Modular Circular Economy in Energy Infrastructure Projects: Enabling Factors and Barriers

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Abstract: There is a growing body of literature surrounding circular economy (CE) and energy infrastructure projects. 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 semistructured 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. **DOI: 10.1061/(ASCE)ME.1943-5479.0000949.** *This work is made available under the terms of the Creative Commons Attribution 4.0 International license, https://creativecommons.org/licenses/by/4.0/.*

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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, p. 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, that is, 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" (p. 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 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 using a systematic literature review. They also theoretically conceptualized the link between modularization and CE, presenting the modular CE, that is, "the factory fabrication, transportation and installation on-site of modules aiming to facilitate the reuse/repair/replacement/recycling of modules/components/materials" (p. 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 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 Development Goals (SDGs), SDG 9 (Industry, Innovation and Infrastructure) is focused on infrastructure. Infrastructure is also considered within SGDs 11 (Sustainable Cities and Communities) and 6 (Clean Water and

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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, that is, $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, that is, modularization and CE in EIPs; the methodology adopted to answer the aforementioned RQs; the results and related discussion; and 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 and 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: a "modular standardized plant," that is, standardization of plant design and modularization of the design to obtain standard modular plants, and "standard modules," that is, modularization of the design and standardization of some modules. The degree of standardization is a key aspect for EIP planning and delivery (Choi et al. 2020c; Shrestha et al. 2020). The most relevant critical standardization 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 higher project management effort (Carelli and Ingersoll 2014), the need to design 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 and processes (i.e., early modular feasibility analysis supported by owner's front-end planning and decision support systems, work processes, and team resource support); (4) timely design freeze by owner and contractors; and (5) early completion recognition; that is, 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, that is, "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, that is, "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. (2020b) showed the innovative technologies and approaches most impactful on modularization success, that is, 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 opportunities for material recovery and reuse. 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" (p. 379)] during the transition to low-carbon infrastructures. Furthermore, Christmann (2018), Dong et al. (2019), Ng et al. (2016), and 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) and Schiller et al. (2017) stressed the fact that 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 future capital stock and properly exploited and managed, 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 favoring 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 favoring 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 favor the implementation of CE initiatives, such as reuse and replacement. Remarkably, there is no empirical research about the identification and examination of the factors favoring 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 discussion.

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 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 bioresources from the CE, generating net waste. Vondra et al. (2019) recommended a vacuum evaporator system and presented a technoeconomic analysis tool to favor 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” (p. 967). Another key topic in this area is cogeneration, that is, 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 multidimensional 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 multidimensional 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 2020b). The oil and gas sector is also relevant to the research because modularization has been practiced 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 semistructured interviews following DiCicco-Bloom and Crabtree (2006)’s recommendations. Experts (interviewees) and researchers have the opportunity, in semistructured 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 10 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, that is, when data collection became redundant and the content was clear to the authors (Hennink et al. 2017). Three out of the

Table 1. Semistructured questionnaire questions. (Adapted from Locatelli et al. 2020.)

Purpose	Semistructured 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 opportunity of reusing 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 opportunity of reusing 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?

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 three pilot interviews led to the final version of the questionnaire. Table 1 shows the final semistructured questionnaire used as a basis for the dialogue and the related purpose.

The expected length of each interview was 30 min, but two interviews lasted around an hour. On average, interviews lasted 31 min. 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), that is, "a method for identifying, analyzing and reporting patterns (themes) within data" (Braun and Clarke 2006, p. 79). It is "a form of pattern recognition within the data, where emerging themes become the categories for analysis" (Fereday and Muir-Cochrane 2006, p. 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 version 12, 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) summarizing in a few words each relevant section; these represented a theme or subtheme (nodes); and (2) reorganizing the long initial list of nodes in a smaller number of themes and subthemes based on similarities (final coding). The coding can start both from themes or subthemes (Nowell et al. 2017). In this case, the final coding started from subthemes.

