LINKING CIRCULAR ECONOMY AND MODULARISATION IN ENERGY INFRASTRUCTURE: STATE OF THE ART AND A WAY FORWARD

Benito Mignacca, Dr Giorgio Locatelli

Developing sustainable infrastructure leveraging the principles of circular economy is essential for the energy sector to give its maximum contribution towards a low carbon world. Traditional energy infrastructure have a lifecycle predetermined by the lifetime of certain components. This means that the residual lifetime of the other components with a longer life is "wasted". Modular infrastructure might be reconfigurable and extend/adapt their lifecycle decoupling the life of the infrastructure from their modules. In a wider perspective, circular economy would be a cornerstone of this novel strategy to enable the lifecycle of sustainable modular infrastructure. Remarkably, despite the growing interest among policymakers, academics and industry in both circular economy and modularisation, there is a lack of research about the link between circular economy 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 circular economy. Building on this literature, this paper presents a Systematic Literature Review highlighting the state-of-the-art and the gap in knowledge.

Keywords: Modularisation, Circular Economy, Sustainability, Module, Prefabrication, Infrastructure, Energy

INTRODUCTION

"Modular construction" is often called indifferently "modularisation" or "modularity" both in the scientific and industrial literature. However, (GIF/EMWG, 2007) defines modularisation as the "process of converting the design and construction of a monolithic or stick-built plant to facilitate factory fabrication of modules for shipment and installation in the field as complete assemblies" (Page 24). Furthermore (EY, 2016) defines modularisation as a "way of simplifying construction by splitting the plant up into packages (modules) which can be factory manufactured, transported to site and assembled in situ, (or close by in an assembly area before being installed)" (Page 20). On the other hand, (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). Figure 1 further clarifies the definition of modularisation and modularity, also highlighting the meaning of stick-built and pure standardisation.

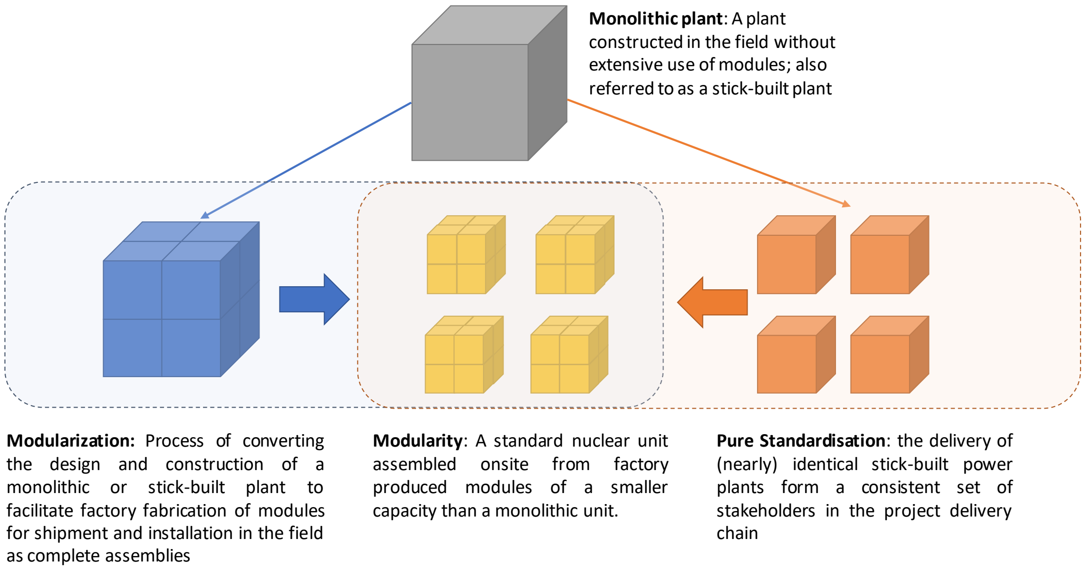

Figure 1: Meaning of modularisation, modularity, standardisation, stick-built. Text adapted from (GIF/EMWG, 2007)

The meaning of modularisation in this paper is based on the definitions of (GIF/EMWG, 2007) and (EY, 2016). Therefore, when the concept of modularisation in several publications is defined as modularity, this paper reports the term "modularisation".

