Design Review and expand New Brunswick office (Moltex Energy, 2019a, 2019b);
- around 7.5 M$ through crowdfunding to support the company through the pre-licensing process in Canada and business

development in the UK (around 170 investors contributed nearly half of the amount) (Moltex Energy, 2019c, 2019b; WNN, 2019); and
- 2.55 M$ from the US DOE to develop Composite Structural Technologies for SSRs (Moltex Energy, 2019d).

In 2020:

- an unspecified amount from Canadian Nuclear Laboratories to progress fuel development (Moltex Energy, 2020); and
- 3.5 M$ from the Advanced Research Projects Agency-Energy (i.e. an agency within the US DOE) to advance SSR technology.

4.2.5. The Elysium's molten chloride salt fast reactor (MCSFR)

The Elysium's MCSFR is a size-flexible (50–1200 MWe) MSR which uses Chloride based Fuel Salt as coolant (Elysium Industries, 2017). However, ARIS does not report on this type of MSR (IAEA, 2020b). Regarding MCSFR economics, (Elysium Industries, 2017) provides only a series of characteristics leading to cost implications:

- Simplified engineering systems with a natural technique for passive operation and safety;
- Simplified reactor control system eliminating human operator actions;
- It operates at relatively low pressure determining the reduction of the size and cost of the reactor, vessel and containment buildings with respect to conventional PWR;
- Solid fuel fabrication and validation are eliminated;
- Passive safety system determines the reduction of the cost associated with the emergency coolant injection system;
- It can be fuelled with spent nuclear fuel, partially addressing waste disposal issues.

The reactor presents a higher burnup than thermal water reactors, and the fuel can be reused in the subsequent reactor. In 2018, Elysium Industries received 3.2 M$ from the US DOE to develop the computational fluid dynamics models to simulate and optimise the flows of chloride molten salt fuel in a reactor vessel and heat exchangers (Energy Central, 2018). Furthermore, in 2018, Elysium Industries received 0.5 M $ from the US DOE to foster technology development (Office of Nuclear Energy, 2018).

4.2.6. Transatomic Power's MSR

Transatomic Power (TAP) modified the design of the 1960s Oak Ridge MSR using a zirconium hydride moderator instead of graphite (TAP, 2017). TAP ceased operation in 2018. TAP website reports the main reason: "*we haven't been able to scale up the company rapidly enough to build our reactor in a reasonable timeframe*" (TAP, 2018). TAP intellectual property will be open source (TAP, 2018). The envisaged first commercial NPP was 520 MWe, characterised by an estimated overnight cost for the NOAK of $3846.15/kWe (TAP, 2017). ARIS does not report on the TAP MSR (IAEA, 2020b).

Regarding TAP financing, TPA received 2 B$ from FF Science, an investment vehicle of Founders Fund (i.e. a San Francisco-based venture capital firm) in 2014 (TAP, 2014). In 2015, TPA received 2.5 B$ from Acadia Woods Partners, Peter Thiel's Founders Fund, and Daniel Aegerter of Armada Investment AG (TAP, 2015).

4.3. Overall summary and comparison

Table 5 summarises and compares the main economic information retrieved from the scientific and industrial literature. Data are scaled to $2020 using the CPI (Consumer Price Index) calculator provided by the US Bureau of Labor Statistics (US Bureau of Labor Statistics, 2020). When the reference year was not provided in the retrieved literature, the publication date was used as the reference year. Fig. 6 provides a general summary of the quantitative economic information about MSR LCOE, OC and Capital cost.

Table 5
Comparison and adjustment for inflation ($2020).

MSR data	LCOE [$/MWh]	Overnight cost [$/kWe]	Capital cost [$/kWe]	Sources
1000 MWe 20% enriched capacity factor (CP) 95%	55.78			Moir (2002)
1000 MWe 20% enriched CP 90%	58.69			Moir (2008)
1000 MWe 100% enriched, CP 90%	47.83			Moir (2008)
IMSR600 (291 MWe)	48.71	3146		Samalova et al. (2017)
IMSR300 (141 MWe)	60.25	4105		Samalova et al. (2017)
IMSR80 (32.5 MWe)	139.14	10,115		Samalova et al. (2017)
Size not specified (SNP)	49.23-134.33			Richards et al. (2017)
ORNL 1000 MWe	119.25	5913	6741	MIT (2018)
Terrestrial Energy (TE) IMSRs (SNP)	<53.12[a]			Terrestrial Energy (2017a)
TE IMSR 300 MWe	43.55[b]-54.44			NEI (2016a)
TE IMSR600 (291 MWe)	47.46[b]			Terrestrial Energy (2015)
TE IMSR300 (141 MWe)	65.13[b]			Terrestrial Energy (2015)
1000 MWe MSR-FUJI	32.67[c]	2,177[d]		IAEA (2016b)
ThorCon (500 MWe)	30.75[e]		819.89-1024	ThorCon (2019)
ThorCon MSR (SNP)	31.22-52.04[f]			WNA (2018)
1 GWe Moltex Energy' SSR		2299		Energy Economist (2015)
1 GWe Moltex Energy' SSR			1478-4087	Energy Economist (2015)
1 GWe Moltex Energy' SSR	48.61		2123	NEI (2016c)
TAP 520 MWe		4085		TAP (2017)

[a] According to (Terrestrial Energy, 2017a), IMSRs can dispatch power under 53.12 $/MWh ($2020).
[b] These values are defined as "levelised cost" (NEI, 2016a; Terrestrial Energy, 2015).
[c] (IAEA, 2016b) defines it "total electricity generation cost".
[d] (IAEA, 2016b) defines it as "construction cost".
[e] (ThorCon, 2019) defines it as "electricity generation cost".
[f] (WNA, 2018) defines the range as "generation cost".

5. What we should know: a research agenda

In this section, the authors present the key areas that need further investigation, suggesting a research agenda.

5.1. Economics

Licensing cost and time. The process of licensing a nuclear design

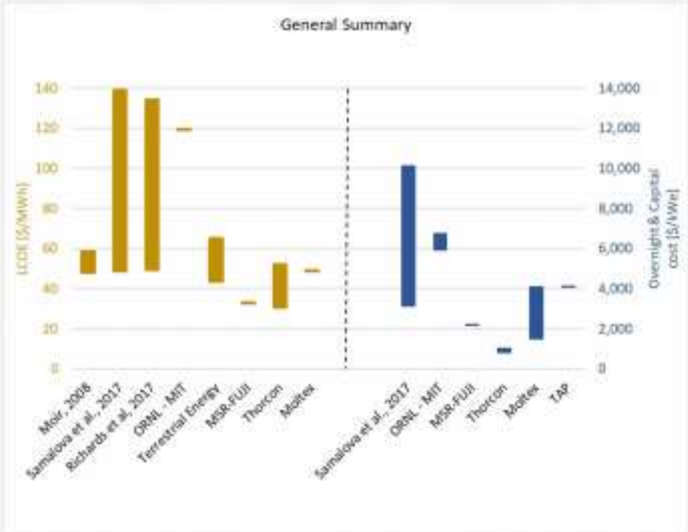


Fig. 6. General summary LCOE, Overnight and Capital cost ($2020).

is, particularly in the US and Europe, a lengthy and expensive process. Even for "classical PWR" the duration and cost are extremely relevant [e. g. 10 years for the AP1000 design to complete the UK regulatory assessment (Office for Nuclear Regulation, 2017a, 2017b)]. The more the NPP deviates from the "classical PWR" design, the longer and more expensive the licensing process is expected to be. For instance, the NuScale SMR design started the US NRC (Nuclear Regulatory Commission) pre-application process in 2008 (NuScale, 2020) and, at the time of writing, it has completed Phase 4 out of the 6 phases of the NRC's design review certification (World Nuclear News, 2019). In Canada, relatively few MSRs are completing pre-licensing vendor design reviews (Canadian Nuclear Safety Commission, 2020). Consequently, particularly for GEN IV reactors, there are a number of challenges across the licensing journey (Sainati et al., 2015). Therefore, more information about the process, cost, financing, time and risk involved in the licensing process would be useful.

