MODULARISATION AND MODULARITY AS A CIRCULAR ECONOMY APPROACH FOR THE BIOGAS PRODUCTION

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Over the last decade, some advances regarding technological applications within the biogas energy sector have been developed. In this sense, modular design is essential to permit disassemblability, maintainability, upgradability, reusability, and recyclability in products, especially in biogas production plants. Those plants could improve their contributing rates to green energy if the circular economy approach could be embedded into its design procedures. This article seeks to deepen the discussion of modularization and modularity strategies under the circular economy umbrella background. The aim was to explore this concept as a business model strategy specifically to disseminate the biogas production and understand what had been researched, the main limitations and the main opportunities to scale up its use. To reach those objectives, a Systematic Literature Review was used to identify the trends of publications, main authors, publication countries, researcher method, and evolution of the subject over the years. According to the chosen sample, five main discussion subjects emerged from the content analysis: the modularisation concept and the bridge with the circular economy context; the competitiveness of the modularisation approach; the modularisation within the biogas context use; the need for innovations within the industrial symbiosis approach and the limitations for the modularisation use.

Keywords: Modularisation; Modularity; Circular Economy; Biogas Production; Innovation.
1. Introduction

Modularisation and Modularity strategy under the Circular Economy principle in the energy sector is increasingly being discussed among policymakers, academics and practitioners (PANDREMENOS et al., 2009; MIGNACCA; LOCATELLI; VELENTURF, 2020). Many studies have discussed the benefits of designing, focusing on functionality and managing the infrastructure end of life optimally since components can become parts of new infrastructure or a new production chain (MOLINA-MORENO et al., 2017). In this sense, the modular design is essential for disassemblability, maintainability, upgradability, reusability, and recyclability in products (HATA; KATO; KIMURA, 2001).

Mignacca et al. (2020) highlight that "Modularisation" and "Modularity" are often used interchangeably, although they have completely different meanings. For these authors, a modular circular economy strategy can benefit from a circular economy perspective when a standard plant is assembled on-site from factory-produced modules of a smaller capacity (modularity effect).

Another aspect of Modularisation and Modularity is the replicability of business models in different contexts. In biofuel production systems, particularly in biogas production, it is necessary and important to establish industrial ecosystems customised to local conditions, which increases costs and uncertainty for the stakeholders involved and the integrating company (TSVETKOVA et al., 2015; TSVETKOVA; GUSTAFSSON, 2012).

Biogas is a gas mixture that contains between 40% and 70% methane, carbon dioxide (CO₂), hydrogen sulfide (H₂S) and other trace gases. Due to the high methane contents, biogas can be used as a fuel to replace fossil fuels in different applications: for heating, in engines for electricity generation, as vehicles gas, and also for hydrogen production (ACHINAS et al., 2017; ZAIN; MOHAMED, 2018). Biogas is produced from the anaerobic digestion (AD) by microorganisms of different organic raw materials, such as vinasse, animal manure, and sludge from wastewater and municipal solid waste (ZAIN; MOHAMED, 2018).

In addition to the production of heat and/or electricity and other applications already mentioned, DA systems for biogas production have different benefits, such as producing a nutrient-rich by-product (digestate) that can be used as a fertiliser. Also, the use of biogas reduces greenhouse gas emissions, like methane, which has a global warming potential of 21 times greater than carbon dioxide, is destroyed through its combustion (ELIZABETH FUNMI et al., 2021; CUÉLLAR; WEBBER, 2008).

Although Biogas systems are already widely used in different European countries and North American countries, such as the United States and Canada and South America, for instance in Brazil (SCARLAT; DALLEMAND; FAHL, 2018; THEUERL et al., 2019). And despite the benefits of increasing the supply of renewable energy sources, like the biogas, and other socio-environmental benefits, the potential for the source's expansion is still underexploited regarding
the many possible opportunities (PAVAN et al., 2021; MITTAL; AHLGREN; SHUKLA, 2018).