Several authors deal with the costs and benefit of modularisation (Azhar et al., 2012; Bondi et al., 2016; De La Torre, 1994; Upadhyay and Jain, 2016). Factory fabrication is usually cheaper than site fabrication, but the costs associated with shipping of modules to the site must also be considered (EY, 2016). Smaller sized plants can take better advantage of modularisation since it is possible to have a greater percentage of factory-made components (Carelli et al., 2010). Although there are a number of publications in the literature describing the qualitative advantages of modularisation, only a few of them are quantitative. (Mignacca et al., 2018) summarise the quantitative information about two key implications of modularisation in infrastructure: schedule reduction (an average of 37.7%) and cost saving (an average of 15%).

Traditional stick-built energy infrastructure have a lifecycle predetermined by certain components. Modular infrastructure could be more reconfigurable and extend/adapt their lifecycle by decoupling the life of the infrastructure from their modules. When a module reaches its end of life, it could be exchanged extending the life of the infrastructure. Furthermore, when the infrastructure reaches the end of life, 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, circular economy would be a cornerstone of this novel strategy to manage sustainable modular infrastructure.

(Vanner et al., 2014) define Circular Economy (CE) as "a development strategy that enables economic growth while aiming to optimise the chain of consumption of biological and technical materials". Furthermore, (Preston and Lehne, 2017) define the meaning of CE pointing out the goal of maintaining resources at the highest value possible: "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;
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 a CE model, the design not only focuses on functionality but also tries to manage 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 applied in the building construction sector contributing to circularity in the following ways (European Environment Agency, 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 stuff, thus determining few 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.

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

In general, when an infrastructure reaches the end of life, it needs to be decommissioned. Decommissioning projects are the new, emerging, global, unavoidable challenges that project managers and policymakers will face more and more severely in the future. Among decommissioning projects, nuclear-decommissioning megaprojects are probably the most studied ones. According to (IAEA, 2019), 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. However, nuclear plants are not the only energy infrastructure to generate decommissioning projects. According to (GWEC, 2019), the total global wind power installed is 540 GWe, the vast majority installed in the last 10 years. Considering an operating life of about 25 years (Ghenai, 2012), in a decade or two, there will be decommissioning megaprojects in the wind farm sector. Similar consideration can be given considering about 500 GWe of solar power installed1. These numbers clarify the importance and the impact of extending the lifetime of the infrastructure and their modules.

This paper aims, through a Systematic Literature Review (SLR), to identify “what we know” about the link between circular economy and modular energy infrastructure. An SLR, instead of a traditional narrative review, has been conducted to allow repeatability, objectivity and transparency. Figure 2 summarises the research area and the research objective.

---

[1] This is an approximated number provided by http://www.solareb2b.it/wp-content/uploads/2016/06/SPE_GMO2016_full_version.pdf .

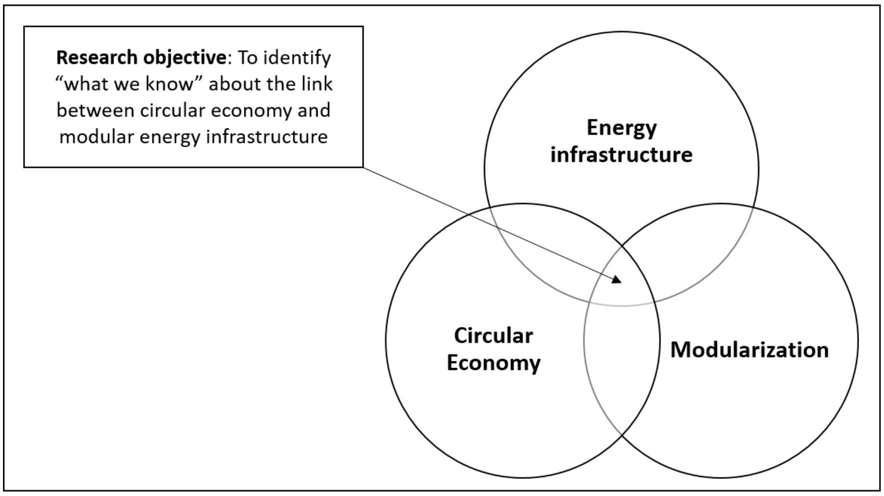

Figure 2: Research area and objective

The rest of the paper is structured as follows: section 2 presents the SLR that highlighted the gap in knowledge; section 3 reports the key lessons learned from other sectors, primarily building and products; section 4 concludes the paper suggesting a way forward.