Construction and operations – Reference plant. MSR proposed outlet temperatures are in the range of 700 °C – 850 °C. Long-term operation above 650 °C determines material challenges related, for instance, to the corrosiveness of fuel salt (MIT, 2018), which could determine the need for unproven and potentially expensive materials increasing the cost of the main components. Furthermore, the peculiar characteristics of MSRs can impact on O&M costs. For instance, in the case of MSRs using fluoride salt as coolant, lithium in the salt produces tritium which will permeate through hot structures requiring workers to use respirators to perform O&M (MIT, 2018). It is often unclear if these and other aspects (e.g. O&M activities during the circulation of dissolved fuel or long-term corrosion increasing the frequency of replacement components) are considered in the economic analysis. Furthermore, most of the analyses refer to very old documents (e.g. (Engel et al., 1980, 1978)) with limited information and potentially controversial assumptions. However, the lack of data determines the need for controversial assumptions in economic analyses. Building a prototype (even of few megawatts) could lead to additional insights, generating new data and thereby creating opportunities to carry out more reliable economic analyses and foster MSR commercial operation.

Fuel - Waste management and decommissioning cost. This is a relevant point since MSRs could help to deal with the waste from traditional LWRs (considering that MSRs can be designed as nuclear waste burners or breeders), but at the same time, even these reactors produce waste (although less high-level waste) (IAEA, 2020a). Moreover, unlike LWRs, the fuel used by MSRs is not a standard "industrial product" with several suppliers. Research is needed across the entire fuel cycle. This implies that the economics of the fuel cycle needs to be investigated considering both costs and, eventually, revenues. Similarly, the economics of decommissioning, already uncertain for LWRs (Invernizzi et al., 2017, 2019b; 2019a, 2020a), need substantial research for MSRs. (Mignacca et al., 2020b) introduce the Modular Circular Economy strategy to improve decommissioning in the general case of energy infrastructure, and (Mignacca et al., 2020a) discusses this strategy in the specific case of SMRs. According to (Mignacca et al., 2020a), SMR modules could be designed in a way that when the SMR plant reaches the end of life modules having still useful life can be reused in other plants. The implementation of this strategy has an impact on economics and finance, and it should be considered in future MSR SMR cost estimations and financial analyses.

5.2. *Financing*

Basis for estimate/third party assessment. As aforementioned, in several references (particularly industrial), the basis for the estimate are unclear. It is often unclear how the costs have been calculated (e.g. how the cost of the turbine has been established) and what has been included/excluded (e.g. owner costs, detailed design). A further research area would therefore be to develop a third-party assessment and standardisation of the cost estimation methods, thereby adding transparency and credibility to the estimates. Adding transparency and credibility to the estimates of both costs and revenues could attract investors. Similarly, a risk analysis is necessary to identify the key cost drivers, their magnitude and uncertainty.

Financing. Financing deals with questions such as "who is providing the money to build the reactor?", "Who is accepting the risk of cost escalation and will provide the money to cover extra-cost?". Most of the retrieved documents focus on MSR economics. The scientific literature neglects MSR financing, and information in the industrial literature is far from comprehensive about who is financing MSR technology development, i.e. mostly governments (e.g. US DOE) and private investors (e.g. Moltex crowdfunding). The financing of the next MSR development stages (e.g. financing NOAK MSRs) is not receiving the necessary attention. This is a common issue for the new advanced nuclear reactors where, in general, publications are scant (Boarin et al., 2012; EFWG, 2018; Mignacca and Locatelli, 2020; Sainati et al., 2020, 2019). Governments across the world are setting up task-forces to address these questions. The studies are often confidential with few exceptions, one being the work done in the UK (EFWG, 2018). Particularly relevant will be distinguishing the financing of the FOAK unit (a very high-risk investment) from the financing of the NOAK unit (where the risk has been reduced by the experience) (Locatelli and Mancini, 2012b).

Furthermore, the retrieved academic and industrial documents point out how the current literature focuses on LCOE (indicator relevant mostly for policy-makers), neglecting indicators of financial performance such NPV and IRR, which are relevant for utility companies (and investors in general) to measure the profitability and risk of the MSR investment. Further studies focusing on other indicators of economic and financial performance are needed.

Revenues. (MIT, 2018) point outs several other potential applications other than electricity production for MSRs, i.e. process heat for producing hydrogen, synfuels and other chemicals, and actinide transmutation for fast MSRs. These applications might ideally be combined with load-following (Locatelli et al., 2018, 2017), enabling potential revenues, which need to be carefully estimated in future economic and financial analyses.

6. Conclusions

MSRs are one of the six GEN IV technologies presented in (GIF, 2014, 2002), and as such share the economic goal of having *"a life cycle cost advantage over other energy sources"* (GIF/EMWG, 2007) (Page 9). If MSRs are potentially a relevant technology for the middle/long term, then the available knowledge about economics and finance of MSRs is very limited, fragmented and in need of further investigation. This paper provides a structured summary of the knowledge about "economics and finance" of MSRs, following two main streams: scientific and industrial literature.

Regarding the scientific literature, only four papers are strictly related to the research objective, focusing on MSR economics whilst neglecting their financing. (Moir, 2008, 2002) point out that a 1000 MWe MSR is characterised by an expected LCOE lower than an equal size PWR and an equal size coal plant. The analysis carried out by (Samalova et al., 2017) points out how the IMSR cost structure is expected to be similar to the PWR one. Generally, MSRs might not need a thick containment unit like LWRs and are characterised by higher temperature determining an increased thermal efficiency. These two characteristics are the main factors determining an expected lower capital cost than LWRs (Moir, 2008; Richards et al., 2017). Manufacturers estimate an overnight cost between $2000/kWe and $4000/kWe for a NOAK MSR (Richards et al., 2017).

Regarding the industrial literature, this paper provides a brief introduction to several MSR designs, followed by economic and financial information. MSR designs have been selected according to the availability of economic and financial information. The results of the industrial literature review analysis show that there are very few economic and financial studies about MSRs, and in most cases, they are provided by reactor vendors with evident conflict of interest. The financing of MSR technology development is met by governments (e.g. US DOE) and private investors (e.g. Moltex crowdfunding). However, the financing of the next stages (e.g. financing NOAK MSR) is not receiving enough attention yet.

In summary, the key takeaways from this paper about the economics and finance of MSRs are:

- There is very limited information on economics and finance. Particularly in the scientific literature where information is very scarce and focuses on MSR economics. The information about MSR economics and finance provided by vendor websites and other external sources (i.e. IAEA) is also fragmented. In general, indicators of financial performance (e.g. NPV, IRR, and LACE) are neglected from both scientific and industrial literature.
- The low quality of the information. The literature does not use a standard method to assess economics and finance, limiting the reliability of the comparison and hindering a critical and in-depth analysis of the data.
- MSRs have a cost breakdown structure similar to LWRs. As shown in Fig. 2, MSRs will be capital intensive.
- There are several gaps in knowledge, as highlighted in Section 5. MSR decommissioning cost and MSR financing represent huge gaps in the literature.
- MSR competitiveness. Based on the literature, MSRs are expected to be cost-competitive with other energy sources. However, further studies are needed.

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.

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 very grateful to the ESPRC and MPA. The authors also wish to thank Mr Ata Babaei, Dr Marco Colombo and Dr Kate Lawrence, who provided substantial feedback. 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.

References

Black, G., Black, M.A.T., Solan, D., Shropshire, D., 2015. Carbon free energy development and the role of small modular reactors: a review and decision framework for deployment in developing countries. Renew. Sustain. Energy Rev. 43, 83–94. https://doi.org/10.1016/j.rser.2014.11.011.

Boarin, S., Locatelli, G., Mancini, M., Ricotti, M.E., 2012. Financial case studies on small- and medium-size modular reactors. Nucl. Technol. 178, 218–232.

