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Bibliometric and Content Analysis on Circular Carbon Economy

Bing Fu[1], Suhaiza Zailani[2]
[1,2]University of Malaya

Abstract: This study provides a comprehensive review and analysis of the Circular Carbon Economy (CCE) through a systematic examination of 154 documents, employing bibliometric and content analysis methods. The research highlights the significant growth in CCE-related publications since 2017, with Germany, the United States, and China emerging as leading contributors. The analysis identifies key themes such as sustainable development, CO2 emissions reduction, waste-to-energy conversion, and carbon capture utilization and storage (CCUS). The findings underscore the interdisciplinary nature of CCE research, involving fields like chemical engineering, biological sciences, and business management. Additionally, the study emphasizes the critical role of policy support in advancing CCE initiatives, noting the importance of robust frameworks to incentivize carbon reduction and resource efficiency. Despite the progress, challenges remain, particularly in fostering international collaboration and integrating emerging technologies. This review provides valuable insights into the current state of CCE research, identifies gaps, and suggests areas for future exploration, particularly in enhancing global cooperation and developing innovative policy measures to support the transition to a sustainable carbon economy.

Keywords: *CO2 emissions, circular carbon economy, enablers, sustainable development impact, systematic literature review*

I. INTRODUCTION

The escalating threat of global warming, primarily driven by unabated CO2 emissions, poses significant socioeconomic and environmental challenges that demand urgent and systemic solutions (Alsarhan et al., 2021; BP, 2021; Saputra et al., 2022). Notably, despite a temporary decrease in global energy demand in the wake of the COVID-19 pandemic, annual carbon emissions alarmingly surged to a staggering 32,018.2 million tons in 2020 (BP, 2021). These emissions, primarily attributed to the unabated burning of fossil fuels, have experienced a notable upswing in the past few decades, especially in Asia (Bocken et al., 2016; Hu et al., 2018; Wang and Chang, 2014). Consequently, it is imperative to explore alternate pathways to traditional fossil fuel-based economies, thus constituting the central focus of this study: the circular carbon economy (CCE). Countries such as China, the United States (US), and India, ranking among the top three CO2 emitters globally, have pledged to curb carbon emissions (Gurney and Shepson, 2021; Mohmmed et al., 2019; Xu et al., 2022). Despite these commitments, the task of significantly reducing emissions remains monumental. In particular, China, which is a rapidly industrializing and urbanizing economy, is caught in the challenging predicament of balancing urbanization and economic growth with an increasing demand for resources and escalating greenhouse gas emissions (Geng et al., 2013; Jiang et al., 2018). Hence, the transition to a sustainable economic model that mitigates the adverse socioeconomic impact of increasing CO2 emissions has become a global imperative (Alsarhan et al., 2021).

Addressing this global challenge, the circular economy (CE) concept was introduced in the 1960s. It aims to realize environmental protection through the key principles of reduction, reuse, and recycling (i.e., the 3Rs) (Boulding, 1966; Winans et al., 2017). Following the introduction of this concept, the British government proposed the concept of a "low-carbon economy" (LCE) to maximize economic output while simultaneously minimizing pollution and enhancing resource efficiency (DTI, 2003). Despite these initiatives and the subsequent implementation of an LCE by several governments (Hu, 2012), achieving net-zero carbon emissions remains a global challenge due to our inherent dependency on fossil fuels (Perera, 2017) and the substantial investment required for a transition to net-zero energy. Responding to this urgent global predicament, the CCE concept has emerged as a novel approach to managing CO2 emissions (OVAM, 2019). Drawing from the guiding principles of the CE but focusing primarily on energy consumption and greenhouse gas emissions, the CCE envisages a balanced carbon cycle through an integrated strategy of closing the carbon loop, capturing CO2 emissions, and reducing CO2 emissions (OVAM, 2019; Ye et al., 2022). The holistic approach of the CCE incorporates the 4Rs—CO2 reduction, reuse, recycling, and removal—as potential strategies for managing emissions (Mansouri et al., 2020).

