Life cycle assessment and life cycle costing of unitized regenerative fuel cells: a literature review

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Abstract

The design of a Polymer Electrolyte Membrane Unitized Regenerative Fuel Cell (PEM-URFC), a compact version of the regenerative PEM fuel cell with a single electrochemical cell, is one of the competent technologies for reducing fossil fuel consumption and greenhouse gases emissions linked to energy power production and energy storages issues. A URFC can produce hydrogen fuel, storing the excess energy produced (e.g., from renewable energy systems, solar plants) and electric energy in a fuel cell mode to meet the energy demands of a specific sector. Life Cycle Assessment and Life Cycle Costing are useful methods to evaluate the potential energy-environmental-economic benefits of these technologies, identifying the main hotspots and comparing them with traditional ones. The research here presented aims to analyse the state of the art of the application of the two methods, LCA and LCC, to the URFC, to verify what is already present in the literature to determine the research trend over the years. A systematic protocol has been chosen as the research method to provide a complete and minimally biased in defining the sample on the life cycle of the PEM-URFC and its components. Then a bibliometric and network analysis is carried out. Regarding the results, the review allows to obtain an overview of the materials and energy flows accounted for in the reversible operation of the device under consideration (i.e., the use of capable bifunctional electrocatalysts, prototypes, etc.) and of the resources and environmental, energy, and economic impacts. Results highlight that there is significant variability in the results, given by the selected boundary systems, the final users (e.g., industry, buildings, vehicles, production of electricity and hydrogen), and the steam reforming of the systems. Regarding the technological features of components, no consensus was reached on the power, materials, and life cycle phases. The analysis highlights the need to have more scientific studies on LCAs and LCCs applied to PEM-URFC systems for evaluating the economic and environmental performances of the emerging technologies. Furthermore, in general, when these methods are combined with an energy model, the mandatory parameters of the life cycle approach are neglected or omitted, reporting limited information on the materials of the prototype studied or environmental /economic datasets. This paper reports the preliminary results of the literature review conducted. The full systematic analysis and methodological issues of the approach applied to the papers selected will be the object of future publications.

Keywords: unitized regenerative fuel cell (URFC), polymer electrolyte membrane (PEM), Life cycle assessment (LCA), Life cycle costing (LCC)

1 Introduction

In the last decades, the European Commission has proposed different energy plans for reducing Greenhouse gas emissions by 2030 to at least 55% compared to 1990, increasing energy efficiency and the use of sustainable energy sources (European Union, 2018). One of these is the new hydrogen strategy set by the European Green Deal (European Commission, 2019) that pushes towards the development of new sustainable hydrogen technologies. In this contest, one of the most relevant efforts into the implementation of hydrogen economy could be focalized on the Proton Exchange Membrane Unitized Regenerative Fuel Cell (PEM-URFC). Its original shape was called Discrete regenerative fuel cell (DRFC) that instead used the electrolyser and the fuel cell technologies separately into the same system. One of the main energy advantages of the URFC system is the possibility to increase self-consume of energy produced by renewable systems in building sectors, converting renewable electricity into hydrogen fuel and the fuel stored in electricity when required. This technology combines the functionality of both electrolyzer and fuel cell in the same bifunctional cell. However, due to the high cost of its main components, it is not still used for the building sector, but only in the military and aerospace fields (Wang et al., 2016; Dutta et al., 2017). To assess the potential energy-environmental-economic benefits of these technologies, Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) are useful methods. They allow to identify the main hotspots and to compare new technologies with conventional plants during their whole life cycle: from raw materials extraction to end-of-life treatments (ISO, 2006a, 2006b). Many researchers carried out a literature review on life cycle thinking approaches applied to both electrolyzer and fuel cell (Longo et al., 2017; Masoni & Zamagni, 2011; Abdelkareem et al., 2021). Based on the authors' knowledge, the available literature reviews on PEM-URFC focus only on its energy, economic and technological aspects, identifying that this system still requires additional optimization (Gabbasa et al., 2014; Millet et al., 2011; Paul & Andrews, 2017). Furthermore, these studies do not apply analysis to the entire life cycle of technology.

Concerning this research gap, the present study aims to evaluate the already existing knowledge on LCA and LCC applied to PEM-URFC and other PEM devices, highlighting the emerging research trends and any good practices and/or critical issues and gaps. In particular, the research questions addressed in this paper are: "What are the emerging research trends in PEM-URFC systems?" and "Which are the most relevant studies on LCA and LCC of PEM devices?". The objectives of this study are pursued by applying a systematic protocol for defining the sample of papers. Then, a bibliometric analysis is carried out to evaluate the trend of this research field. The results can assist efforts aiming at presenting knowledge on URFC economic and environmental performances and to identify patterns between authors, keywords, and subject area.

The paper is structured in 4 sections. After the introduction in which the contest and aim of the research are reported, the second section describes the methods applied for conducting the literature review. The third section presents the results and discussion, focusing on presenting the research trends, synthesizing bibliometric findings, and pointing out the main features of PEM devices. Furthermore, the last section remarks on the conclusion and future research perspectives.