After the first coding process, several discussions between the authors led to the final list of themes and subthemes. 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 two themes (enabling factors and barriers) and 10 subthemes. The "enabling factors" theme includes four subthemes: 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 subthemes: regulation, political pressures, lack of a market, economics, lack of maintenance, and module and component contamination.

Results

Enabling Factors

Monitoring of Module and Component Conditions

A relevant factor enabling reuse is the monitoring of module and component conditions. An interviewee explained why and for

Table 2. Examples of the coding process

Extract from the interviews	Preliminary coding (nodes)	Final coding (subthemes)	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		

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 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 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 reuse. 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 particularity 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 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 the 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."

Discussion

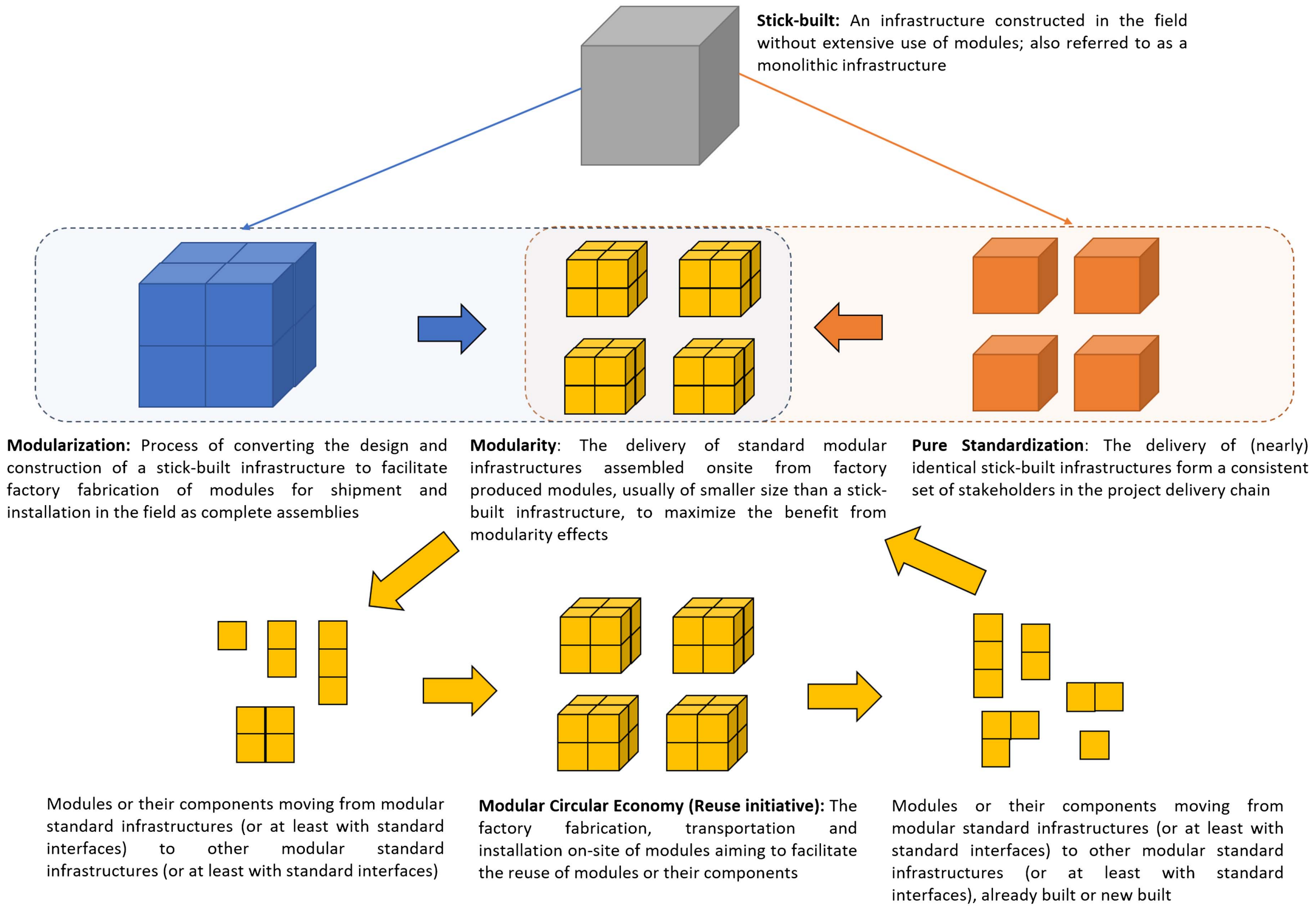
The words modularization and modularity are often used interchangeably in EIP scientific and industrial literature, although they have different meanings. Fig. 1 clarifies the difference between modularization and modularity in EIPs and provides a graphical summary of the construction strategies discussed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