This article seeks to deepen the discussion of Modularisation and Modularity strategies under the circular economy umbrella background (HOMRICH et al., 2018). The aim was to explore this concept as a business model strategy specifically to disseminate the biogas production and understand what had been researched, the main limitations and the main opportunities to scale up its use. To reach the research objectives, a Systematic Literature Review was used to identify the trends of publications, main authors, publication countries, and evolution of the subject over the years. In this sense, the justification for this study is that, with the transfer of technology and knowledge, it might be possible to scale up this kind of business model, and new opportunities for the application of modularity and modularisation strategies may arise.

This paper is structured as follows; after a brief introduction of the main aspects involving the modularisation concept in the circular economy background, energy systems and specifically in the biogas research field, the method chosen to deepen those research areas is presented. Therefore, Section two presents the stages and main decisions taken to perform the systematic literature review (SLR). The findings were discussed in section three, providing a panorama of connections, recommendations, and limitations to enable CE principles for biogas production and some competitiveness highlights that this area could comprehend. The fourth section brings the main insights identified so far, research limitations and future research paths to improve opportunities within the field.
2. Methodology

To explore modularisation and modularity concepts as a strategy for biogas production, we adopted a systematic literature review (SLR) method where the focus lies on examining what has been written about Modularisation or (Modularity) focused on biogas production in peer-reviewed journals. Descriptive statistics analyses the literature to get an overview of the sample and within a qualitative approach to summarise studies which have discussed Modularisation or modularity strategies for biogas production, contextualising the SLR findings.

2.1 Data collection

The authors have chosen the SLR since it represents a structured way of selecting and collecting academic literature within a specific field or scope. It can also help provide an overview of areas in which the research is disparate and interdisciplinary. In addition, the SLR is a way of synthesising research findings to show evidence on a meta-level and to uncover areas in which more research is needed. Moreover, the other advantage of SLR lies in the rigour, transparency, and replicability of the process, which helps to limit bias and reduce the effects of chance (SNYDER, 2019).

Snyder (2019) mentioned that developing a systematic literature review is iterative. In this sense, we did a preliminary search to select which words to use in search queries. We evaluated which terms appeared most in research related to modular systems for general energy generation, mainly to produce biogas (MIGNACCA; LOCATELLI; VELENTURF, 2020; TSVETKOVA et al., 2015; TSVETKOVA; GUSTAFSSON, 2012). Then, different search criteria and Boolean word strings were tested and evaluated before the final search criteria were chosen.

It is worth mentioning that the search was performed in the Scopus and Web of Science databases due to the wide range of peer-reviewed journals. For example, the search criteria "biogas" and "modul*" were initially included in the search, but a huge number of documents were revealed (more than 300), which upon analysis, we noticed that the results were not relevant for the purpose of this study. As well as, the Boolean word strings ("biogas" AND "modularisation" OR "modularisation" OR "modularity") weren’t a good strategy for searching since we have found many documents in the Scopus database, but the Web Science database provided only five records. We decided to use the search for "biogas" AND "modular*".

Other limitations made in the database search were selection by topic (title, abstract and keywords) and only peer-reviewed articles in English. During the selection papers process, depicted in the flow diagram (Fig. 1), 29 records duplicated were removed first, followed by the screening of the remaining 57 articles. We performed the duplicate verification manually, helped by a spreadsheet in excel with keyword filters, checking the first author, and then validation by the full title.

In the first stage of the screening process, 39 articles that did not meet the criteria for discussing mobility and Modularisation as a strategy of biogas production were excluded. This first
screening through title and abstract reading yielded 15 articles that were all read in full of deepening since their relevance in modularity for the biogas ecosystem, thus removing 2 more articles. And creating a final list of 13 articles for review. The design of the SLR is represented in Fig. 1

![Fig. 1. Systematic Literature Review flowchart](image)

3. Results and Discussions

3.1 SLR descriptive statistics

Each paper was classified according to four descriptive elements: (i) the distribution of papers by publication year, (ii) journals of publication, (iii) country of research development, and (iv) research method.

