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THE USE OF ADDITIVE MANUFACTURING TO PRODUCE PROTON EXCHANGE MEMBRANE ELECTROLYZER CELL COMPONENTS: A SYSTEMATIC REVIEW

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Abstract. *The transition from fossil fuels to sustainable energy sources has driven extensive research into renewable options such as wind, solar, and green hydrogen. Proton Exchange Membrane Electrolyzer Cells (PEMECs) are considered a promising technology for hydrogen production, with bipolar plates (BPs) playing a crucial role in their structure and reactant transfer. Additive Manufacturing (AM), known for its cost-effective production of intricate 3D structures, has gained attention into electrochemical sciences. This study aims to explore the application of AM in manufacturing electrolytic cells, focusing on low-cost and high-efficiency PEMEC development. A systematic review was conducted using Scopus and Web of Science databases, identifying relevant articles based on topic-related keywords. The results reveal the versatility of AM in printing various materials, including metals and polymers, using different 3D printing technologies. Although limited studies exist on AM applied for green hydrogen components production, the technique demonstrates suitability in manufacturing complex components with high precision, reduced production time, and lower costs in this field. Further research is needed to fully explore the potential of AM in achieving sustainable and efficient hydrogen production in PEMECs.*

Keywords: Additive manufacturing; Proton exchange membrane electrolyzer cells; Green hydrogen; Bipolar plate

1. INTRODUCTION

Additive manufacturing (AM) technology has revolutionized the manufacturing process by offering a groundbreaking approach to fabricating complex structures with minimal material waste. In contrast to traditional processes, AM overcomes the limitations associated with producing intricate designs with complex flow channels. It enables manufacturers to explore new possibilities in creating customized and intricate designs by building objects layer by layer based on 3D computer-aided design (CAD) models. With its ability to efficiently produce complex structures and minimize post-processing requirements, AM opens new opportunities in manufacturing (Crankovic, 2020; Javaid et al., 2021).

In the energy sector, additive manufacturing holds significant importance, especially in the context of sustainable and green hydrogen production. Hydrogen, a clean fuel with versatile applications, is considered crucial for storing renewable and intermittent energy from sources like wind and solar. Additive manufacturing, particularly in the production of electrolysis cells, presents promising potential for generating hydrogen through water electrolysis. By using AM, electrolysis cells can be fabricated with innovative designs that streamline assembly processes and reduce capital costs. Researchers have explored the application of additive manufacturing in various components of electrochemical systems, such as chassis, membranes, electrodes, and flow plates. This technology offers opportunities to enhance the efficiency and performance of electrochemical devices used in different energy applications (Celik et al., 2022; O'Neil et al., 2016; Piri et al., 2020; Wappler et al., 2022; Yang et al., 2017, 2019).

The AM applied to electrochemical devices has generated interest in the suitability of manufacturing electrolytic cells. The use of additive manufacturing in the production of electrolytic cells has a potential for optimizing cell performance and improving the overall efficiency by incorporating improved multiscale graded interfaces, addressing challenges such as interfacial contact resistances. This innovative approach propels advancements in energy conversion and storage systems, contributing to the development of sustainable and efficient energy technologies (Ahn et al., 2020; Tarancón & Esposito, 2021).

Hydrogen has emerged as a highly regarded medium for storing renewable and intermittent energy. To efficiently produce hydrogen, low-temperature proton exchange membrane electrolyzer cells (PEMECs) have gained attention for their rapid response to power inputs, high-purity hydrogen generation, and ability to operate at high current densities and pressures. A typical PEMEC configuration includes a catalyst-coated membrane (CCM), two liquid/gas diffusion layers (LGDLs), two bipolar plates (BPs), and two current distributors (CDs). However, the limited efficiency and high cost/complexity associated with PEMECs have hindered their widespread commercialization, Figure 1. Efforts are ongoing to optimize the design and performance of these components to achieve higher efficiency and cost-effectiveness in hydrogen production, with reduce weight and volume, and increase component count for widespread commercial adoption (Hornés et al., 2021; Yang et al., 2019; Yang, Mo, et al., 2018; Yang, Yu, et al., 2018).