Fig. 2 summarizes the factors favoring 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, Fig. 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 standardization at the infrastructure level.

The standardization of module and component 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 standardization than a whole power plant. This is consistent with the study of Choi et al. (2020a), which highlights that in defining the standardization strategy, the impetus may be first given at the component level, followed by the module level, and eventually at the infrastructure level.



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

Modularization: Process of converting the design and construction of a stick-built infrastructure to facilitate factory fabrication of modules for shipment and installation in the field as complete assemblies

Modularity: The delivery of standard modular infrastructures assembled onsite from factory produced modules, usually of smaller size than a stick-built infrastructure, to maximize the benefit from modularity effects

Pure Standardization: The delivery of (nearly) identical stick-built infrastructures form a consistent set of stakeholders in the project delivery chain

Modules or their components moving from modular standard infrastructures (or at least with standard interfaces) to other modular standard infrastructures (or at least with standard interfaces)

Modular Circular Economy (Reuse initiative): The factory fabrication, transportation and installation on-site of modules aiming to facilitate the reuse of modules or their components

Modules or their components moving from modular standard infrastructures (or at least with standard interfaces) to other modular standard infrastructures (or at least with standard interfaces), already built or new built

Fig. 1. Modularization, modularity, pure standardization, modular circular economy. (Data from Mignacca and Locatelli 2020a.)

