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Modularisation as enabler of circular economy in energy infrastructure

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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;

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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.

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[1] Approximated number by http://www.solareb2b.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).

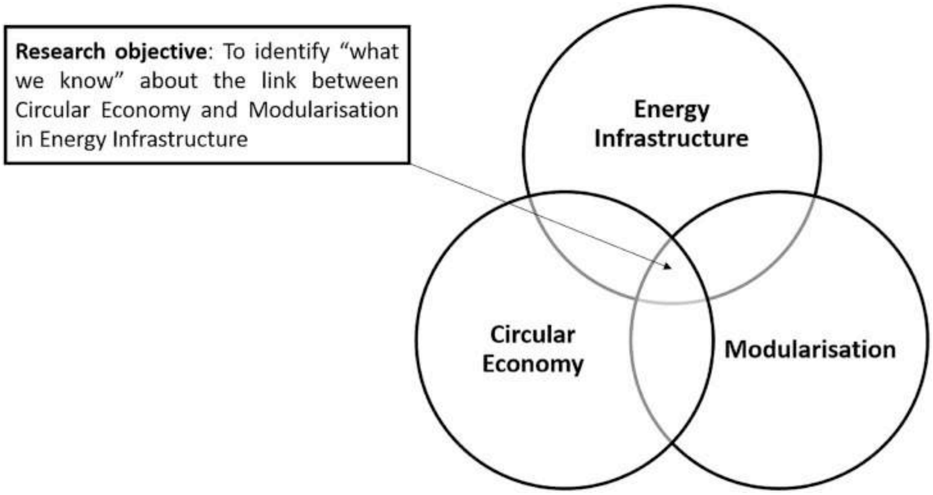


Fig. 1. Research area and objective.

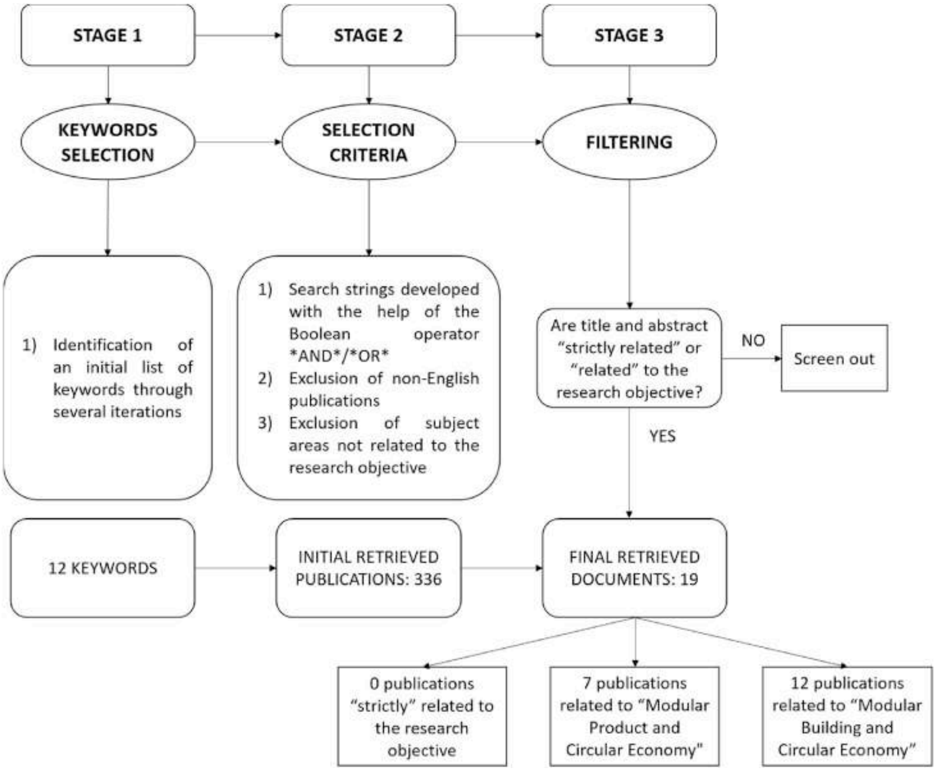


Fig. 2. Selection process – Section A. Layout adapted from (Di Maddaloni and Davis, 2017).