Figure 2 presents the number of publications dealing with modularity strategies for biogas production. The first paper published in 2010 (DAMRONGSAK; TIPPAYAWONG, 2010) discussed the technological and environmental benefits of using modular technologies for small-scale biogas production, but there wasn't still no focus on modularity as a strategy for a circular economy. In the following years, the concepts of Modularisation into CE principles were discussed by Tsvetkova et al. (2015); Tsvetkova and Gustafsson (2012).
Table 1 presents the leading papers published on the subject and primary research methods. It is noted that there is no marked recurrence in a particular Journal, despite the Journal of Cleaner Production and Renewable Energy had the highest number of publications (two papers in each Journal). The studies on modularity or modularisation of biogas systems are still predominantly related to experimental cases (about 62% of the articles included in the SLR, pilot plants linked to innovation).

Table 1. Journals of publication, primary research methods

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<td><strong>Journal</strong></td>
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<td>Applied Energy</td>
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<td>Applied Sciences</td>
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<td>Applied Thermal Engineering</td>
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<td>Biomass &amp; Bioenergy</td>
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<td>Chemical Engineering Transactions</td>
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<td>Energies</td>
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<td>Environmental and Climate Technologies</td>
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<td>Fuel</td>
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<tr>
<td>International Journal of Hydrogen Energy</td>
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<tr>
<td>Journal of Cleaner Production</td>
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<td>Process</td>
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<td>Renewable Energy</td>
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Table 2 presents the leading countries that published on the subject. Regarding the place where the research was carried out, the European countries were the ones that most appeared in the evaluated publications. It is noted that Finland, Italy, Netherlands, Poland and Russia present recurrent publications on biogas within remote areas. This might occur because of the policy scheme of incentives in vigour within these countries: green certificates and auction market.

Table 2. Country of research

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<td>Canada</td>
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<td>Germany</td>
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<td>South Africa</td>
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<td>Thailand</td>
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3.2 Discussion

3.2.1 Modularisation and the bridge to the Circular Economy Context

The Modularisation within the circular economy context should include three main aspects (MIGNACCA; LOCATELLI; VELENTURF, 2020): reusing and repairing products; recovering components and using them into new products or for new uses; restructuring a system so that the waste of one process can be the feedstock for another one.

Modularity refers to the product or process structure composed of modules that can be designed and eventually changed independently (MACHADO; MORIOKA, 2021). However, they work integrated. Good modularity is recognised when there is flexibility between the modules in the case of a need to change within a system (HÖLTTÄ; OTTO, 2005). In this sense, modularity can be implemented in three dimensions (PANDREMENOS et al., 2009): in the product (architecture and design project), in the production (assembly line) and use (ease of use and customisation by the consumer).
Although the benefits of modularity are relatively intuitive for the circular economy, there are still many barriers to its implementation (CHOUINARD et al., 2019), for instance, in the case of the mechatronics industry. The authors emphasise that there is still a lack of common design language to represent a concept; transferring the information between the engineering disciplines and assessing the consequences of choices between alternatives is sometimes difficult to predict. And the same paradigm could be applied to the biogas modularisation context.

3.2.2 Competitiveness of the Modularisation approach

In the biogas context, due to the complexity of engineering parameters, a customised system would be economically unfeasible to individually design and engineer regarding the widespread of this energy source approach among various smaller farms (WHITE; KIRK; GRAYDON, 2011). So, the modularisation concept is being discussed to be applied in terms of favouring the economics involved in the systems by standardising and designing them in a modular fashion. Cost calculation reveals that depending on the price parameters, the modularisation process is economically competitive with the petroleum-based process (GÜRSEL et al., 2014). Due to lower product separation and upgrading requirements and lower indirect costs with modular processing, capital cost reduction is possible.