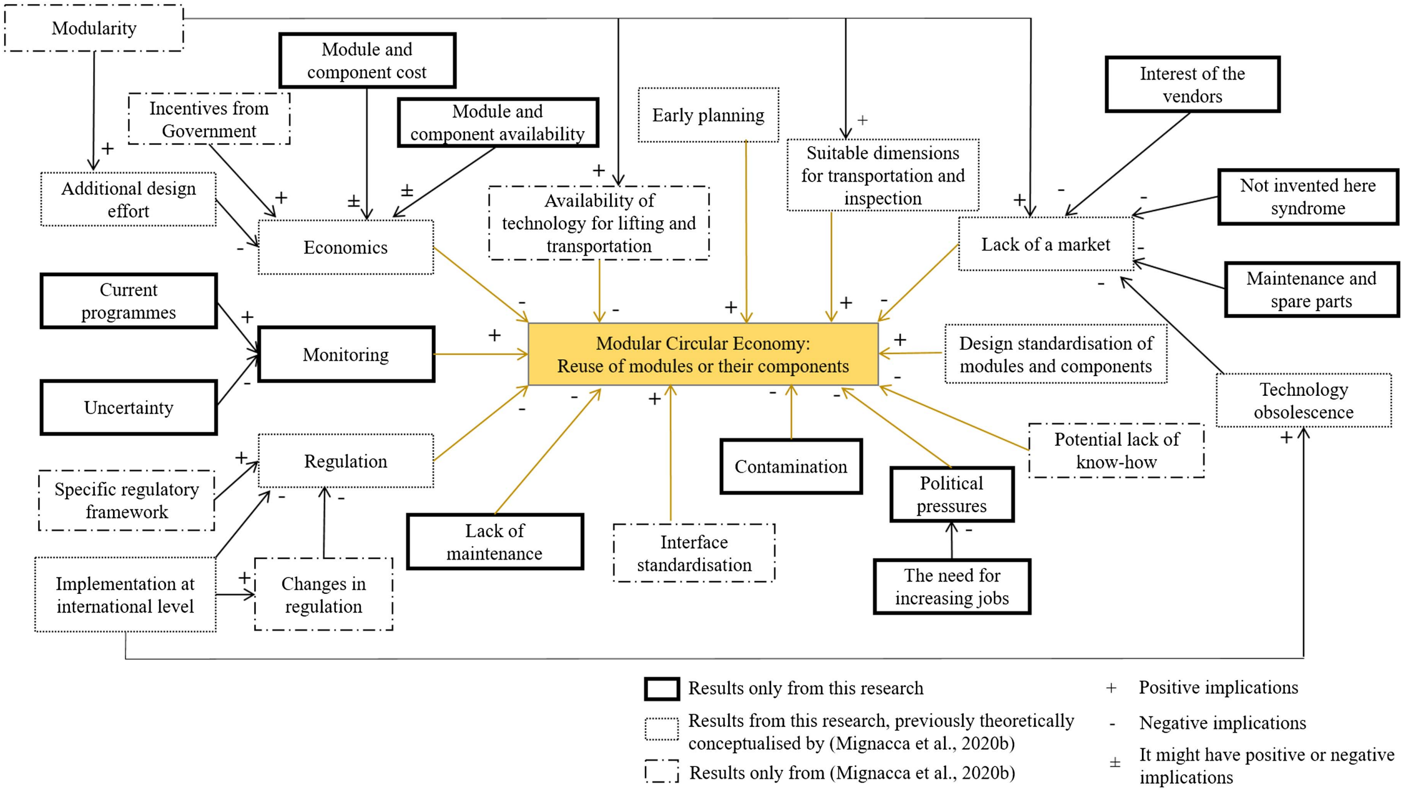


Fig. 2. Enabling factors and barriers for the reuse of modules and components—comparison with the literature about modular CE in EIPs.