Boldon, L., Sabharwall, P., Painter, C., Liu, L., 2014. An overview of small modular reactors: status of global development, potential design advantages, and methods for economic assessment. Int. J. Energy Environ. Econ. 22, 437–459.

Cantech letter, 2016. Terrestrial Energy Surpasses $20 Million Financing in Advance of UN Forum. https://www.cantechletter.com/2016/09/terrestrial-energy-surpasses-20-million-financing-advance-un-forum/ (accessed 6.13.20).

Carelli, M.D., Ingersoll, D.T., 2014. Handbook of Small Modular Nuclear Reactors. Woodhead Publishing, Elsevier. https://doi.org/10.1533/9780857098535.2.149.

Carelli, M.D., Locatelli, G., Mycoff, C.W., Garrone, P., Mancini, M., Ricotti, M.E., Trianni, A., Trucco, P., 2008. Competitiveness of small-medium, new generation reactors: a comparative study on capital and O&M costs. In: 16th International Conference on Nuclear Engineering. ASME, Orlando, Florida, USA, May 11–15, 2008, pp. 1–8. https://doi.org/10.1115/1.4000613.

Carelli, M.D., Petrovic, B., Mycoff, C.W., 2007. Economic comparison of different size nuclear reactors. In: Simposio LAS/ANS 2007/2007 LAS/ANS Symposium. Cancun, Quintana Roo, MEXICO, July 1-5, 2007, pp. 653–662.

Canadian Nuclear Safety Commission, 2020. Pre-Licensing Vendor Design Review. https://nuclearsafety.gc.ca/eng/reactors/power-plants/pre-licensing-vendor-design-review/index.cfm?pedisable=true (accessed 6.13.20).

Di Maddaloni, F., Davis, K., 2017. The influence of local community stakeholders in megaprojects: rethinking their inclusiveness to improve project performance. Int. J. Proj. Manag. 35, 1537–1556. https://doi.org/10.1016/j.ijproman.2017.08.011.

DOE, 2018. Secretary of Energy Rick Perry Announces $60 Million for U.S. Industry Awards in Support of Advanced Nuclear Technology Development [WWW