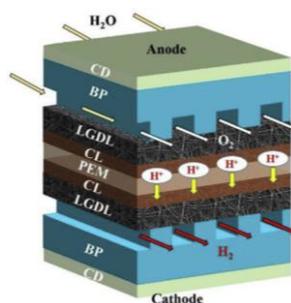


Figure 1. Schematic of an internal structure of a PEMEC (Yang, Yu, et al., 2018).

Bipolar plates (BPs) and liquid/gas diffusion layers (LGDLs) are two of the most expensive and complex components in a proton exchange membrane electrolyzer cell. The manufacturing process of BPs, typically made from graphite or titanium, significantly impacts their cost, weight, and volume. Traditional methods involve multiple steps, such as roll-cladding, annealing, stamping, punching, and additional coating, leading to increased expenses and fabrication time. BPs and LGDLs account for a significant portion (60-70%) of the overall cost of a PEMEC stack, and up to 60% of its total weight (Piri et al., 2020; Yang et al., 2021).

Efforts to reduce the cost and enhance the performance of PEMECs involve exploring alternative catalyst materials and optimizing various components within the system. BPs play a critical role in PEMECs by distributing reactants and products while conducting current. Graphite has traditionally been used as the preferred material due to its ease of fabrication and corrosion resistance. However, the production of thin graphite plates presents challenges due to their brittleness and gas permeability. Additionally, incorporating liquid cooling between the anode and cathode flow plates in graphite BPs can lead to costly and time-consuming manufacturing processes. The cost, weight, and volume of BPs pose significant hurdles in the commercial application of PEMECs. Similarly, LGDLs, composed of titanium and carbon, are

manufactured using weaving, sintering, or etching processes, each with its limitations and associated costs. Despite efforts to optimize the properties and structures of BPs and LGDLs, the issue of interfacial contact resistance remains unresolved, limiting the development of cost-effective and efficient PEMEC systems. Simplifying component design and configuration is a key challenge that must be addressed to enable the widespread adoption of PEMEC technology (Yang et al., 2017, 2019; Yang, Yu, et al., 2018).

The production of BPs and LGDLs can be simplified by AM, reducing manufacturing steps and associated material costs. The challenge of additive manufacturing applied to PEMEC fabrication is to maintain or even increase cell efficiency, reduce final costs through material substitution and geometry optimization, and facilitate production scalability. These goals make additive manufacturing a viable alternative for large-scale production of PEMEC components (Carmo et al., 2013; Lettenmeier et al., 2017).

This innovative approach has the potential to optimize the design and performance of PEMECs, making them more affordable and efficient. Additionally, additive manufacturing allows for the exploration of novel materials and improved structural configurations, further enhancing the overall functionality of these components. The integration of additive manufacturing in the production of BPs and LGDLs represents a promising avenue for advancing the commercial viability of PEMEC technology and accelerating the adoption of hydrogen as a clean energy solution (Yang et al., 2017, 2019, 2021; Yang, Mo, et al., 2018; Yang, Yu, et al., 2018).

Based on this context, is the aim of this research was to carry out a systematic review on the manufacturing of components for proton exchange membrane electrolyzer cells using additive manufacturing. The review focused on articles related to the topic, aiming to identify the main AM technologies and materials employed, as well as the 3D-printed components of PEMECs.

2. METHODOLOGY

The methodology employed in this study aimed to systematically survey and analyze pertinent literature regarding additive manufacturing for the fabrication of components in proton exchange membrane electrolysis cells. The research process was carried out the Web of Science and Scopus databases until July 15th, 2023, and was limited to Article, Article Review, Conference Paper, Conference Review publications type. The search targeted article titles, abstracts, and keywords using specific search strings presented in the Table 1.

Table 1. Keywords and strings applied on the Web of Science and Scopus platform for article selection.