METHODOLOGY

This methodology section deals with the SLR. Remarkably, if the three elements (circular economy, modularisation, energy infrastructure) are searched together, there are not meaningful publications found (even changing the keywords). Therefore, the authors decided to expand the search by dropping the keywords related to energy infrastructure and analyse all the papers emerged by looking at circular economy and modularisation.

This paper combines the methodologies to conduct an 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 key 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".
- Modularization: "modularization", "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 "modularization" 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 publications retrieved 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 zero publications strictly focused on the research objective. However, 7 publications highlight the link between modular building and circular economy, and 12 publications highlight the link between circular economy and modular product. These publications have been carefully read and analysed. Figure 3 summarises the Section A of the selection process.

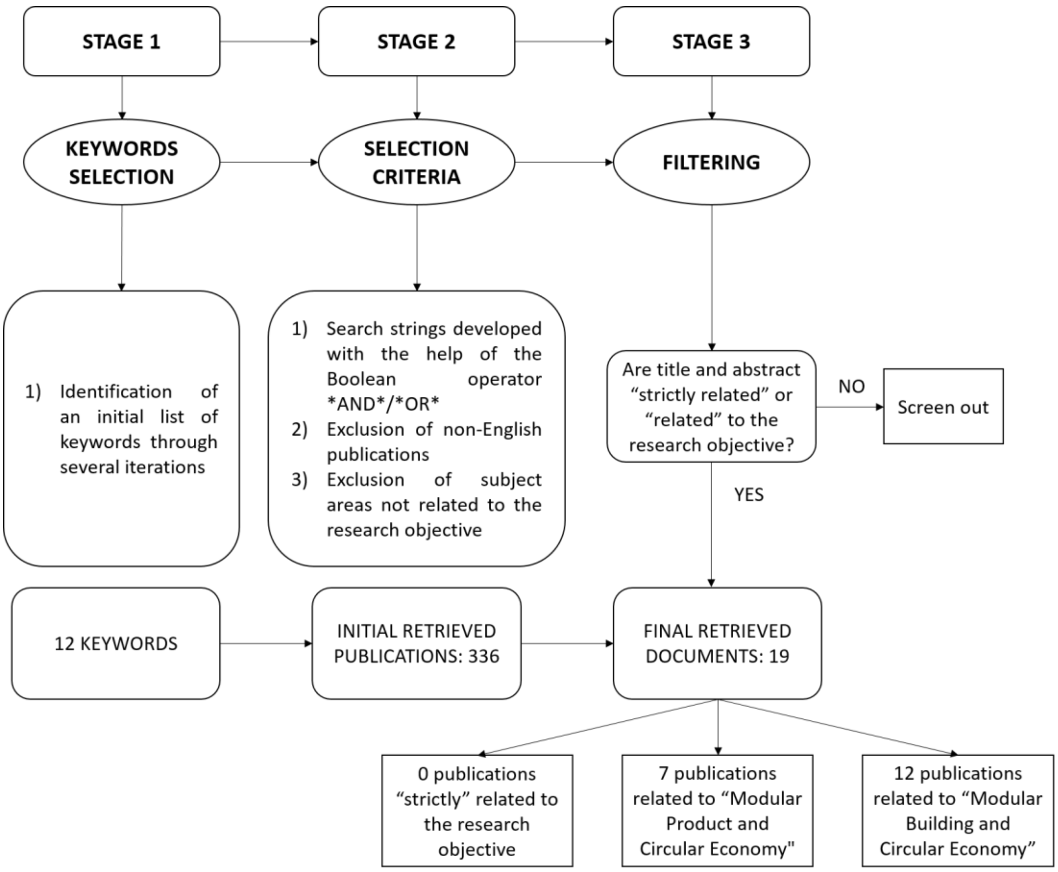

Figure 3: Selection process – Section A. Layout adapted from (Di Maddaloni and Davis, 2017)

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 leading in publishing freely available 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 one publication strictly related to the research objective was retrieved. Only (ARUP, 2016) shows the link between modularisation and circular economy but focusing on the building construction sector. Table 1 (in the appendix) reports the retrieved publications in Section A and Section B of the selection process.

Figure 4 presents the number of publications that highlighted the link between “modular product and circular economy” and “modular building and circular economy” per year.