Document]. https://www.energy.gov/articles/secretary-energy-rick-perry-announces-60-million-us-industry-awards-support-advanced (accessed 6.13.20).
EFWG, 2018. Market Framework for Financing Small Nuclear.
Ehrhardt, R., 2011. Financial Management: Theory and Practice, thirteenth ed. South-Western Cengage Learning.
EIA, 2019. Levelized cost and levelized avoided cost of new generation resources. Ann. Energy Outlook, 2019.
EIA, 2015. Levelized cost comparisons help explain value of various electric generation technologies - today in Energy - U.S. Energy Information Administration (EIA). https://www.eia.gov/todayinenergy/detail.php?id=21492 (accessed 6.22.20).
Elysium Industries, 2017. The Molten Chloride Salt Fast Reactor. http://www.elysiumindustries.com/technology (accessed 6.13.20).
Energy Central, 2018. DOE Awards $60M for Advanced Nuclear Energy R&D. https://energycentral.com/c/ec/doe-awards-60m-advanced-nuclear-energy-rd (accessed 6.14.20).
Energy Economist, 2015. The SMR a new path for nuclear energy?.
Engel, J.R., Grimes, W.R., Bauman, H.F., McCoy, E.H., Dearing, J.F., Rhoades, W.A., 1980. Conceptual Design Characteristics of a Denatured Molten-Salt Reactor with Once-Through Fueling.
Engel, J.R., Grimes, W.R., Rhoades, W.A., Dearing, J.F., 1978. Molten-Salt Reactors for Efficient Nuclear Fuel Utilization without Plutonium Separation.
EY, 2016. Small Modular Reactors - Can Building Nuclear Power Become More Cost-Effective?.
GIF/EMWG, 2007. Cost Estimating Guidelines for Generation IV Nuclear Energy Systems.
GIF, 2014. Technology Roadmap Update for Generation IV Nuclear Energy Systems.
GIF, 2002. A Technology Roadmap for Generation IV Nuclear Energy System.
IAEA, 2020a. Molten Salt Reactors. https://www.iaea.org/topics/molten-salt-reactors (accessed 6.14.20).
IAEA, 2020b. Advanced Reactors Information System (ARIS). https://aris.iaea.org/ (accessed 6.13.20).
IAEA, 2019. Nuclear Power Reactors in the World.
IAEA, 2018. Economic Assessment of the Long Term Operation of Nuclear Power Plants: Approaches and Experience.
IAEA, 2016a. Status Report - IMSR 400.
IAEA, 2016b. Status Report - MSR-FUJI.
IAEA, 2013. Cost Estimation for Research Reactor Decommissioning.
IAEA, 2006. IAEA Safety Glossary.
IAEA, 2005. Country Nuclear Power Profiles 2004 Edition.
International Thorium Molten-Salt Forum, 2017. International Thorium Molten-Salt Forum.
Invernizzi, D.C., Locatelli, G., Brookes, N.J., 2020a. Characterising nuclear decommissioning projects: an investigation of the project characteristics that affect the project performance. Construct. Manag. Econ. 1–17. https://doi.org/10.1080/01446193.2020.1775859.
Invernizzi, D.C., Locatelli, G., Brookes, N.J., 2019a. An exploration of the relationship between nuclear decommissioning projects characteristics and cost performance. Prog. Nucl. Energy 110, 129–141. https://doi.org/10.1016/j.pnucene.2018.09.011.
Invernizzi, D.C., Locatelli, G., Brookes, N.J., 2017. How benchmarking can support the selection, planning and delivery of nuclear decommissioning projects. Prog. Nucl. Energy 99, 155–164. https://doi.org/10.1016/j.pnucene.2017.05.002.
Invernizzi, D.C., Locatelli, G., Grönqvist, M., Brookes, N.J., 2019b. Applying value management when it seems that there is no value to be managed: the case of nuclear decommissioning. Int. J. Proj. Manag. 37, 668–683. https://doi.org/10.1016/j.ijproman.2019.01.004.
Invernizzi, D.C., Locatelli, G., Velenturf, A., Love, P.E., Purnell, P., Brookes, N.J., 2020b. Developing policies for the end-of-life of energy infrastructure: coming to terms with the challenges of decommissioning. Energy Pol. 144, 111677. https://doi.org/10.1016/j.enpol.2020.111677.
Investopedia, 2019a. Understanding Microeconomics vs. Macroeconomics.
Investopedia, 2019b. Net Present Value (NPV).
Investopedia, 2019c. Internal Rate of Return (IRR) Definition.
Locatelli, G., 2018. Why Are Megaprojects, Including Nuclear Power Plants, Delivered Overbudget and Late? Reasons and Remedies - Report MIT-ANP-TR-172, Center for Advanced Nuclear Energy Systems (CANES). Massachusetts Institute of Technology.
Locatelli, G., 2017. Fusion: go small to go fast. In: 25th International Conference on Nuclear Engineering, ICONE 2017; Shanghai; China; 2 July 2017 through 6 July 2017; Code 131175. American Society of Mechanical Engineers (ASME).
Locatelli, G., Bingham, C., Mancini, M., 2014. Small modular reactors: a comprehensive overview of their economics and strategic aspects. Prog. Nucl. Energy 73, 75–85.
Locatelli, G., Boarin, S., Fiordaliso, A., Ricotti, M.E., 2018. Load following of Small Modular Reactors (SMR) by cogeneration of hydrogen: a techno-economic analysis. Energy 148, 494–505. https://doi.org/10.1016/j.energy.2018.01.041.
Locatelli, G., Fiordaliso, A., Boarin, S., Ricotti, M.E., 2017. Cogeneration: an option to facilitate load following in Small Modular Reactors. Prog. Nucl. Energy 97, 153–161.
Locatelli, G., Mancini, M., 2012a. A framework for the selection of the right nuclear power plant. Int. J. Prod. Res. 50, 4753–4766. https://doi.org/10.1080/00207543.2012.657965.
Locatelli, G., Mancini, M., 2012b. Looking back to see the future: building nuclear power plants in Europe. Construct. Manag. Econ.
Locatelli, G., Mancini, M., 2011. Large and small baseload power plants: drivers to define the optimal portfolios. Energy Pol. 39, 7762–7775. https://doi.org/10.1016/j.enpol.2011.09.022.
Locatelli, G., Mancini, M., 2010. Competitiveness of small-medium, new generation reactors: a comparative study on decommissioning. J. Eng. Gas Turbines Power 132.
Macpherson, H.G., 1985. The molten salt reactor adventure. Nucl. Sci. Eng. 90, 374–380.
Maronati, G., Petrovic, B., Wyk, J.J. Van, Kelley, M.H., White, C.C., 2017. EVAL: a methodological approach to identify NPP total capital investment cost drivers and sensitivities. Prog. Nucl. Energy 104, 190–202. https://doi.org/10.1016/j.pnucene.2017.09.014.
Mignacca, B., Alawneh, M., Locatelli, G., Invernizzi, D.C., 2018. We never built small modular reactors (SMRs), but what do we know about modularization in construction?. In: International Conference on Nuclear Engineering, Proceedings, ICONE. https://doi.org/10.1115/ICONE26-81604.
Mignacca, B., Alawneh, A.H., Locatelli, G., 2019. Transportation of small modular reactor modules: what do the experts say?. In: International Conference on Nuclear Engineering, Proceedings, ICONE.
Mignacca, B., Locatelli, G., 2020. Economics and finance of Small Modular Reactors : a systematic review and research agenda. Renew. Sustain. Energy Rev. 118, 109519. https://doi.org/10.1016/j.rser.2019.109519.
Mignacca, B., Locatelli, G., Sainati, T., 2020a. Deeds not words: barriers and remedies for small modular nuclear reactors. Energy. https://doi.org/10.1016/j.energy.2020.118137, 118137.
Mignacca, B., Locatelli, G., Velenturf, A., 2020b. Modularisation as enabler of circular economy in energy infrastructure. Energy Pol. 139 https://doi.org/10.1016/j.enpol.2020.111371.
MIT, 2018. The Future of Nuclear Energy in a Carbon Constrained World.
Moir, R.W., 2008. Recommendations for a restart of molten salt reactor development. Energy Convers. Manag. 49, 1849–1858. https://doi.org/10.1016/j.enconman.2007.07.047.
Moir, R.W., 2002. Cost of electricity from molten salt reactors. Nucl. Technol. 138, 93–95. https://doi.org/10.13182/NT02-A3281.
Moltex Energy, 2020. Moltex Receives Funding from Canadian Nuclear Laboratories to Progress Fuel Development. https://www.moltexenergy.com/news/details.aspx?positionId=139 (accessed 6.14.20).
Moltex Energy, 2019a. Moltex Energy Secures Multi-Million Dollar Funding from Leading Global Consulting Firm IDOM. https://www.moltexenergy.com/news/details.aspx?positionId=115 (accessed 6.13.20).
Moltex Energy, 2019b. Moltex Energy Is Crowd Funding. https://www.moltexenergy.com/news/details.aspx?positionId=118 (accessed 6.13.20).
Moltex Energy, 2019c. Moltex: Crowd Funding Success!. https://www.moltexenergy.com/news/details.aspx?positionId=124 (accessed 6.13.20).
Moltex Energy, 2019d. US Department of Energy Awards $2.55m Grant to Moltex Energy. https://www.moltexenergy.com/news/details.aspx?positionId=122 (accessed 6.13.20).
Moltex Energy, 2018a. Moltex Successful in the UK Government £300k Advanced Modular Reactors Competition. https://www.moltexenergy.com/news/details.aspx?positionId=105 (accessed 6.13.20).
Moltex Energy, 2018b. Moltex Energy Signs Agreement for First Deployment of its SSR-W Nuclear Reactor in New Brunswick. https://www.moltexenergy.com/news/details.aspx?positionId=106 (accessed 6.13.20).
NEA, 1994. The Economics of the Nuclear Fuel Cycle.
NEI, 2016a. Terrestrial CEO: Plant Costs of $40-$50/MWh Set to Displace Fossil Fuels. https://analysis.nuclearenergyinsider.com/terrestrial-ceo-plant-costs-40-50mwh-set-displace-fossil-fuels (accessed 6.14.20).
NEI, 2016b. Canada Edges Closer to SMR Build after VC Funding Deal. https://analysis.nuclearenergyinsider.com/canada-edges-closer-smr-build-after-vc-funding-deal (accessed 6.14.20).
NEI, 2016c. Moltex Energy Sees UK, Canada SMR Licensing as Springboard to Asia | Nuclear Energy Insider. https://analysis.nuclearenergyinsider.com/moltex-energy-sees-uk-canada-smr-licensing-springboard-asia (accessed 6.13.20).
Nuclear Street News, 2016. Terrestrial Energy, General Fusion, Among Canada's Grant Recipients. https://nuclearstreet.com/nuclear_power_industry_news/b/nuclear_power_news/archive/2016/03/10/terrestrial-energy_2c00_-general-fusion_2c00_-among-canada_2700_s-grant-recipients-031002#.XvCnH7X0nDk (accessed 6.14.20).
NuScale, 2020. Licensing | NuScale Power.
Oak Ridge National Laboratory, 2010. An Account of Oak Ridge National Laboratory's Thirteen Nuclear Reactors.
OECD/NEA, 2011. Current Status, Technical Feasibility and Economics of Small Nuclear Reactors.
Office for Nuclear Regulation, 2017a. Design Acceptance Confirmation for the AP1000® Reactor.
Office for Nuclear Regulation, 2017b. New Nuclear Reactors: Generic Design Assessment.
Office of Nuclear Energy, 2018. U.S. Advanced Nuclear Technology Projects to Receive $18 Million from the. U.S. Department of Energy. https://www.energy.gov/ne/articles/us-advanced-nuclear-technology-projects-receive-18-million-us-department-energy (accessed 6.14.20).
Richards, J., Sabharwall, P., Memmott, M., 2017. Economic comparison of current electricity generating technologies and advanced nuclear options. Electr. J. 30, 73–79. https://doi.org/10.1016/j.tej.2017.11.005.
Sainati, T., Locatelli, G., Brookes, N., 2017. Special Purpose Entities in Megaprojects: empty boxes or real companies? Proj. Manag. J. 48.
Sainati, T., Locatelli, G., Brookes, N., 2015. Small modular reactors: licensing constraints and the way forward. Energy. https://doi.org/10.1016/j.energy.2014.12.079.
Sainati, T., Locatelli, G., Smith, N., 2019. Project financing in nuclear new build, why not? The legal and regulatory barriers. Energy Pol. 129, 111–119. https://doi.org/10.1016/j.enpol.2019.01.068.
Sainati, T., Locatelli, G., Smith, N., Brookes, N., Olver, G., 2020. Types and functions of special purpose vehicles in infrastructure megaprojects. Int. J. Proj. Manag. 38, 243–255. https://doi.org/10.1016/j.ijproman.2020.05.002.