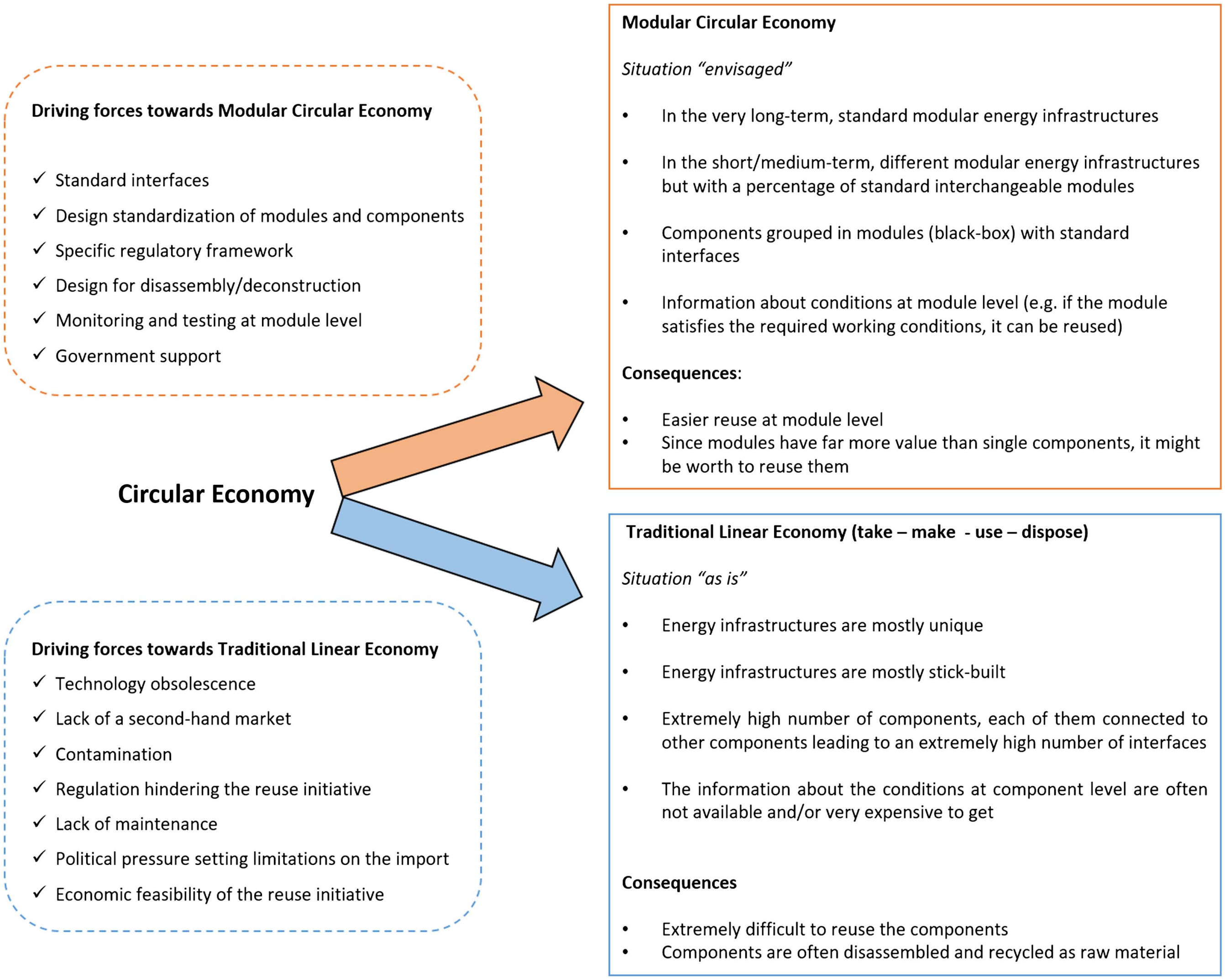
Another key enabling factor mentioned by the interviewees is the monitoring of module and component conditions to evaluate their residual lifetime. This is also highlighted by Allwood et al. (2011) in the case of modular products and by Mignacca et al. (2020a) in the specific case of SMRs. The interviewees 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, which 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, that is, "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, consistent 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, "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, implementation at the international level could make the regulatory challenges associated with reuse even more complicated, as pointed out by the interviewees, due to 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



Driving forces towards Modular Circular Economy

- ✓ Standard interfaces
- ✓ Design standardization of modules and components
- ✓ Specific regulatory framework
- ✓ Design for disassembly/deconstruction
- ✓ Monitoring and testing at module level
- ✓ Government support

Driving forces towards Traditional Linear Economy

- ✓ Technology obsolescence
- ✓ Lack of a second-hand market
- ✓ Contamination
- ✓ Regulation hindering the reuse initiative
- ✓ Lack of maintenance
- ✓ Political pressure setting limitations on the import
- ✓ Economic feasibility of the reuse initiative

Circular Economy

Modular Circular Economy

Situation "envisaged"

- In the very long-term, standard modular energy infrastructures
- In the short/medium-term, different modular energy infrastructures but with a percentage of standard interchangeable modules
- Components grouped in modules (black-box) with standard interfaces
- Information about conditions at module level (e.g. if the module satisfies the required working conditions, it can be reused)

Consequences:

- Easier reuse at module level
- Since modules have far more value than single components, it might be worth to reuse them

Traditional Linear Economy (take – make - use – dispose)

Situation "as is"

- Energy infrastructures are mostly unique
- Energy infrastructures are mostly stick-built
- Extremely high number of components, each of them connected to other components leading to an extremely high number of interfaces
- The information about the conditions at component level are often not available and/or very expensive to get

Consequences

- Extremely difficult to reuse the components
- Components are often disassembled and recycled as raw material

Fig. 3. Driving forces towards modular circular economy and traditional circular economy.

strategies involving relevant stakeholders within a specific regulatory framework.

In summary, Fig. 3 presents comprehensive sense-making about the main forces pulling from a circular economy to modular circular economy and from a circular economy to traditional linear economy. The authors derived Fig. 3 informed by the empirical results presented and discussed in this paper and the theoretical conceptualization of the modular CE.