#	Theme	Keywords
1	Additive Manufacturing	("additive manufacturing" OR "3D printing" OR "rapid prototyping" OR "layered manufacturing")
2	Green hydrogen products by electrolyzer cells	("hydrogen production" OR "green hydrogen" OR "sustainable energy") AND ("electrolyte" OR "electrolysis cell" OR "electrolyzes cell" OR "electrolyze cell" OR "bipolar plate" OR "electrolyzer" OR "flow field")
3	Additive Manufacturing & Green hydrogen products by electrolyzer cells	("additive manufacturing" OR "3D printing" OR "rapid prototyping" OR "layered manufacturing") AND ("hydrogen production" OR "green hydrogen" OR "sustainable energy") AND ("electrolyte" OR "electrolysis cell" OR "electrolyzes cell" OR "electrolyze cell" OR "bipolar plate" OR "electrolyzer" OR "flow field")

After carried out searches in both databases, the first step involved eliminating duplicate articles. Subsequently, a preliminary selection was made by conducting a thorough reading of the titles and abstracts of each article, aiming to identifying those relevant to the topic. In the next stage, a more detailed analysis was conducted by analyzing the selected articles in their entirety. This step allowed for a refined filtering process, ensuring that only the most pertinent articles were included. During this process, relevant information, such as the printed components and specific additive manufacturing technologies employed, was carefully collected and documented.

Quantitative analysis involved creating graphical representations of the selected articles publication dates. Additionally, VOSviewer software was used to perform graphical analyses, facilitating the identification of frequently used terms and their relationships within the selected literature. Finally, the study concluded with a concise summary of the top three articles, emphasizing the benefits of utilizing additive manufacturing for component fabrication.

This chosen methodology ensured a rigorous and structured approach to identify, analyze, and synthesize pertinent articles. The systematic search process, incorporating multiple stages of screening and data analysis, provided a comprehensive overview of the current research landscape concerning additive manufacturing for PEMEC components in the production of green hydrogen.

3. RESULTS AND DISCUSSION

3.1 Quantitative analysis

Figure 2 presents a logarithmic scale graph comparing the scientific publication search carried out using the quantitative results obtained from the combinations listed in the Table 1. Keyword set #1, related to additive manufacturing, and keyword set #2, associated with green hydrogen products by electrolyzer cells, were utilized. The graph demonstrates a narrowing focus in research and a growing interest in the proposed topics, particularly since 2019. This information is presented in terms of absolute numbers and percentages.

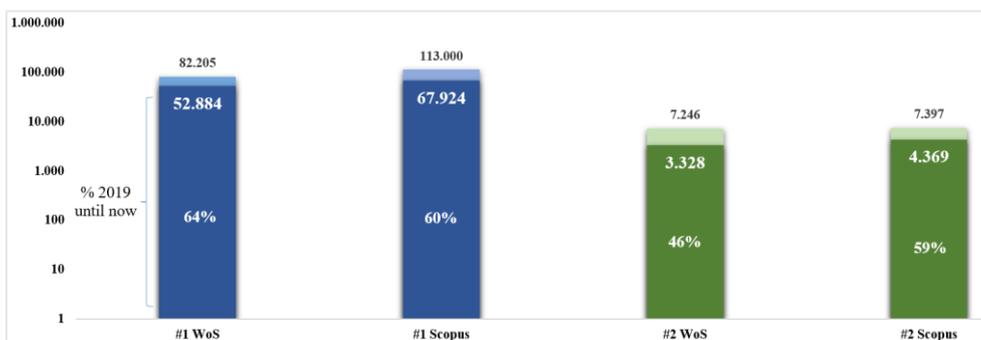


Figure 2. Comparative logarithmic analysis of scientific publications on additive manufacturing and green hydrogen products by electrolyzer cells.

Based on the results obtained and visualized in Figure 2, it can be inferred that the research is highly relevant, particularly in the field of additive manufacturing, with approximately 82,000 and 113,000 publications, respectively, in #1 WoS and #1 Scopus. The analysis also reveals that within the total universe of published works on these topics, 64% and 60% were published from 2019 onwards, in the last 5 years, for the field of additive manufacturing. For the production of green hydrogen using electrolyzer cells, the percentages are 46% and 59% in #2 WoS and #2 Scopus, respectively.

According to the methodology employed, the literature search for keyword combination #3 from the previous table yielded a total of 138 results. After removing duplicates, 75 articles remained. Following a review of titles and abstracts, 22 articles were selected for full-text reading. Ultimately, after the final screening process, 15 articles were chosen as highly relevant to the present topic. The figure below illustrates the flowchart outlining the stages of identification, selection, eligibility, and inclusion of articles, while the table below provides a list of the selected articles along with the printed components manufactured using additive manufacturing and the respective technology employed. Out of the previously selected 22 articles, all were published between the years 2016 and nowadays.