Samalova, L., Chvala, O., Maldonado, G.I., 2017. Comparative economic analysis of the Integral Molten Salt Reactor and an advanced PWR using the G4-ECONS methodology. Ann. Nucl. Energy 99, 258–265. https://doi.org/10.1016/j.anucene.2016.09.001.
Saraf, N., Devarajan, A., Mohanti, S.S., Rao, G., Dalal, V., Sr, P., 2018. Molten Salt Reactor and their development over the years - a review. Int. J. Mech. Prod. Eng. Res. Dev. 8, 175–182.
Serp, J., Allibert, M., Beneš, O., Delpech, S., Feynberg, O., Ghetta, V., Heuer, D., Holcomb, D., Ignatiev, V., Kloosterman, J.L., Luzzi, L., Merle-Lucotte, E., Uhlíř, J., Yoshioka, R., Zhimin, D., 2014. The molten salt reactor (MSR) in generation IV: overview and perspectives. Prog. Nucl. Energy 77, 308–319. https://doi.org/10.1016/j.pnucene.2014.02.014.
Sovacool, D., 2019. Nuclear Power: Politics, Practices, and the Future. Scrivener Publishing - Wiley.
TAP, 2018. Open Source. http://www.transatomicpower.com/open-source/ (accessed 6.15.20).
TAP, 2017. The Science. http://www.transatomicpower.com/the-science/ (accessed 6.15.20).
TAP, 2015. Transatomic Power Raises Additional $2.5 Million in Oversubscribed Round.
TAP, 2014. FF Science Invests $2 Million to Support Transatomic Power's Breakthrough Nuclear Reactor.
Terrestrial Energy, 2017a. How it Works. https://www.terrestrialenergy.com/technology/molten-salt-reactor/ (accessed 6.15.20).
Terrestrial Energy, 2017b. Cost Competitive. https://www.terrestrialenergy.com/technology/competitive/ (accessed 6.15.20).
Terrestrial Energy, 2015. Submission to the South Australian Nuclear Fuel Cycle Royal Commission.
ThorCon, 2019. Economics – ThorCon. http://thorconpower.com/economics/ (accessed 6.16.20).
ThorCon, 2018. The Do Able Molten Salt Reactor.
Trendowicz, A., Jeffery, R., 2014. Software Project Effort Estimation, pp. 125–152. https://doi.org/10.1007/978-3-319-03629-8.
US Bureau of Labor Statistics, 2020. CPI Inflation Calculator [WWW Document].
UxC Consulting, 2013. SMR Market Outlook.
Wang, C., Liu, M., Zhang, D., Qiu, S., Su, G.H., Tian, W., 2020. Experimental study on transient performance of heat pipe-cooled passive residual heat removal system of a molten salt reactor. Prog. Nucl. Energy. https://doi.org/10.1016/j.pnucene.2019.103113.
WNA, 2018. Molten Salt Reactors - World Nuclear Association [WWW Document]. https://www.world-nuclear.org/information-library/current-and-future-generation/molten-salt-reactors.aspx (accessed 6.10.20).
WNN, 2019. Moltex Energy Raises USD7.5 Million through Crowdfunding : Corporate - World Nuclear News. https://www.world-nuclear-news.org/Articles/Moltex-Energy-raises-USD7-5-million-through-crowdf (accessed 6.15.20).
Wooten, D., Fratoni, M., 2020. Linear optimization for predicting material compositions in molten salt reactors. Ann. Nucl. Energy 139, 107159. https://doi.org/10.1016/j.anucene.2019.107159.
World Nuclear Association, 2008. The Economics of Nuclear Power.
World Nuclear News, 2019. SMR Design Review Enters Final Phases. https://www.world-nuclear-news.org/Articles/SMR-design-review-enters-final-phases (accessed 6.10.20).
World Nuclear News, 2016. Terrestrial Energy to Complete US Loan Guarantee Application. https://www.world-nuclear-news.org/NN-Terrestrial-Energy-to-complete-US-loan-guarantee-application-1409167.html (accessed 6.14.20).
Zeng, W., Jiang, Q., Xie, J., Yu, T., 2020. Core outlet fuel temperature control of liquid molten salt reactor during load following operation. Prog. Nucl. Energy 121, 103214. https://doi.org/10.1016/j.pnucene.2019.103214.
Zheng, G., Wu, H., Wang, J., Chen, S., Zhang, Y., 2018. Thorium-based molten salt SMR as the nuclear technology pathway from a market-oriented perspective. Ann. Nucl. Energy 177–186.
Zhou, J., Chen, J., Wu, J., Xia, S., Zou, C., 2020. Influence of 7Li enrichment on Th-U fuel breeding performance for molten salt reactors under different neutron spectra. Prog. Nucl. Energy 120. https://doi.org/10.1016/j.pnucene.2019.103213.
Zhuang, K., Li, T., Zhang, Q., He, Q., Zhang, T., 2020. Extended development of a Monte Carlo code OpenMC for fuel cycle simulation of molten salt reactor. Prog. Nucl. Energy. https://doi.org/10.1016/j.pnucene.2019.103115.

D.5 Publication IX

Locatelli, G., Sainati, T., Mignacca, B., 2021. Developing UK strategy for nuclear SMRs. Brief 6, Policy Leeds, University of Leeds.

Policy Leeds

UNIVERSITY OF LEEDS

Developing UK strategy for nuclear SMRs

Brief No.6
06 Jan 2021

Policy Leeds
University of Leeds
leeds.ac.uk/policyleeds

Giorgio Locatelli, Tristano Sainati, Benito Mignacca

Nuclear Small Modular Reactors (SMRs) can play a role in UK decarbonisation, providing low-carbon electricity and heat. SMR investments are more affordable and less risky, therefore attracting a wider range of potential investors. The UK government needs to develop a consistent strategy to support UK SMRs.

Overview

- **Compared to large nuclear reactors, Small Modular Reactors (SMRs) could be cheaper, easier to finance and a less risky investment.**
- **However, our research suggests that novelty, construction cost risk, regulations, and long term economic uncertainty can be key barriers for SMR construction.**
- **We recommend the UK government develop short to medium term policy and regulation to support the development, licensing and construction of the first SMRs with substantial investment. A long-term policy should support market mechanisms to build and operate a fleet of standardised SMRs in the UK.**

In order to meet climate change commitments, the UK energy sector needs to decarbonise. Nuclear energy is a low-carbon energy source that can alter its output to match demand, as well as providing heat for non-electricity energy needs, potentially playing a valuable role in decarbonisation.

Multibillion megaprojects are financially risky investments, historically often delivered over-budget and late. Traditional large nuclear reactors megaprojects are not an exception, as recently seen in the EU and USA (Locatelli, 2018), leading to significantly higher cost of financing, and thus higher cost of electricity. Decreasing the size of investment (e.g. building SMRs) is a strategy to reduce the investment risk and cost of financing, so nuclear energy is more financially sustainable.

The Government has indicated their commitment to nuclear energy in their **ten point plan for a green industrial revolution**. This has been supported by an announcement in the **2020 spending review of investment of £525 million**

Developing UK strategy for nuclear SMRs — Page 1

for nuclear energy projects, including small modular reactors and next generation advanced modular reactors.

It is important the UK Government clarifies its strategy for future deployment of SMRs. It must decide whether to support their development, which will largely determine if the UK will be an importer or exporter of SMRs. If the Government decides to support domestic reactor vendors, decisive and timely actions are required. This could include laying the foundations for the early deployment of SMRs in the UK to gain credibility in the international market. A UK position of 'first mover advantage' is possible and an essential aspect to gain shares of the SMR market globally.

The case for nuclear power

In June 2019, the UK Parliament approved legislation to reduce carbon emissions to net-zero by 2050. Progress since 1990 has been good with greenhouse emissions reduced by in excess of 43% (BEIS, 2020). However, since the UK started with a high carbon base (e.g. coal), decarbonising the next 40% might be harder than the previous 40%. As of 2018 the biggest source of greenhouse gas emissions is transport (28%) but decarbonising by electrifying transport, will further increase the demand for electricity.

Net-zero carbon electricity can be produced both by renewable resources (e.g. wind, solar, hydropower) and nuclear power plants. These technologies have unique qualities and therefore combinations of all of them may be needed on the power network. Wind and solar plants are becoming cheaper to construct and operate, but depend on primary sources that are intermittent, and uncorrelated to the need of electricity. For the proper operation of the electrical grid and the systems connected, the production of electricity needs to match the demand very closely. Today, the variability of renewables is mostly compensated by gas plants. However, the increasing share of electricity generated by renewables, and the phase out of coal and gas, will require more elaborate and expensive solutions, including energy storage and demand management.