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

Three main considerations about modular CE can be derived from Fig. 4: (1) extending the life of infrastructures by replacing modules 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, and (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 with disassembly in mind, include and improve systems to monitor the conditions of modules and components, promote ad hoc policies to promote reuse instead of disposal (e.g., 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 sectors and examining the data collected through thematic analysis, two RQs have been answered. Regarding the first RQ, that is, "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

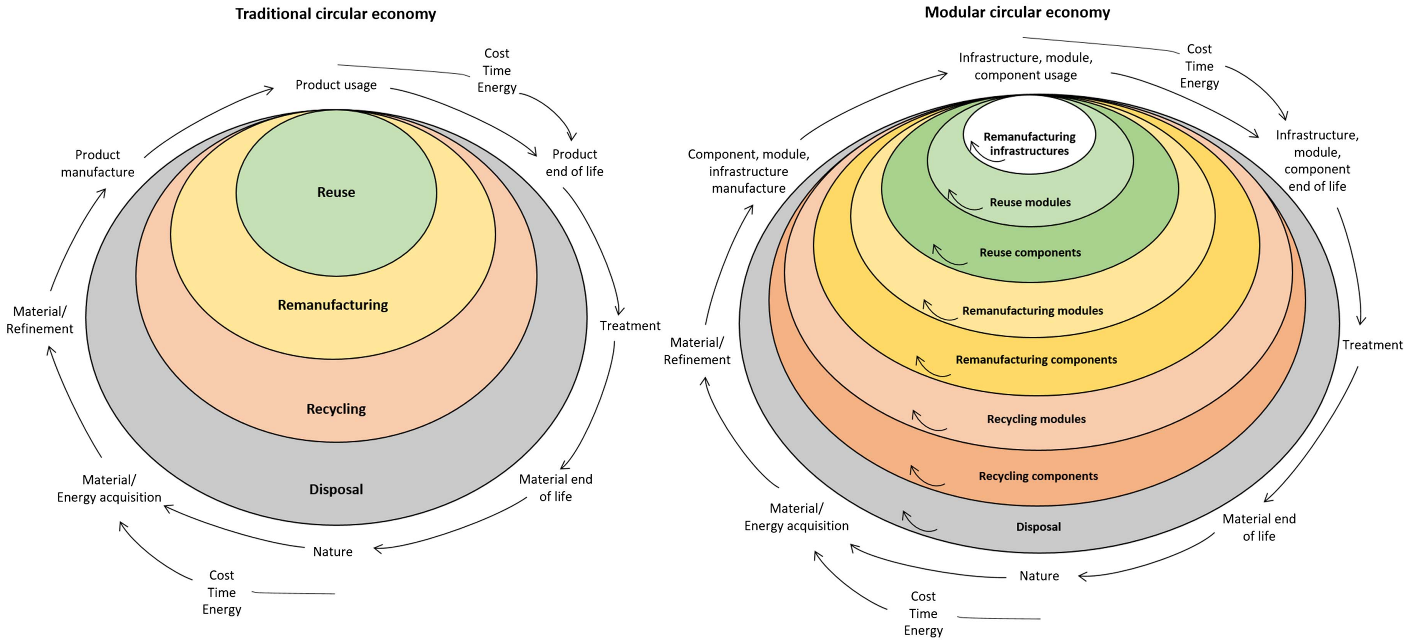


Fig. 4. Traditional circular economy approach (data from Mihelcic et al. 2003) versus modular circular economy approach.

transportation and inspection, and early planning. Regarding the second RQ, that is, "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 were discussed through the lens of the existing literature and the authors' 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 industries. 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 because they are now at the design stage, where modular CE can provide a 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 blade 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 reuse rather than providing solutions on how to reuse. Modularization can be a step forward toward the solution. This research empirically investigated which factors enable or hinder the opportunity to reuse 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 favor 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 favor 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; and
- Quantitatively evaluate the economic and environmental impact of the modular CE.

Appendix. Profiles of the Interviewees

No.	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

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.

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