2 Methods

A literature review of scientific articles is carried out to analyse the research trends of LCA and LCC studies applied to URFC, focusing on PEM devices. The systematic protocols used consists of 4 steps: i) identification of all the papers that contain specific words in the title, abstract, and authors' keywords; ii) application of screening processes to papers (fistful only on the title and abstract and then on full text); iii) collection and management of data; and iv) synthesis of quantitative and qualitative results in graphs and tables.

To identify the scientific literature, a search query was used which consisted of terms related to LCA, LCC, URFC, PEM, and other systems with similar technological properties (i.e., *fuel cell (PEMFC)* and *electrolyzer (PEMWE)*). The words were selected after a previous search on unitized regenerative fuel cells, briefly summarized into the results section, to provide an overview of the emerging research trend of the technology. The papers were collected by the Scopus database, limiting the analysis to English peer-reviewed articles. Instead, all the other documents, such as conference proceedings, book, review, and grey literature were excluded from the analysis. After the double screening process, the sample includes only papers published before February 2021 that respect the following eligibility criteria: i) the paper reports complete LCA and LCC studies and ii) focuses on PEM devices.

For each of the selected papers, bibliometric and technical data were collected. The bibliometric data includes data on authors, abstract, keywords, affiliations, journal, and year of publication. These data were analysed using two bibliometric platforms: "Analyse search results" function in Scopus and SciVal for statistical analysis (Elsevier, 2021). Both provide results in terms of the number of reports, author institution, country. Furthermore, the latter tool allows to observe the research and keywords evolution into the last decades and to analyse the topics and subject area of the research, limiting the analysis to a declared period of publication (such as 2010-2019, 2015-2020, etc.). In addition to the statistical analysis, it was possible identifying the networks between bibliometric data through VoSviewer. Then, a discussion of the main technical features of case studies is proposed using the technical data. They were collected from the full-text interpretation to point out useful information on data assumptions for phases, datasets, lifespan, and features. The synthesized results could be used for improving life cycle thinking modelling for future research on hydrogen technologies and develop more feasibility studies.

3 Results and Discussion

3.1 URFC and Life cycle approach research trends

The URFC is an electrochemical device that converts electricity in hydrogen and hydrogen into electrical energy using a bifunctional electrochemical cell (Lucia, 2014; Wang et al., 2016). The bifunctional electrochemical cell combines into a single device the functions of fuel cell and electrolyzer components. Although the materials, design, and energy performance of URFC systems were analysed in literature by Gabbasa et al. (2014), the application of LCA and LCC analysis still needs to be investigated as demonstrated by the keyword search conducting in Scopus in February 2021.

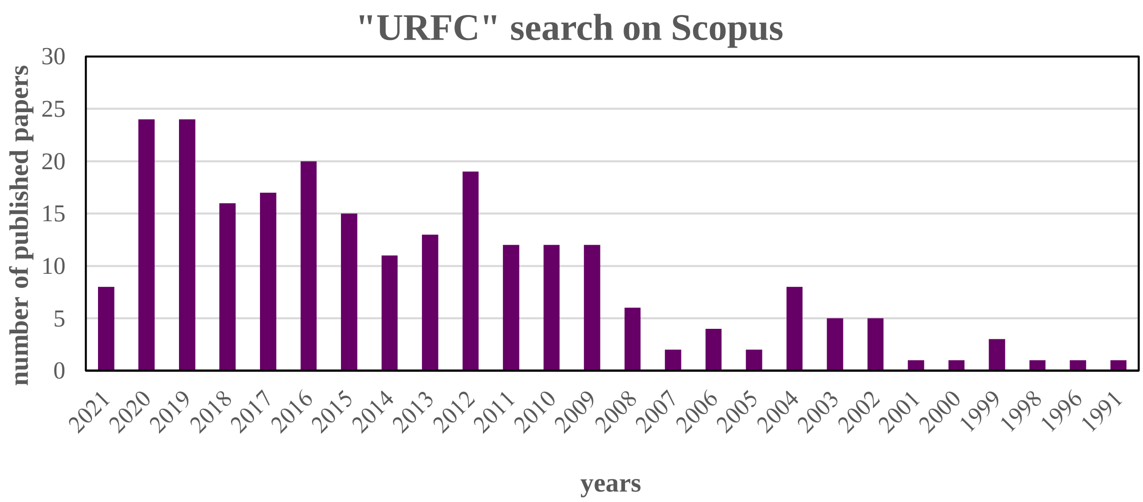

Figure 1 *Yearly trends of published papers on URFC systems*

The resulted sample was characterized by 243 documents that include the words URFC or “Unitized regenerative fuel cell” in title, abstract, and keywords, excluding articles that are related to the biological field. It was observed that the first documents on URFC systems were published in 1991 and 1996 (Chmielewski & Pyle, 1991; Murphy et al., 1996). Since that date, the interest in this technology has grown exponentially, as reported in Figure 1. Concerning the documents published between 2015 and 2021 (123 papers), the main subject area involved in the research field is energy, chemistry, materials science, and engineering, working on topics such as electrolysis, regenerative fuel cell, and alkaline water (biggest green bubble) (Figure 2).