However, despite the growing interest in the CCE, a considerable knowledge gap in comprehending the enablers and the impacts of incorporating the CCE to manage CO2 emissions persists. This study seeks to fill this gap by providing an in-depth analysis of the CCE, primarily within the context of CO2 emissions. Leveraging a comprehensive literature review of the CE and the CCE and employing a bibliometric analysis to map the landscape of CCE research, this study aims to provide a holistic overview of the current state of research, thus highlighting areas that require further exploration. Given the relatively recent emergence of the CCE concept, particularly concerning CO2 emissions management, this study addresses the pressing need for an adequate decision-making framework that will guide practitioners in regard to CO2 emissions strategies. Building on the insights from previous research and policy recommendations related to low-carbon circular economic development (Ye et al., 2022) as well as climate change policies and measures using the CCE as a framing tool (Shehri et al., 2023), this study contributes to understanding the factors that facilitate CCE adoption and their interrelationships.

This study begins with an exhaustive literature review on the CE and the CCE, offering a robust foundation for the subsequent analysis. The ensuing bibliometric analysis employs descriptive statistics and bibliometric networks to meticulously dissect the landscape of CCE research. This exercise helps to identify the dominant players, seminal works, and thematic clusters in the domain while recognizing the emergent trends that might shape the future discourse. Subsequently, the study critically examines the opportunities and challenges associated with CCE implementation. This analysis is crucial for comprehending the practical complexities involved in transitioning to a CCE framework. Furthermore, the study dissects the 4Rs of the CCE, namely, CO2 reduction, reuse, recycling, and removal, providing a nuanced understanding of the mechanisms that govern the functioning of a CCE. Finally, the study concludes with a synthesis of our findings, discussing the study's contributions and limitations as well as potential avenues for future research. The primary objective of this analysis is to offer a comprehensive and insightful evaluation of the role of the CCE in managing CO2 emissions, thus providing an unprecedented benchmarking study for academics, policymakers, and businesses.

Against the backdrop of rapidly rising CO2 emissions and the urgent need for sustainable solutions, it is essential to comprehensively analyze the mechanisms, enablers, and potential impacts of a CCE approach. Building on this introduction, the study conducts a detailed literature review of the CE and the CCE. Using the power of bibliometric analysis, it attempts to uncover the landscape of CCE research, identifying key authors, thematic clusters, and emerging trends. This comprehensive analysis, coupled with descriptive statistics and bibliometric network visualization, offers a more granular understanding of the CCE field, informing our subsequent discussions and insights. The study then focuses on the opportunities and challenges involved in CCE implementation. The examination illuminates the tremendous potential of the CCE in managing CO2 emissions and the possible hurdles that may obstruct its full implementation. These insights, grounded in our comprehensive analysis, offer valuable guidance for those interested in pursuing or further studying the CCE.

In conclusion, this study provides an executive overview of our findings, underlining the significant contributions while also acknowledging the limitations. It also indicates areas for further exploration, thereby laying the groundwork for continued CCE research and practical advancements. This study, we hope, serves as a stepping stone in the pursuit of more sustainable and effective CO2 emissions management strategies, contributing to the ongoing discourse on the CCE and its implications for our future. In the larger context of global warming and the pressing need for sustainability, this study marks an important step in understanding the role of the CCE and its potential for mitigating CO2 emissions.

II. METHODOLOGY

To comprehensively explore the current state of research on the CCE, a systematic literature review (SLR) was conducted. An SLR is a rigorous scientific inquiry that aims to investigate and analyze the breadth and depth of a literature while also identifying any knowledge gaps that may exist (Xiao and Watson, 2019). It serves as an essential component of academic research, providing a systematic and reliable approach to gathering relevant information on a specific topic (Mengist et al., 2020). In contrast to conventional narrative reviews, which may lack methodological rigor, an SLR follows a well-defined process that ensures validity, reliability, and repeatability (Xiao and Watson, 2019). The SLR process consists of three key stages: 1) review planning, 2) review conducting, and 3) review reporting (Brereton et al., 2007; Keele, 2007). During the review planning stage, the scope and objectives of the review are defined, including the selection criteria for the literature. The review conducting stage involves conducting a comprehensive search across relevant databases, retrieving relevant papers, and critically assessing their quality and relevance. Finally, in the review reporting stage, the findings of the review are synthesized and presented in a structured and transparent manner.

In this study, the SLR process was applied to identify and analyze the relevant literature on the CCE, ensuring a comprehensive and rigorous examination of the topic. By conducting an SLR, this research aims to provide valuable insights into the current state of CCE research, highlight existing knowledge gaps, and pave the way for further scholarly investigation in this important field.