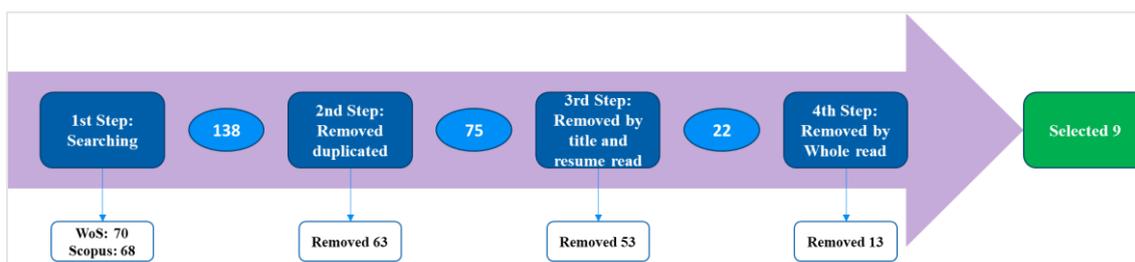


Figure 3. Flowchart of Article Identification, Selection and Eligibility Process.

In order to perform a more detailed analysis of the complete set of keywords, a co-occurrence network of the topic was generated using VOSviewer software with metadata from the 75 articles found prior to the pre-filtering stage. This selection was necessary as a meaningful co-occurrence network cannot be constructed with a small number of articles. The co-occurrence network graph was created with respect to the timeline Figure 4. The lines connecting the terms represent their relationships, and the size of each item's circle is determined by its weight, indicating the frequency of the term appearing in the title, abstract, and keywords. The color coding of each term in the co-occurrence network indicates its temporal relevance, with yellow representing recent references and dark blue representing older references in the literature. Notably, the term “*bipolar plate*”, one of the key components of an electrolytic, is highlighted and it is linked to other terms such as “*electrochemical performance*”, “*hydrogen production*”, “*printing*” and “*proton exchange membrane electrolyzer cells*”. Of particular interest is the term “*printing*” which appears to be one of the most recent developments in the field.

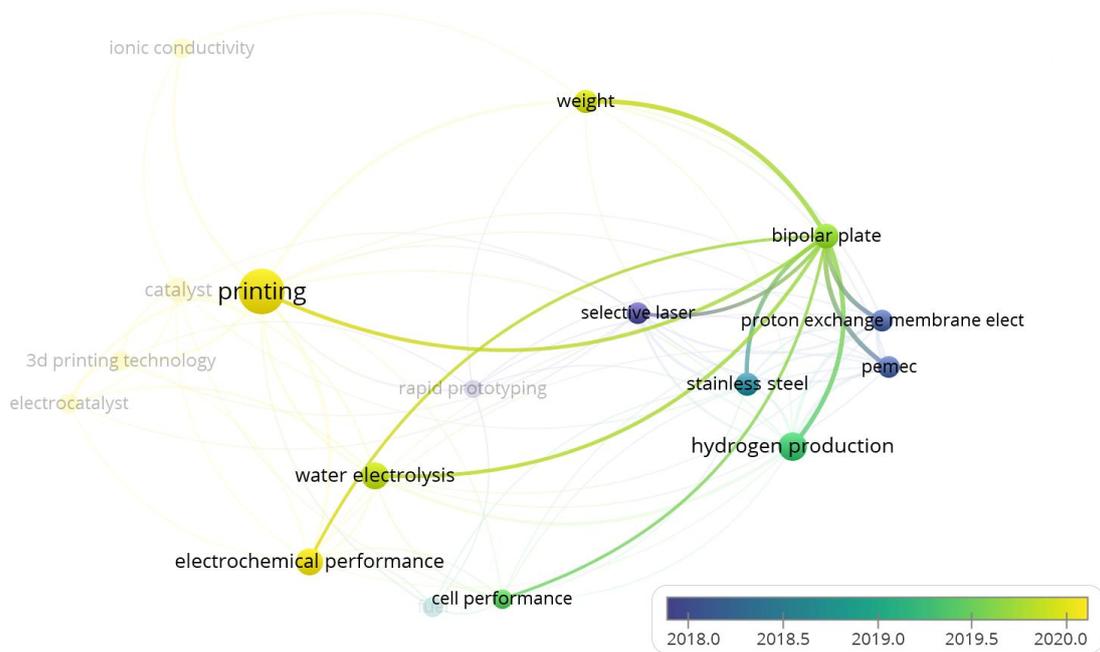
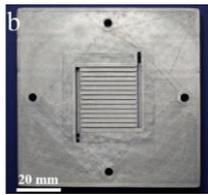
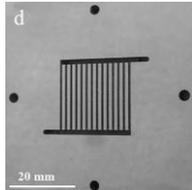
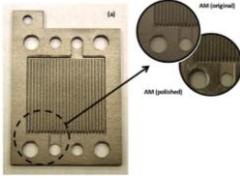
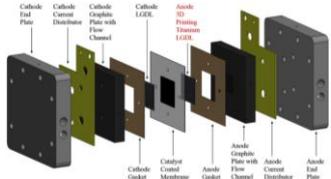
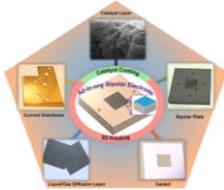
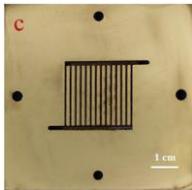
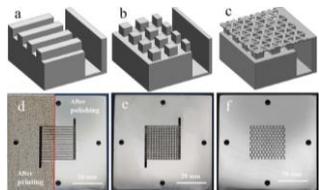