Since pre-manufactured modules assembled into a highly functional plant environment facilitates piping, utility, control and safety requirements in its infrastructure (HESSEL et al., 2012). In this sense, designing a distributed system can be preferable to large scale plants because they can be built in a shorter time with a faster time-to-market (GÜRSEL et al., 2014). However, it is mandatory to simplify the process equipment, e.g., limiting the number of gas treatment units and implementing alternative reaction systems (BIRTH; HEINEKEN; HE, 2014). Adding to that, transportation which has associated costs and emissions, is reduced by decentralised production (GÜRSEL et al., 2014). Still, regarding the production in modular plants, the main benefits come from feed flexibility, scalability and faster time-to-market.

The same authors mention that the presence of a variety of bioresources feeds flexibility and capacity adaptation, which is fundamental to these plants. The liquid fuels produced from bioresources cause lower greenhouse gas emissions since the feedstock captures carbon dioxide and it offsets carbon dioxide emissions from burning fuel(GÜRSEL et al., 2014).

3.2.3 Modularisation within the Biogas Context Use

Anaerobic digestion (AD) is a promising option to obtain renewable energy in the form of biogas and reduce the anthropogenic impact on the environment (KOVALEV et al., 2022). Biogas production may come "from various substrates, such as cow dung, poultry droppings, cassava biomass, vegetable and fruit waste, and their mixture" (SAWYERR et al., 2020).
There are two additional factors favourable to biogas exploitation: reducing energy consumption in the waste treatment process and the burning of methane instead of being released into the atmosphere (MONTEIRO; MANTHA; ROUBOA, 2011). However, research on biogas systems for rural use connected to the modularisation concept is limited in the literature (DAMRONGSAK; TIPPAYAWONG, 2010). In this sense, the potential for a compact system module in remote localities may provide a suitable solution due to its availability at a relatively low cost and simplicity to use, maintenance and repair (KIATSIRIROAT; EUAKITT, 1997).

Since agricultural activities offer the majority of substrates for agricultural biogas production, the establishment of agricultural biogas plants provides many options for multifunctional agriculture development (CHODKOWSKA-MISZCZUK; KULLA; NOVOTNÝ, 2017). Therefore, the farming sector and agro-food industry are among the main potential areas of biogas production and consumption (MONTEIRO; MANTHA; ROUBOA, 2011). Also, the need to reduce greenhouse gas emissions, ammonia, human labour and energy inputs are the subject of the development of modular design for dairy cows in an open cycle infrastructure (ROMANIUK et al., 2021).

Still, regarding the context of the application, in Thailand, as an example, biogas technology has been successfully developed and widely disseminated (PRASERTSAN; SAJJAKULNUKIT, 2006), where rural households use biogas for cooking. Many farms also use it for heat, shaft power and electricity (TIPPAYAWONG; PROMWUNGKWA; RERKKRIANGKRAI, 2007). Biogas powered refrigeration systems in a compact module may also offer an alternative option for applications in remote areas, such as agro-based rural areas for air and water cooling and food and vaccine preservation (DAMRONGSAK; TIPPAYAWONG, 2010).

Therefore, biogas systems implementation is subjected to several support measures and several constraints related to policy measures on energy, waste treatment and agriculture (MONTEIRO; MANTHA; ROUBOA, 2011).

Add to this scenario described before; it is suggested that Modularisation within the biogas context might allow for a comprehensive investigation and application of alternative measures in technology, size, spatial distribution, and land-use change (ROZAKIS et al., 2021), that can leverage its employment.

### 3.2.4 The need for Innovations within the industrial symbiosis approach

The modularisation strategy is highly relevant to industries that rely on industrial symbiosis (GÜRSEL et al., 2014), for instance, the biofuel industry. The "green energy" generation is allowed by utilising bio-resources producing biogas, bioethanol, or biodiesel. At the same time, use by-products in farming or other industries in the proximity, allowing the practical cycling of nutrients naturally.
The Modularisation faced as a spreadable business model strategy may offer a good opportunity to exchange value since this type of industrial symbiosis requires complex business constellations involving various business actors unaccustomed to working within one system (GUSTAFSSON; STOOR; TSVETKOVA, 2011).