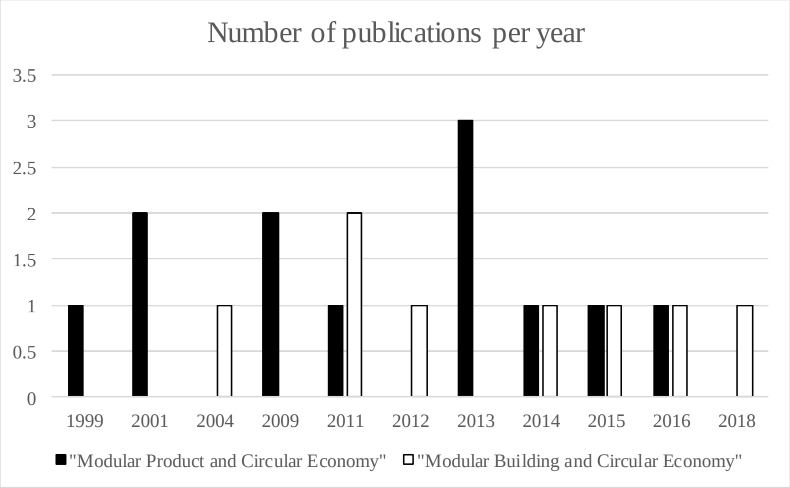

Figure 4: Number of publications per year

MODULAR ENERGY INFRASTRUCTURE AND CIRCULAR ECONOMY: LESSON LEARNED

Remarkably, there are no publications focusing on the link between circular economy and modularisation in energy infrastructure. Few publications focus on this link in the building construction sector, and several publications point out the link between circular economy and modular product. Following the procedures from Section 2, the authors scrutinised in detail 20 publications (listed in the appendix) showing several concepts and practises related to the link between modularisation and circular economy. 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.

---

[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).

Modular building

- Reduction of the construction and demolition waste

Prefabrication can reduce construction and demolition waste (Cheng et al., 2015); however, the authors do not explain 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 £800m per year (ARUP, 2016). (Li et al., 2014) 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.

- Achievement of the 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. However, the authors do not provide details about the reasons and the effective implications of modularisation.

- Reduction of the 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 results up to 50% higher than the conventional one, 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. Reusing allows a reduction of the required space for landfill and the reduction of the use of virgin raw materials.

- Design toward adaptability

Design toward adaptability is one of the strategies for reducing material consumption in the building construction sector. Modular design and standardisation represent two key strategies toward adaptability (Minunno et al., 2018). The authors do not provide other details about the impact of modular design and standardisation on the design toward adaptability.

Modular product

The modular design could improve performances in disassemblability, maintainability, upgradability, reusability, and recyclability (Hata et al., 2001; Umeda et al., 2009). A design characterised by modules that can be assembled in different ways allows applying the required changes without rendering a solution obsolete

(Schulte, 2013). However, several factors need to be considered to achieve optimal performances in terms of circular economy.

- Assessment in the early design stages

The link between modular design and the increased 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 "circular economy" 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 stress that a different approach would determine a waste of 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 not recyclable or 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 expire date of the modules according to their use (Allwood et al., 2011).

- Different modularisation methods and different goals

Each modularisation method of the product has one or more goals (e.g. schedule reduction, sustainability, product variety, etc.). According to (Halstenberg et al., 2015), there are two groups of modularisation methods: "methods for single product modularization" and "methods for product family modularization". 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 Modularization Method" which allows defining product architecture based on specific goals. However, the authors only provide the generation method of different product architecture alternatives (generated according to similarity and dependency analysis) and do not provide details about choosing goals and the related implications.

Furthermore, (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 modularization (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 exchange the key components easily 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 circular economy strategies (Schischke et al., 2016).

- 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. Furthermore, (Fukushige et al., 2009) present a modular design method based on the lifecycle scenario. The method considers modules characterised by components suitable for the same lifecycle options permitting modules undergoing the lifecycle options without disassembly, and evaluate the modular structure in terms of resource efficiency.

- Modularisation is a key enabler of the inverse manufacturing

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

CONCLUSION AND A WAY FORWARD

Developing sustainable infrastructure leveraging the principles of circular economy is 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, circular economy would be a cornerstone of this novel strategy to manage sustainable modular infrastructure.

This paper, through an SLR, aims to identify "what we know" about the link between circular economy and modular energy infrastructure. Remarkably, despite the growing interest of policymakers, academics and industry in both circular economy and modularisation, there are no publications focusing on the link between circular economy 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 circular economy.

There are no publications bringing the ideas of energy infrastructure, modularisation and circular economy together.