Figure 4. Co-occurrence network analysis of key terms in additive manufacturing for green hydrogen production: a visual exploration.

Table 2. List of articles and respective component printed by additive manufacturing.

#	Component	AM Process	Material	Image	Reference
1	Bipolar Plate (BP)	Stereolithographic (SLA)	Clear resin		(Piri et al., 2020)
2	Bipolar Plate	Fused deposition modeling (FDM)	Polylactic acid (PLA)		(Yang et al., 2019)
3	Bipolar Plate	Power Bed Fusion (PBF) / Selective laser melting (SLM)	Stainless steel 316L		(Yang et al., 2017)
4	Bipolar Plate	Power Bed Fusion (PBF) / SLM	Stainless steel 316L		(Sánchez-Molina et al., 2021)

#	Component	AM Process	Material	Image	Reference
5	Liquid/gas diffusion layers (LGDLs)	Electron Beam Melting (EBM)	Ti-6Al-4V		(Mo et al., 2016)
6	All-in-one bipolar electrode: Catalyst layer, Carbon paper (CP) LGDL, BP, CD, and gasket.	not mentioned	not mentioned		(Yang et al., 2021)
7	Bipolar Plate	Power Bed Fusion (PBF) / SLM	Stainless steel 316L		(Yang, Yu, et al., 2018)
8	Bipolar Plate	Selective Laser Sintering (SLS)	Titanium		(Celik et al., 2022)
9	BP, LGDL, gasket, and current distributor	Power Bed Fusion (PBF) / SLM	Stainless steel 316L		(Yang, Mo, et al., 2018)

3.2 Qualitative analysis

In this section, we will discuss two articles that are particularly relevant to the topic at hand. These studies provide valuable insights and contribute to the understanding of the subject matter. In the article titled “*Fully Printed and Integrated Electrolyzer Cells with Additive Manufacturing for High-Efficiency Water Splitting*” (#9), the authors presented a pioneering approach to fabricating electrolyzer cells using additive manufacturing. They successfully integrated four conventional components, including the liquid/gas diffusion layer, bipolar plate, gasket, and current distributor, into a single multifunctional AM plate,

Figure 5. This integration was achieved without the need for specialized tools or molds, representing a significant advancement in the field. The primary objective of the study was to analyze the efficiency of the printed assembly with the aim of reducing costs. To fabricate the integrated plate, the researchers used powder bed fusion (PBF) technology, with 316L stainless steel selected as the material. The structural innovations implemented in the printed plate offer a fundamental development in simplifying PEMECs. This innovation offers significant benefits by reducing the number of required parts from four to one, resulting in a substantial decrease in overall weight from 266.90 g in conventional cells to 144.15 g. It contributes to potential cost savings and enhances the efficiency of hydrogen generation. The AM PEMECs demonstrate remarkable improvements in hydrogen generation rates, with increases 61.81% compared to the conventional cell. These performance enhancements save feedstock and energy, with a positive impact on the overall hydrogen levelized cost, which accounts for 71.9% of the total cost. The results demonstrated that the AM 316L plate exhibited excellent corrosion resistance during operation. Additionally, the durability was confirmed at the cathode side, indicating its suitability for long-term use (Yang, Mo, et al., 2018).