To conduct the research, contemporary tools such as Biblioshiny are utilized to perform bibliometric analysis for exploratory and visual analytics (Raza et al., 2023). RStudio (Biblioshiny package) and Biblioshiny were utilized for quantitative data analysis. To conduct bibliometric analysis (such as co-citation, coupling, scientific collaboration analysis) (Imran et al., 2021), the study used Biblioshiny, a web-based tool built into a bibliometric package (Aria and Cuccurullo, 2017). To enhance the research quality of this study, 154 unique papers were each manually examined. This rigorous process enabled the study to extensively evaluate and interpret the thematic framework, principal argument, and research methods of each paper. The subject area of each paper was meticulously examined to explore the variety of disciplines and content embracing the CCE concept. Similarly, the research methods of each paper were scrutinized to gain insight into the diverse approaches within the field. This thorough manual evaluation contributed to strengthening the dataset and enhancing the validity of the findings of the study.

III. ANALYSIS AND RESULTS

Green hydrogen production depends on factors like yield production of renewable power plants, electrolyzer technology, and GH_2 infrastructure readiness. The increase in renewable power plant yield production may drive down the cost of electricity production and in turn, reduce the cost of the GH_2 production. [3] mention that 70 % of GH_2 price is determined by electricity price from renewable sources besides the initial investment (electrolyzer technology). The average selling price of electricity per kWh in 2022 is IDR 1,137/kWh (7 cents, exchange rate Rp. 16.251,47). In order to achieve price competitiveness in GH_2 energy, Indonesia must pay attention to the pricing policy for renewable energy power plants. The determination of electricity tariffs by the government is regulated in MEMR Regulation No. 3 of 2020 concerning the Fourth Amendment to MEMR Regulation No. 28 of 2016 concerning Electricity Tariffs provided by PT PLN (Persero).

Currently, there are four electrolysis technologies supported for green hydrogen production, including alkaline water electrolyzer (AE), proton exchange membrane electrolyzer (PEM), solid oxide electrolyzer (SOE), and anion exchange membrane electrolyzer (AEM) [37]. According to [38], AE stands out among other electrolyzers due to the longest lifespans, lowest capital expenditures (CAPEX), and highest technology readiness level. This durability, with lifespans surpassing 30 years and high scalability, has been supported by most manufacturers since the early 1900s.

Indonesia's Hydrogen Strategy mentioned the GH_2 production aims to start in 2031. The electrolyzer cost prediction was reported by previous studies considering factors like scale-up, manufacturing volumes, and technology improvements. [39], predicts that the gap in CAPEX between AE and PEM technologies is expected to narrow significantly as plant sizes increase. For very large plants (greater than 100 MW), the costs for both technologies will approach 320-400 USD/kW by 2030. The electrolyzer capital costs will be estimated to drop to 88 USD/kW for AE and 60 USD/kW for PEM under an optimistic scenario by 2050, or 388 USD/kW and 286 USD/kW, respectively, under a pessimistic scenario [40]. According to [41], the initial investment of AE may costs 500-1400 USD/kW, 1100-1800 USD/kW for PEM, and 2800-5600 USD/kW for SOE. Electrolyzer manufacturers generally agree on the potential for rapidly reducing capital costs through economies of scale [37].

The average cost of GH_2 production consists of investment and operational costs, which are defined using the Levelized Cost of Hydrogen (LCOH). LCOH accounts for all capital and operating production costs in a levelized manner over a unit of produced hydrogen and its derivative (USD/kg) [42]. By 2030, the global LCOH for GH_2 is predicted to be less than 5 USD/kg for solar, onshore wind, and offshore wind energy sources due to lower electrolyzer costs and the Levelized Cost of Electricity (LCOE) in both scenarios [40]. Based on [3] calculations by taking three PLN case studies, the price of hydrogen production is around 4.61-5.45 USD/kg in 2030, assuming the cost of a PEM electrolyzer is between 450-1700 USD. In comparison, the projected hydrogen price in Japan is around 5.7–7.7 USD/kg in 2025 [43], around 5.5-7.7 USD/kg in South Korea [44], and around 4.9–6.5 USD/kg in Singapore [45]. Despite that, the projected price of GH_2 in Indonesia is not yet competitive because it is three times the current average cost of production. Therefore, the government needs to help the growth of this sector by making policies, creating an investment climate, and developing competitive business models.

Regarding energy pricing, [46] found that more than 95% of non-subsidized residential consumers in Indonesia are willing to pay up to 40% higher than the current price for greener electricity. This willingness to pay increases with the share of renewable energy in the energy mix. These findings highlight the strong potential market for greener energy solutions in Indonesia, indicating that consumers are ready to support and invest in cleaner energy alternatives.