Renewables are cost-competitive in terms of pure "generation cost" (usually measured as Levelised Cost of Electricity) but they need also backup costs (e.g. the cost to provide electricity when power plants are not working), balancing costs (e.g. reserves to ensure system stability) and possibly storage cost (e.g. hydrogen or batteries). In the UK, with scarce hydroelectric resources, nuclear power plants are the only available technology that can produce net-zero carbon electricity "on demand", with lower backup and balancing cost with respect to renewable plants. As today, nuclear power produces about one quarter of UK electricity, however all but one of these power stations will close by 2030.

What are SMRs

The International Atomic Energy Agency (IAEA) defines SMRs as "*newer generation reactors designed to generate electric power typically 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*" (IAEA, 2020). SMRs are a family of technologies and design philosophies. SMRs include water cooled reactors, which account for the vast majority of reactors in operation and under construction. This technology is well understood and the necessary elements (e.g. the nuclear fuel cycle) exist or require relatively little technological development. Still, there are no SMR designs certified for UK deployment and the designs require detailed engineering and development. It is unlikely that any of these designs will be in a position to produce electricity in the UK before 2030 unless substantial investments and political commitments are made. Other technologies (e.g. molten salt) have technical advantages, but far less construction and operating experience. They might require substantial R&D and may not be deployable until after 2030 (Locatelli et al., 2013; Mignacca and Locatelli, 2020a).

The case for SMRs

Large reactors, like Hinkley Point C in the UK, incorporate the technological lessons learned from over the last 60 years. Due to their size, they require massive multibillion investments and long construction times (a decade is common), leaving them prone to large budget over-runs and delays in construction (Locatelli, 2018). Consequently stakeholders are extremely cautious about investing. In the UK, in the last 15-20 years, several nuclear plants have been proposed, but only Hinkley Point C has started construction.

The challenge of delivering megaprojects is not limited to nuclear power plants. The majority of megaprojects are affected by cost overruns and delays in planning and construction, as the vast literature on this shows (Locatelli, 2018). In this regards, cost escalation is common for long-planned, multi-billion pounds, one-of-a-kind infrastructure projects. The literature, supported by several empirical studies, shows that the larger the project, the greater is the likelihood and magnitude of cost overrun and experience of a delay. The uniqueness in design and investment size are the critical drivers and predictors for likelihood and magnitude of cost overrun and delay of construction projects.

SMRs are designed to be small and standardised so that they can be largely manufactured in series in factories, which is less exposed to external factors such as the weather resulting in poor productivity as characterised by megaproject construction sites (Mignacca and Locatelli, 2020b). The smaller size means the financial cost and risk are significantly reduced compared to traditional nuclear plants because the investment required for an SMR is a correspondingly small. SMR construction time is shorter, allowing for earlier revenues which increase investor confidence, which further lower the financial cost and risk. Lower financial cost and risk make investments in nuclear more sustainable and more able to attract private investors. Private investors need a degree of certainty, therefore are unlikely to finance the first SMR units, but could support the financing of a subsequent SMR fleet. SMRs are ideal for co-generation of electricity and heat particularly if built close to cities or industrial parks (Locatelli et al., 2018).

Barriers to SMR deployment

For the past 20 years there has been an interest in SMRs for electricity and heat. The latest IAEA report (IAEA, 2020) identifies 72 reactor designs, developed in 18 countries, at

Policy Leeds

various stages of development; however, only 2 units are in operation, and the vast majority still at the design stage. We identified the main elements hindering SMR construction by collecting opinions from around 100 nuclear experts (Mignacca et al., 2020).

Financing of the first unit(s): Although SMRs are a less risky investment in terms of value, compared to larger reactors, the lack of a "first unit" and the lack of a supply chain create a higher perceived investment risk.

Economics: Availability of cheaper alternative technologies to generate electricity and low wholesale price of electricity are a threat to SMR economics and competitiveness in the electricity market. Today the electricity market considers only generation costs, disregarding backup, balancing and storage costs, penalising plant that can "produce electricity on demands" like nuclear power plants.

Technological readiness: The lack of a first unit, technology readiness and supply chain availability are barriers related to SMR technological readiness (and in a certain extent to SMR financing).

Licensing and regulatory constraints, lack of political support: These are barriers related to SMR policy and regulation readiness. Political support in developing specific SMR licensing processes could be a solution to overcome these barriers and lower perceived investment risk by investors.

Public acceptance: Public acceptability of nuclear power may be improved with SMRs because of better security, less environmental impact, proliferation resistance, passive safety system and massive deployment. However SMRs can also be perceived as "novel and therefore more risky".

Licensing and regulations

The licensing process can be a key hurdle for SMRs (Sainati et al., 2015). Nuclear installations, including SMRs, are subjected to a strict regulatory control concerning nuclear safety, security, safeguards and environmental protection.

In the UK, the Office for Nuclear Regulation (ONR) grants, amends, suspends and revokes nuclear site licenses. The nuclear site license allows the licensee to undertake activities such as the construction, testing, and operation of nuclear power plants. The licensing system in the UK is relatively unique with a high degree of flexibility for ONR and the licensing applicant. The applicant is comparatively free to propose new reactor designs but needs to provide convincing "safety case" to the ONR to obtain the nuclear site license. This process is uncertain and can postpone the construction and operation of nuclear power plants by months or years.

The ONR is committed to reducing the time and perception of investment risk for stakeholders with non-binding guidelines, early meetings, and issuing Generic Design Assessments (GDAs). The GDA is a regulatory assessment providing preliminary and general safety assessment on new reactor designs. This approach reduces the perceived investment risk and promote licensing applications from alternative reactor designs, including SMRs. GDA does not substitute the nuclear site license and is not formally binding, even if the expectation is that it anticipates part of the regulatory assessment. The ONR has resource constraints, therefore an SMR design needs political support to secure the possibility of being scrutinise for a GDA. The engineering and experimental work related to a GDA is expensive, financial support is therefore important.

Financial arrangements

The deployment of SMRs is considered as the business under which the nuclear sector will evolve and renovate, including the financing approach, even if challenges remain (Sainati et al., 2019). For these reasons, the UK Department for Business, Energy and Industrial Strategy (BEIS), in 2018, convened an independent Expert Finance Working Group to produce an assessment of the market framework for financing SMRs (EFWG, 2018). This initiative identified alternative financing structures and models, including alternative forms of project financing, bespoke models inspired by existing projects in the UK and overseas, in nuclear and other sectors. The study highlights that the role of Government can be pivotal for promoting SMRs, particularly for the first units deployed.

The international dimension

Many countries are interested in building SMRs, however most of them are not keen to buy an SMR that has not been already successfully built elsewhere because it is perceived as a risky investment. Most SMR vendors aspire to gain significant market share because it is essential to manufacture at scale and reduce costs. Economic feasibility, is often reliant on the ability to manufacture and install many SMRs in multiple sites. Under this view, SMRs could become cheaper thanks to a sort of "mini-mass production" similar to aircraft production.

Many reactor vendors are supported by their respective Governments. For instance, Russia has a long tradition in the nuclear sector and it is aiming to export SMRs along with providing extensive financial and technical support. China aims at producing cost competitive and reliable SMRs, offering a competitive financial package to prospective buyers/importers of SMRs. The USA is traditionally oriented toward the open electricity market and does not promote their domestic reactor vendors directly, but does so indirectly, e.g. with grants for companies developing SMR. Vendors such as NuScale are gaining significant interest and reputation due to their ability to obtain nuclear licenses in the USA.

The UK has some advantages including:

- A long tradition of developing nuclear power plants.
- A flexible regulatory process that it is open for alternative reactor technology.
- An excellent reputation for safe nuclear installation.
- Long established political and commercial relations with foreign countries, particularly in the Commonwealth.
- Reactor vendors such as Rolls Royce with extensive experience in small nuclear reactors (a technology comparable to SMRs) which are historically used for military applications such as the nuclear submarines.