The results of the literature review analysis suggest that 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 module facilitates the achievement of the circular economy goals. Furthermore, modularisation could reduce the construction and demolition waste and improve the deconstruction process. Modularisation could also reduce the lifecycle energy requirement and material consumption.

In the case of a modular product, there are several modularisation methods, and each method is related in a different way to circular economy. A precondition to achieving the expected advantages of modularisation in a "circular economy" perspective is the assessment of the lifecycle options of components/modules in the early design stages. Furthermore, several methods that allow evaluating the impact of modularisation in a "circular economy" perspective have been developed already at an academic level, less at an industrial level.

The stakeholders involved in the planning and delivery of energy infrastructure should familiarise with these concepts and practises to develop sustainable energy infrastructure reducing waste, CO_2 emission, minimising the use of raw materials, etc. Furthermore, the stakeholders should evaluate the preconditions, enabling factors, and barriers related to the design of modular energy infrastructure in a "circular economy" perspective.

The gap in knowledge about circular economy in modular energy infrastructure 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.

- Research questions dealing with legislation: What are the implications of the link between circular economy and modular energy infrastructure from a legal point of view? What are the consequences if the legislation changes and a module cannot be used anymore? In a wider perspective, what is the relationship among countries with different legislation about energy infrastructure? To what extent regulatory harmonisation between countries could promote the benefit of modularisation in a circular economy perspective?

- Research questions dealing with innovation: Could innovation be a barrier of the link between circular economy and modularisation? Could a new technology make unworthy the re-use of the module?

- Research question dealing with 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 circular economy perspective, module lifting and transportation could be more critical than a "traditional" one. How are module lifting and transportation exactly related to the link between modularisation and circular economy?

- Research question dealing with the value of resources/ geographical inhomogeneity: 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 this disparity could address the issues related to innovation and legislation?

- Research question dealing with standardisation of the interfaces: A precondition of the link between modularisation and circular economy is the standardisation of interfaces. Who should be responsible for the standardisation of the interfaces?

- Research questions dealing with the end of life cost: Which is the impact of the link between modularisation and circular economy on the end of life cost? Could it decrease?

Furthermore, emerging technologies such as the Internet of Things, digital twin and cyber-physical systems could foster the development of energy modular infrastructure in a “circular economy” perspective.

Finally, “learning the right way to fully exploit the benefits of modularisation from a circular economy perspective” leveraging the experience accumulated over the year in other sectors could be a key success factor to develop sustainable modular energy infrastructure.

APPENDIX

Table 1: Publication/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

ACKNOWLEDGEMENTS

This work was supported by the UK Engineering and Physical Sciences Research Council (EPSRC) grant EP/N509681/1. Furthermore, this work was partially supported by the Major Project Association (MPA). The authors are immensely grateful to the MPA members for their support. The opinions in this paper represent only the point of view of the authors, and only the authors are responsible for any omission or mistake. This paper should not be taken to represent in any way the point of view of MPA or EPSRC or any other organisation involved.

REFERENCES

Allwood, J.M., Ashby, M.F., Gutowski, T.G., Worrell, E., 2011. Resources , Conservation and Recycling Material efficiency : A white paper. Resour. Conserv. Recycl. 55, 362–381.

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

Aye, L., Ngo, T., Crawford, R.H., Gammampila, R., Mendis, P., 2012. Life cycle greenhouse gas emissions and energy analysis of prefabricated reusable building modules. Energy Build. 47, 159–168.

Azhar, S., Lukkad, M.Y., Ahmad, I., 2012. Modular v. Stick-Built Construction : Identification of Critical Decision-Making Factors, in: 48th ASC Annual International Conference Proceedings.

Bondi, A., Magagnini, A., Mancini, M., Micheli, G.J.L., Travaglini, A., 2016. Supporting Decisions on Industrial Plant Modularization : A Case Study Approach in the Oil and Gas Sector, in: International Conference on Industrial Engineering and Operations Management. Kuala Lumpur, pp. 742–753.

Carelli, M., Garrone, P., Locatelli, G., Mancini, M., Mycoff, C., Trucco, P., 2010. Economic features of integral, modular, small-to-medium size reactors. Prog. Nucl. Energy 52, 403–414.

Cheng, J.C.P., Won, J., Das, M., 2015. Construction and Demolition Waste Management using BIM technology, in: Proc. 23rd Ann. Conf. of the Int'l. Group for Lean Construction. Perth, Australia.