3.2.5 Limitations for Modularisation use

There are natural limitations in the available technologies and facilities suitable for the full-scale operation of biogas modularised plants (KOVALEV et al., 2022). In the agro-industrial complex, there is still a problem with processing a large amount of organic waste that accumulates around livestock farms (ROMANIUK et al., 2021). The same authors mention that another aspect for small agricultural organisations is the introduction of innovative technologies that might have a long payback period, which is unbearable for the financial sustainability of those properties.

Regarding the policy issues, due to unavailability issues within a wide number of small properties, the state should subsidise new technological solutions for better performance results. Once this policy "presence" increases the investment attractiveness of such projects (ROMANIUK et al., 2021), the standards in technological development and the needs of investors maintain the investment level. However, to diminish the number of investments, in the case of no-modularised systems, the aspects regarding centralised plants arise as a good solution for efficient disposal (KARAEVA, 2021).

Important problems associated with synthesis from biomass are that it is widely distributed, and its composition and amount differ with location and season. Due to its large water content, its transportation is costly. Also, large biomass stocks need to be stored near the production plant because of their low energy density (GÜRSEL et al., 2014).

4. Conclusions

This article seeks to deepen the understanding of modularisation strategies under the circular economy umbrella. The aim was to explore this concept as a business model strategy specifically to disseminate the biogas production and understand what had been researched, the main limitations and the main opportunities to scale up its use. To reach research objectives was used an SLR to identify the trends of publications, main authors, publication countries and evolution of the subject over the years.

Although it might be considered a work in progress, some advances regarding technology application within the biogas energy sector have been developed over the last decade. However, from 86 publications within the research field of Modularisation and biogas, only 13 studies were included in this review paper since the modularisation aspect was not enough explored in the remaining sample. Most journals have a background in the energy sector, as expected. Regarding the countries of research group affiliations, it was identified that most cases are prevenient from countries where policy on green energy and auction market is most developed.
According to the chosen sample, five main discussion subjects emerged from the content analysis: the modularisation concept and the bridge with the circular economy context; the competitiveness of the modularisation approach; the Modularisation within the Biogas Context Use; the need for innovations within the industrial symbiosis approach and the limitations for the modularisation use.

Regarding the bridge with the circular economy context, it was made evident that the modularisation of biogas plants contributes to both the biological and technical cycles. The first regarding better energy use, and the second helping to prolong products and materials lives. According to the authors looked up in this research, the competitiveness is also improved once the same modular plant could be replicated, diminishing investments for small farms, in which the long payback cycle can constitute a problem. In this sense, policy issues came to the discussion, in which government could play a special role in subsidising the distributed implantation. In this sense, estimating the agricultural biogas potential in economic terms can contribute to refining policies inciting effective sector development.

Another prolific field for the use of Modularisation is the industrial symbiosis approach; once the variety of business actors working within one same system is increased, and modularisation business strategy could facilitate the maintenance of biogas shared plant opportunity. The limitations for modularisation use in the biogas field are many, such as the limitation of dealing with a large amount of organic waste, the relatively uncertain financial sustainability in small properties, the different types of biomass needs, like storage near the production plant, and high transportation cost, which impacts in need of distributed biogas plants.

However, with the proper development of new technological solutions, which are already taking place, the increasing need for green energy and social pressure related to widespread auction market regulations and public policies to monitor these change needs, those limitations may be overcome in the near future.

Although developed under a well-disseminated method (SRL), this research has intrinsic limitations regarding the authors' bias. The main subsections are chosen to represent the content analysis align with the authors' interests and expectations for future research in the field. Besides that, future research fields identified with this research point at improving the modelling aspects, economic sensitivity parameters, overcoming cultural policy paradigms and further partnership development among smaller users to promote viability.

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References