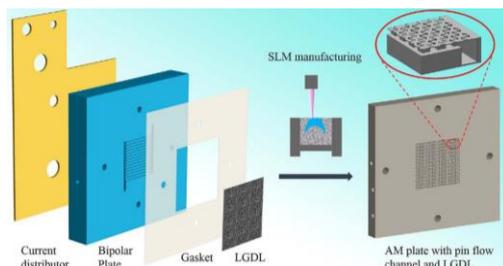


Figure 5. Integrated components of a PEMEC via additive manufacturing (Yang, Mo, et al., 2018).

The article “A Novel PEMEC with 3D Printed Non-Conductive Bipolar Plate for Low-Cost Hydrogen Production from Water Electrolysis” (#2) presents an innovative approach to PEMECs using an AM bipolar plate made of not conducted PLA material, Figure 6. The BP functions more as a structural component, while the liquid/gas diffusion layers serve as the primary electron transporter. This novel design offers several advantages, including reduced mass, cost, and mechanical support for the cell. The use of a thin Ti LGDL film provides excellent electrical conductivity. Compared to graphite conventional BP, PEMECs with PLA BPs exhibit an extremely low cost, with PLA BPs being only 10% of the cost of graphite BPs. Furthermore, the hydrogen production rate per unit BP cost is nearly 6 times higher in the case of PEMECs with PLA BPs when compared to conventional cell. These findings demonstrate the potential of using accessible and highly cost-effective BP materials, such as PLA, in various applications beyond water electrolysis. This includes the development of plastic materials for low-cost energy conversion devices like batteries, solar cells, and fuel cells. The combination of affordability and satisfactory electrochemical performance opens up new possibilities for the widespread implementation of these devices, enabling more sustainable and accessible energy solutions (Yang et al., 2019).

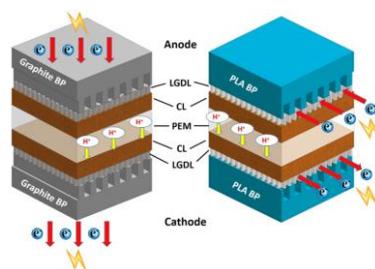


Figure 6. Configuration and electron-conducting path of conventional PEMECs and Novel PEMECs with PLA BPs (Yang et al., 2019).

The discussed and researched studies are still in initial stages, but they validate the use of additive manufacturing for PEMEC component. These findings highlight the potential and feasibility of AM in advancing the development and production of PEMECs. Further research and technological advancements in this field are needed to fully exploit the benefits, large-scale and optimize its application in PEMECs. These studies provide a promising foundation for future advancements in additive manufacturing for PEMECs.

4. CONCLUSION

In conclusion, this study has demonstrated the immense potential of additive manufacturing in revolutionizing the production of electrolyzer cells. The successful printing of the bipolar plate, a crucial component of PEMECs, has shown promising results in terms of increased efficiency and cost reduction and versatility to utilize metals or polymers as printing materials. The development of multi-material printing techniques is crucial for enabling the production of fully integrated devices through a single printing process. This advancement will further streamline the manufacturing process and contribute to the overall cost-effectiveness and efficiency of electrolyzer cells. AM has the capability to enhance sustainability efforts by enabling efficient and cost-effective hydrogen production. Additionally, further research is needed to compare the efficiency of hydrogen production among different materials, allowing for a comprehensive evaluation of their viability in future applications and understand large-scale production costs.

By leveraging advanced materials, intelligent design strategies, and scalable manufacturing techniques, AM has the capability to drive the development of efficient and cost-effective PEMECs, contributing to a greener and more sustainable future. Overall, this study highlights the significant impact of additive manufacturing in advancing the field of electrolyzer cells and green hydrogen production.

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