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)

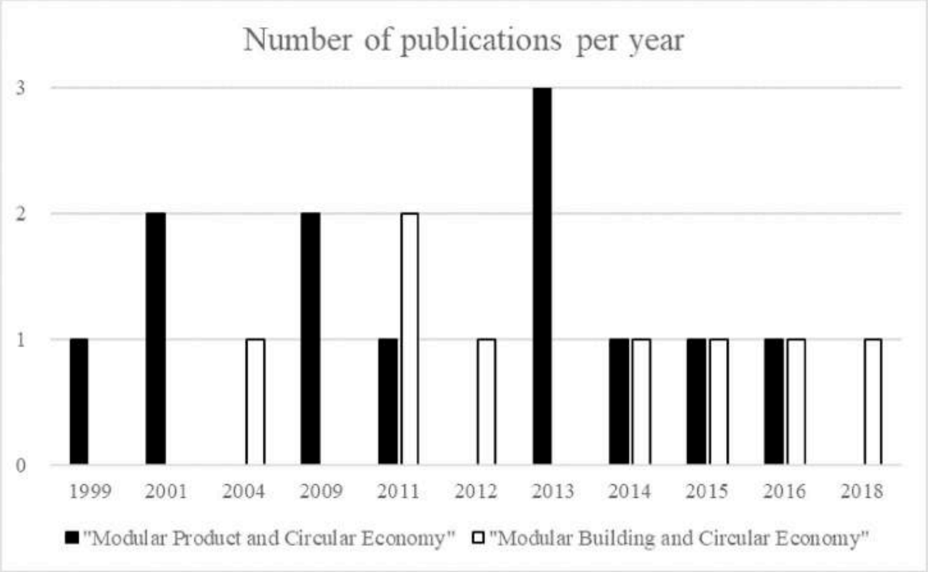


Fig. 3. Number of publications per year.

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

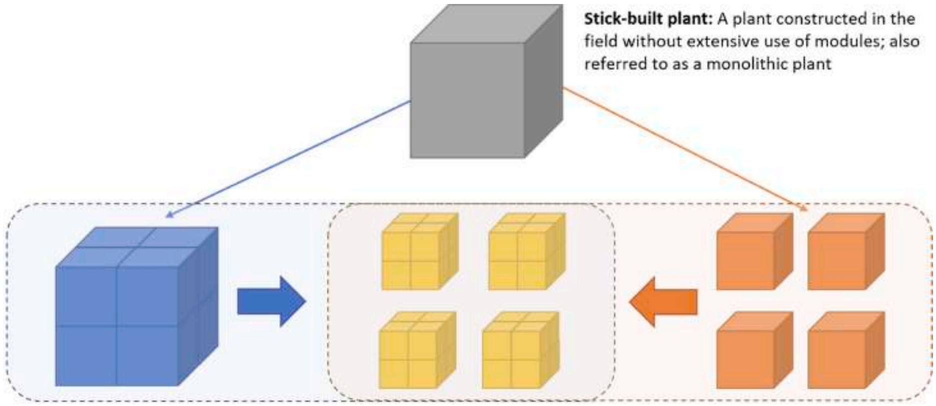
Policies fostering the development of sustainable infrastructure leveraging the principles of CE are essential for the energy sector. Traditional stick-built energy infrastructure have a lifecycle predetermined by the lifetime of their components. Modular infrastructure might be reconfigurable and extend/adapt 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, CO₂ emissions, minimising the use of raw materials, etc.

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



Stick-built plant: A plant constructed in the field without extensive use of modules; also referred to as a monolithic plant

Modularisation: 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

Modularity: A standard unit assembled onsite from factory produced modules, usually of smaller capacity than a monolithic plant, to maximize the benefit from modularity effects

Pure Standardisation: the delivery of (nearly) identical stick-built power plants form a consistent set of stakeholders in the project delivery chain

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.

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Appendix 1

Table 2
Publications - Link highlighted

Publication/Link highlighted	Modular Product and Circular Economy	Modular Building and Circular Economy
Nonomura 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

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