De La Torre, M.L., 1994. A review and analysis of modular construction practices. Lehigh University.

Di Maddaloni, F., Davis, K., 2017. The influence of local community stakeholders in megaprojects: Rethinking their inclusiveness to improve project performance. Int. J. Proj. Manag. 35, 1537–1556.

European Environment Agency, 2017. Circular by design - Products in the circular economy, EEA Report, No. 6/2017.

EY, 2016. Small modular reactors - Can building nuclear power become more cost-effective?

Fukushige, S., Tonoike, K., Inoue, Y., Umeda, Y., 2009. Product Modularization and Evaluation Based on Lifecycle Scenarios, in: Proceedings of the 5th International Conference on Leading Edge Manufacturing in 21st Century, LEM 2009.

Ghenai, C., 2012. Life Cycle Analysis of Wind Turbine, in: Sustainable Development - Energy, Engineering and Technologies - Manufacturing and Environment.

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

GIF/EMWG, 2005. Cost estimating guidelines for generation IV nuclear energy systems.

GWEC, 2019. Global Statistics [WWW Document]. URL http://www.solareb2b.it/wp-content/uploads/2016/06/SPE_GMO2016_full_version.pdf (accessed 2.22.19).

Halstenberg, F.A., Buchert, T., Bonvoisin, J., Lindow, K., 2015. Target-oriented Modularization– Addressing Sustainability Design Goals in Product Modularization Friedrich. Procedia CIRP 29, 603–608.

Hata, T., Kat, S., Kimura, F., 2001. Design of Product Modularity for Life Cycle Management, in: 2nd International Symposium on Environmentally Conscious Design and Inverse Manufacturing. pp. 93–96.

IAEA, 2019. Power Reactor Information System [WWW Document]. URL https://pris.iaea.org/PRIS/home.aspx (accessed 2.22.19).

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

Kimura, F., Kato, S., Hata, T., Masuda, T., 2001. Product Modularization for Parts Reuse in Inverse Manufacturing. CIRP Ann. 50, 89–92.

Lehmann, S., 2011a. Optimizing Urban Material Flows and Waste Streams in Urban Development through Principles of Zero Waste and Sustainable Consumption. Sustainability 155–183.

Lehmann, S., 2011b. Resource Recovery and Materials Flow in the City: Zero Waste and Sustainable Consumption as Paradigms in Urban Development. Sustain. Dev. Law Policy 11.

Li, Z., Qiping, G., Alshawi, M., 2014. Measuring the impact of prefabrication on construction waste reduction : An empirical study in China. Resour. Conserv. Recycl. 91, 27–39.

Liu, L., 2013. The exploration of recycling design of furniture products based on structure. Adv. Mater. Res. 695–607, 44–48.

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

Minunno, R., O'Grady, T., Morrison, G.M., Colling, M., Gruner, R.L., 2018. Strategies for Applying the Circular Economy to Prefabricated Buildings. Building.

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

Nonomura, A., Umeda, Y., 1999. Life cycle simulation for the inverse manufacturing, in: Proceedings First International Symposium on Environmentally Conscious Design and Inverse Manufacturing. IEEE, Tokyo, Japan.

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

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

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

Schischke, K., Proske, M., Nissen, N.F., Lang, K., 2016. Modular Products : Smartphone Design from a Circular Economy Perspective Modularity, in: Electronics Goes Green 2016+ (EGG). Berlin, Germany, pp. 1–8.

Schulte, U.G., 2013. New business models for a radical change in resource efficiency. Environ. Innov. Soc. Transitions 9, 43–47.

Umeda, Y., Fukushige, S., Tonoike, K., 2009. Evaluation of scenario-based modularization for lifecycle design. CIRP Ann. - Manuf. Technol. 58, 1–4.

Upadhyay, A.K., Jain, K., 2016. Modularity in nuclear power plants: a review. J. Eng. Des. Technol. 14.

Vanner, R., Bicket, M., Withana, S., Brink, P. Ten, Razzini, P., Dijl, E. Van, Watkins, E., Hestin, M., Tan, A., Guilche, S., Hudson, C., 2014. Scoping study to identify potential circular economy actions , priority sectors, material flows and value chains.

Yan, J., Feng, C., 2014. Sustainable design-oriented product modularity combined with 6R concept : a case study of rotor laboratory bench. Clean Techn Env. Policy 95, 95–109.