Policy Leeds

Recommendations

Our research indicates that to support SMR deployment the UK government needs to develop a long-term energy policy for nuclear energy aiming at the construction of a fleet of identical SMRs, with a standard supply chain involved in the construction, operation and decommissioning. We recommend the following actions:

Developing a SMR strategy

- **Pick a winner.** The UK government needs to select and support a specific design for the UK. This design will need financial backing during the design, licensing and construction of first units. There are several financial mechanisms available for the UK government to support this design. The design should be based on a proven technology (i.e. light water reactors) and developed by a company with established know-how, ideally in the UK.
- **Invest in the design.** It could take about £1 billion from the conceptual reactor design to pass through the GDA. It is extremely unlikely that such money can be entirely raised in the market. A share of this money needs to come from the UK government.
- **Invest in the "British" supply chain.** To design and build a nuclear reactor requires a network of organisations: manufacturers, regulators, service providers, universities, etc. These companies need to invest to build capacity, including training people. They need UK government support.
- **Support the construction of the first unit(s).** It is extremely difficult to raise capital for a first of a kind nuclear reactor. First unit(s) are perceived as risky investments and are needed to "prove the design". The UK government should support, financially, the first unit(s). In particular, the Government should considered an effective mix of Government debt guarantee, contract for difference and direct investments (e.g. equity contributions).
- **Take a programme perspective, not a project one.** The advantages of SMRs won't be realised at a single unit scale. SMRs need to be conceived as a programme, both for the UK needs and exports. The UK government should develop partnerships at international level for building SMRs.
- **Take a life cycle perspective.** SMRs are designed to operate 60 years. This means that between construction, operation and decommissioning the life cycle can easily be a century. The UK government needs to understand how it is possible to both create value and distribute value for SMRs across the entire life-cycle.

About the authors

Giorgio Locatelli is a Professor of Project Management and expert on energy megaprojects in the School of Civil Engineering, University of Leeds. He was a member of the BEIS 2018 Expert Finance Working Group.
Email: g.locatelli@leeds.ac.uk

Tristano Sainati is an expert of financing and contracting in infrastructures, also based in Civil Engineering at Leeds.
Email: t.sainati@leeds.ac.uk

Benito Mignacca is a PhD candidate working with Professor Locatelli on energy megaprojects.
Email: cnbm@leeds.ac.uk

Disclosure statement

Locatelli and Sainati's work for preparing this document has been funded by the University of Leeds. Mignacca's PhD is sponsored by the EPSRC grant EP/N509681/1. This document only represents the point of view of the authors.

References

BEIS, 2020. 2018 UK **Greenhouse Gas Emissions, Final figures**

EFWG, 2018. **Market framework for financing small nuclear**

IAEA, 2020. **Advances in small modular reactor technology developments** 2020 Edition.

Locatelli, G., 2018. **Why are Megaprojects, Including Nuclear Power Plants, Delivered Overbudget and Late? Reasons and Remedies** - Report MIT-ANP-TR-172, Center for Advanced Nuclear Energy Systems (CANES), Massachusetts Institute of Technology.

Locatelli, G., Boarin, S., Fiordaliso, A., Ricotti, M.E., 2018. Load following of Small Modular Reactors (SMR) by cogeneration of hydrogen: A techno-economic analysis. Energy 148, 494–505.

Locatelli, G., Mancini, M., Todeschini, N., 2013. Generation IV nuclear reactors: Current status and future prospects. Energy Policy 61, 1503–1520.

Mignacca, B., Locatelli, G., Sainati, T., 2020. **Deeds not words: Barriers and remedies for Small Modular nuclear Reactors**. Energy 206, 118137.

Mignacca, Locatelli, G., 2020a. **Economics and finance of Small Modular Reactors: A systematic review and research agenda**. Renew. Sustain. Energy Rev. 118, 109519.

Mignacca, Locatelli, G., 2020b. **Economics and finance of Molten Salt Reactors**. Prog. Nucl. Energy 129, 103503.

Sainati, T., Locatelli, G., Brookes, N., 2015. Small Modular Reactors: Licensing constraints and the way forward. Energy 82, 1092-1095.

Sainati, T., Locatelli, G., Smith, N., 2019. Project financing in nuclear new build, why not? The legal and regulatory barriers. Energy Policy 129, 111–119.

Tel. +44 (0)113 243 1751
policyleeds@leeds.ac.uk
leeds.ac.uk/policyleeds
@policyleeds

UNIVERSITY OF LEEDS

Policy Leeds
University of Leeds
Leeds, United Kingdom LS2 9JT

References

Auverny-Bennetot, C., Demol, J.., Nicolini, E., Allenovskiy, A., Petrishin, A., 2019. Yamal LNG: REX on a mega Oil&Gas Project built on the permafrost, in: XVII ECSMGE-2019. p. 2019.

Bjørnstad, S., 2009. Shipshaped: Kongsberg industry and innovations in deepwater technology, 1975-2007.

Brusoni, S., Prencipe, A., 2001. Unpacking the Black Box of Modularity: Technologies, Products and Organizations. Ind. Corp. Chang. 10, 179–205.

Busch, J., Steinberger, J.K., Dawson, D.A., Purnell, P., Roelich, K., 2014. Managing critical materials with a technology-specific stocks and flows model. Environ. Sci. Technol. 48, 1298–1305. https://doi.org/10.1021/es404877u

Carelli, M.D., Ingersoll, D.T., 2014. Handbook of Small Modular Nuclear Reactors, Woodhead Publishing, Elsevier. https://doi.org/10.1533/9780857098535.2.149

Choi, J.O., O'Connor, J.T., Kim, T.W., 2016. Recipes for Cost and Schedule Successes in Industrial Modular Projects: Qualitative Comparative Analysis. J. Constr. Eng. Manag. 142, 4016055.

Choi, J.O., O'Connor, J.T., Kwak, Y.H., Shrestha, B.K., 2019. Modularization Business Case Analysis Model for Industrial Projects. J. Manag. Eng. 35, 1–11. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000683

Christmann, P., 2018. Towards a More Equitable Use of Mineral Resources. Nat. Resour. Res. 27, 159–177. https://doi.org/10.1007/s11053-017-9343-6

Cooperman, A., Eberle, A., Lantz, E., 2021. Wind turbine blade material in the United States: Quantities, costs, and end-of-life options. Resour. Conserv. Recycl. 168, 105439. https://doi.org/10.1016/j.resconrec.2021.105439

Dong, D., Tukker, A., Van der Voet, E., 2019. Modeling copper demand in China up to 2050: A business-as-usual scenario based on dynamic stock and flow analysis. J. Ind. Ecol. 23, 1363–1380. https://doi.org/10.1111/jiec.12926

Ellen MacArthur Foundation, 2020. Financing the circular economy Capturing the opportunity.

Fuldauer, L.I., Ives, M.C., Adshead, D., Thacker, S., Hall, J.W., 2019. Participatory planning of the future of waste management in small island developing states to deliver on the Sustainable Development Goals. J. Clean. Prod. 223, 147–162. https://doi.org/10.1016/j.jclepro.2019.02.269

Ghenai, C., 2012. Life Cycle Analysis of Wind Turbine, in: Sustainable Development - Energy, Engineering and Technologies - Manufacturing and Environment. https://doi.org/10.5772/29184

GIF/EMWG, 2007. Cost estimating guidelines for generation IV nuclear energy systems.

GWEC, 2019. Global Statistics.

Heath, G.A., Silverman, T.J., Kempe, M., Deceglie, M., Ravikumar, D., Remo, T., Cui, H., Sinha, P., Libby, C., Shaw, S., Komoto, K., Wambach, K., Butler, E., Barnes, T., Wade, A., 2020. Research and development priorities for silicon photovoltaic module recycling to support a circular economy. Nat. Energy 5, 502–510. https://doi.org/10.1038/s41560-020-0645-2

HM Government, 2020. The Ten Point Plan for a Green Industrial Revolution.

IAEA, 2021. Power Reactor Information System.