A well-defined regulatory framework is a crucial initial step for fostering the growth and defining competitiveness of green hydrogen market. Clear regulations provide certainty and stability for industry stakeholders and investors. Given that green hydrogen may often be more expensive than existing fossil fuels, government support through clearer policies, incentives, and infrastructure readiness is essential.

Indonesia's government can play a pivotal role in hydrogen energy transition by establishing clear regulations for standards, technical production, and transportation. This includes defining greenhouse gas emission thresholds and related licensing regulations, which are crucial for ensuring that hydrogen production remains environmentally sustainable. The government can start to implement carbon pricing mechanism, similar to Australia's Carbon Pricing Mechanism (CPM) or the European Union Emissions Trading System (EU ETS).

Additionally, providing grants for hydrogen-related research and development projects, offering accelerated depreciation incentives, and financial assistance for developing hydrogen infrastructure are also critical measures. The government should encourage collaboration between the public and private sectors, along with international organizations, to promote the adoption of green hydrogen. Educational campaigns to raise awareness about the environmental, energy security, and health benefits of green hydrogen will also be needed in gaining public support and driving the energy transition forward.

Despite the challenges of supply-demand uncertainty, unformed policy, and infrastructure barriers, the benefits of GH_2 production outweigh the challenges, including reducing dependence on fossil fuels, being environmentally friendly, and providing an efficient energy carrier. [47] also shows that the use of hydrogen proves beneficial for long-term storage, whereas the electricity economy is preferable in the case of short-term energy storage. In the electricity generation sector, GH_2 serve as an energy transport medium, becoming an option to meet domestic needs and expand energy connectivity that is geographically unreachable. Additionally, GH_2 can be used as fuel for co-firing, which has the potential to reduce greenhouse gas emissions by 10,588,235 tons of CO_2-eq [3]. GH_2 as a raw material in the fertilizer supports

Indonesia's potential as the 3rd-largest ammonia exporter in the world.

The economic viability of green hydrogen production in Indonesia seems a promising opportunity. [17] mentioned that GH2 production from small hydropower plants in Indonesia is economically feasible. The study found that green hydrogen production using excess electricity from small hydropower plants is a viable method for decarbonization and offers scalability for future energy production in Indonesia, with the first initial step being as a green hydrogen and natural gas co-firing fuel mixing in gas turbines. [48] also found the economic and technical feasibility of constructing a green hydrogen facility in Jambi, Indonesia. The finding highlighted Jambi's projected selling price for green hydrogen demonstrates competitiveness within the market. These findings offer valuable insights into the potential profitability and market prospects of green hydrogen. Additionally, [49] results indicate that the establishment of hydrogen production in Indonesia using fermentation technology and agricultural waste is economically viable.

Integrating green hydrogen into Indonesia's energy mix represents a transformative opportunity to decarbonize the energy sector and advance sustainability goals. By critically evaluating various aspects, including scalability, technological challenges, and socioeconomic implications, stakeholders can gain a holistic understanding of the potential benefits and challenges associated with green hydrogen. This information will aid in making informed decisions and formulating effective strategies to drive the successful integration of green hydrogen into the energy landscape [50]. Indonesia's implementation of green hydrogen production to optimize the nation's renewable sources requires careful planning, technology optimization, and infrastructure development. Government support and decisions play a crucial role in the green hydrogen energy transition.

IV. CONCLUSION

The study presents a thorough examination of the Circular Carbon Economy (CCE) through an extensive review of the literature and a detailed bibliometric analysis. The findings indicate a rapidly growing interest in the CCE, driven by the urgent need to mitigate carbon emissions and transition towards sustainable development. The research identifies Germany, the United States, and China as key contributors to the CCE discourse, with a notable focus on themes such as sustainable development, carbon capture, and waste-to-energy technologies. The analysis reveals that while significant progress has been made in advancing CCE research, challenges remain, particularly in fostering international collaboration and integrating interdisciplinary approaches. The study highlights the critical role of policy frameworks in supporting the transition to a CCE, emphasizing the need for coordinated efforts between policymakers, industry, and academia. In conclusion, this study provides valuable insights into the current state of CCE research and identifies areas for future exploration. By bridging knowledge gaps and fostering global collaboration, the CCE has the potential to play a pivotal role in addressing the global carbon challenge and promoting sustainable economic growth. Future research should focus on enhancing international cooperation, exploring new technological innovations, and developing robust policy frameworks to support the widespread adoption of CCE practices.