Ikpe, E., Kumar, J., Jergeas, G., 2015. Analysis of Modularization Compared to Total Project Cost in Alberta Oil and Gas Projects. Glob. Adv. Res. J. Manag. Bus. Stud. 4, pp 116-120.

Infrastructure Outlook, 2020. Forecasting infrastructure investment needs and gaps. URL https://outlook.gihub.org/?utm_source=GIHub+Homepage&utm_medium=Project+tile&utm_campaign=Outlook+GIHub+Tile (accessed 2.8.21).

Invernizzi, D.C., Locatelli, G., Velenturf, A., Love, P.E., Purnell, P., Brookes, N.J., 2020. Developing policies for the end-of-life of energy infrastructure: Coming to terms with the challenges of decommissioning. Energy Policy 144, 111677. https://doi.org/10.1016/j.enpol.2020.111677

Jensen, P.D., Purnell, P., Velenturf, A.P.M., 2020. Highlighting the need to embed circular economy in low carbon infrastructure decommissioning: The case of offshore wind. Sustain. Prod. Consum. 24, 266–280. https://doi.org/10.1016/j.spc.2020.07.012

Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: An analysis of 114 definitions. Resour. Conserv. Recycl. 127, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005

Krausmann, F., Wiedenhofer, D., Lauk, C., Haas, W., Tanikawa, H., Fishman, T., Miatto, A., Schandl, H., Haberl, H., 2017. Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use, in: Proceedings of the National Academy of Sciences of the United States of America. pp. 1880–1885. https://doi.org/10.1073/pnas.1613773114

Lapko, Y., Trianni, A., Nuur, C., Masi, D., 2019. In Pursuit of Closed-Loop Supply Chains for Critical Materials: An Exploratory Study in the Green Energy Sector. J. Ind. Ecol. 23, 182–196. https://doi.org/10.1111/jiec.12741

Liguori, R., Faraco, V., 2016. Biological processes for advancing lignocellulosic waste biorefinery by advocating circular economy. Bioresour. Technol. 215, 13–20. https://doi.org/10.1016/j.biortech.2016.04.054

Lloyd, C.A., Roulstone, T., Lyons, R.E., 2021. Transport, constructability, and economic advantages of SMR modularization. Prog. Nucl. Energy 134, 103672. https://doi.org/10.1016/j.pnucene.2021.103672

Locatelli, G., Boarin, S., Fiordaliso, A., Ricotti, M.E., 2018. Load following of Small Modular Reactors (SMR) by cogeneration of hydrogen: A techno-economic analysis. Energy 148, 494–505. https://doi.org/10.1016/j.energy.2018.01.041

Locatelli, G., Boarin, S., Pellegrino, F., Ricotti, M.E., 2015. Load following with Small Modular Reactors (SMR): A real options analysis. Energy 80, 41–54.

Locatelli, G., Fiordaliso, A., Boarin, S., Ricotti, M.E., 2017. Cogeneration: An option to facilitate load following in Small Modular Reactors. Prog. Nucl. Energy 97, 153–161.

Maronati, G., Petrovic, B., Wyk, J.J. Van, Kelley, M.H., White, C.C., 2017. EVAL: A methodological approach to identify NPP total capital investment cost drivers and sensitivities. Prog. Nucl. Energy 104, 190–202. https://doi.org/10.1016/J.PNUCENE.2017.09.014

Mignacca, B., Locatelli, G., 2021. Modular circular economy in energy infrastructure projects: Enabling factors and barriers. J. Manag. Eng. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000949

Mignacca, Locatelli, G., Velenturf, A., 2020. Modularisation as enabler of circular economy in energy infrastructure. Energy Policy 139. https://doi.org/10.1016/j.enpol.2020.111371

Minunno, R., O'Grady, T., Morrison, G.M., Gruner, R.L., 2020. Exploring environmental benefits of reuse and recycle practices: A circular economy case study of a modular building. Resour. Conserv. Recycl.

160, 104855. https://doi.org/10.1016/j.resconrec.2020.104855

Ng, K.S., Head, I., Premier, G.C., Scott, K., Yu, E., Lloyd, J., Sadhukhan, J., 2016. A multilevel sustainability analysis of zinc recovery from wastes. Resour. Conserv. Recycl. 113, 88–105. https://doi.org/10.1016/j.resconrec.2016.05.013

NuScale, 2018. How the NuScale Module Works.

O'Connor, J.T., O'Brien, W.J., Choi, J.O., 2015. Standardization strategy for modular industrial plants. J. Constr. Eng. Manag. 141, 1–10. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001001

O'Connor, J.T., O'Brien, W.J., Choi, J.O., 2014. Critical success factors and enablers for optimum and maximum industrial modularization. J. Constr. Eng. Manag. 140, 1–11. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000842

Preston, F., Lehne, J., 2017. A Wider Circle? The Circular Economy in Developing Countries.

Purnell, P., 2019. On a voyage of recovery: a review of the UK's resource recovery from waste infrastructure. Sustain. Resilient Infrastruct. 4, 1–20. https://doi.org/10.1080/23789689.2017.1405654

Purnell, P., Velenturf, A.P.M., P.D., J., Cliffe, N., Jopson, S.J., 2018. Developing Technology, Approaches and Business Models for Decommissioning of Low-Carbon Infrastructure.

Rausch, C., Sanchez, B., Edwards, C., Haas, C., 2020. A computational model for product cycling of modular buildings, in: EG-ICE 2020 Workshop on Intelligent Computing in Engineering.

Reuter, M.A., Matusewicz, R., Van Schaik, A., 2015. Lead, zinc and their minor elements: Enablers of a circular economy. World Metall. - ERZMETALL 68, 134–148.

Roelich, K., Dawson, D.A., Purnell, P., Knoeri, C., Revell, R., Busch, J., Steinberger, J.K., 2014. Assessing the dynamic material criticality of infrastructure transitions: A case of low carbon electricity. Appl. Energy 123, 378–386. https://doi.org/10.1016/j.apenergy.2014.01.052

Saunders, M., Lewis, P., Thornhill, A., 2015. Research Methods for Business Students, 7th ed. New York.

Schiller, G., Müller, F., Ortlepp, R., 2017. Mapping the anthropogenic stock in Germany: Metabolic evidence for a circular economy. Resour. Conserv. Recycl. 123, 93–107. https://doi.org/10.1016/j.resconrec.2016.08.007

UxC Consulting, 2013. SMR Market Outlook.

Velenturf, A.P.M., Archer, S.A., Gomes, H.I., Christgen, B., Lag-Brotons, A.J., Purnell, P., 2019. Circular economy and the matter of integrated resources. Sci. Total Environ. https://doi.org/10.1016/j.scitotenv.2019.06.449

Velenturf, A.P.M., Purnell, P., 2021. Principles for a Sustainable Circular Economy. Sustain. Prod. Consum. https://doi.org/10.1016/j.spc.2021.02.018

Venkata Mohan, S., Nikhil, G.N., Chiranjeevi, P., Nagendranatha Reddy, C., Rohit, M. V., Kumar, A.N., Sarkar, O., 2016. Waste biorefinery models towards sustainable circular bioeconomy: Critical review and future perspectives. Bioresour. Technol. https://doi.org/10.1016/j.biortech.2016.03.130

Vondra, M., Touš, M., Teng, S.Y., 2019. Digestate evaporation treatment in biogas plants: A techno-economic assessment by Monte Carlo, neural networks and decision trees. J. Clean. Prod. 238. https://doi.org/10.1016/j.jclepro.2019.117870

Wrigley, P.A., Wood, P., O'Neill, S., Hall, R., Robertson, D., 2021. Off-site modular construction and design in nuclear power: A systematic literature review. Prog. Nucl. Energy 134, 103664. https://doi.org/10.1016/j.pnucene.2021.103664

Yang, Y., Pan, M., Pan, W., Zhang, Z., 2021. Sources of Uncertainties in Offsite Logistics of Modular Construction for High-Rise Building Projects. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000905