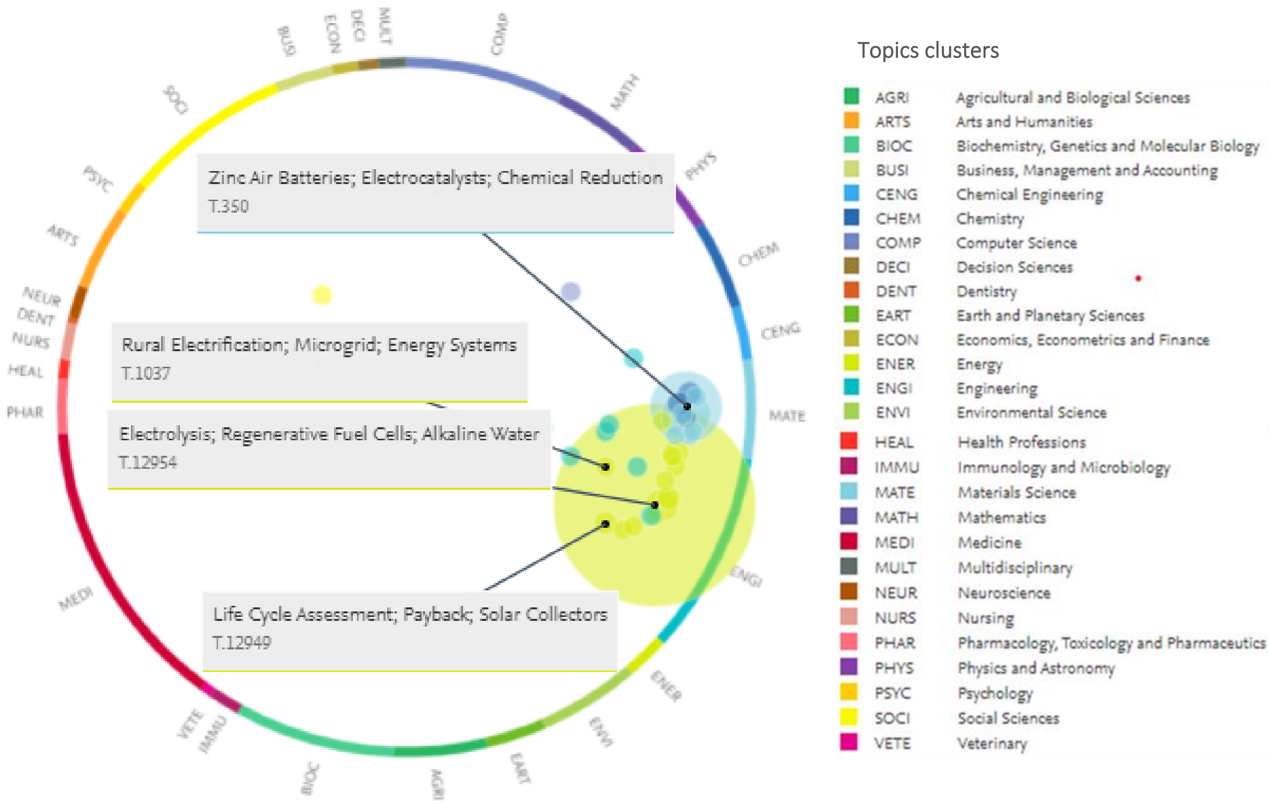

***Figure 2** Topics analysis of articles that report the keyword "URFC" in articles' title, abstract, and authors keywords - Year range: 2015 to 2021 Data source: Scopus, up to 19 May 2021*

Instead, others are clustered on topics linked to the energy vectors produced in URFC systems, such as hydrogen, electricity, and renewable energy. In other cases, the URFC system is associated with similar energy sustainable effects to batteries (small blue bubbles), accounting for both technologies that could be accomplished to renewable energy plants (e.g., wind turbine, photovoltaic panels, etc.) and storing energy vectors.

However, only a few documents are clustered in the life cycle assessment topic. Introducing the keywords "life cycle assessment" or "life cycle costing" the sample is reduced from 243 to 4 documents. Finally, adding the words "Proton Exchange Membrane" and/or PEM into the search queries, the sample includes only one peer-reviewed paper (Mendecka et al., 2020) and 2 conference articles. For that reason, to collect more reliable information on PEM device processes, such as costs, raw materials extraction, or recycling treatment as well as environmental datasets, the keyword search was expanded to fuel cell and electrolyzer as well as to regenerative fuel cell.

The latter search queries allowed to identify 80 documents, of which 45% were excluded because they do not respect the above-mentioned eligibility criteria and 1% was not available for the full-text screening. In the end, the sample includes 44 English peer-reviewed papers published from 2001 to 2021, confirming an increase of interest also in studying the PEM devices through the life cycle thinking approaches (Figure 3). While the field is still in an early growth stage, it has been rapidly evolving with exponential growth in the number of academic publications in the field in recent years. Instead, 78% of the sample has been published during the period from 2017 to 2021.

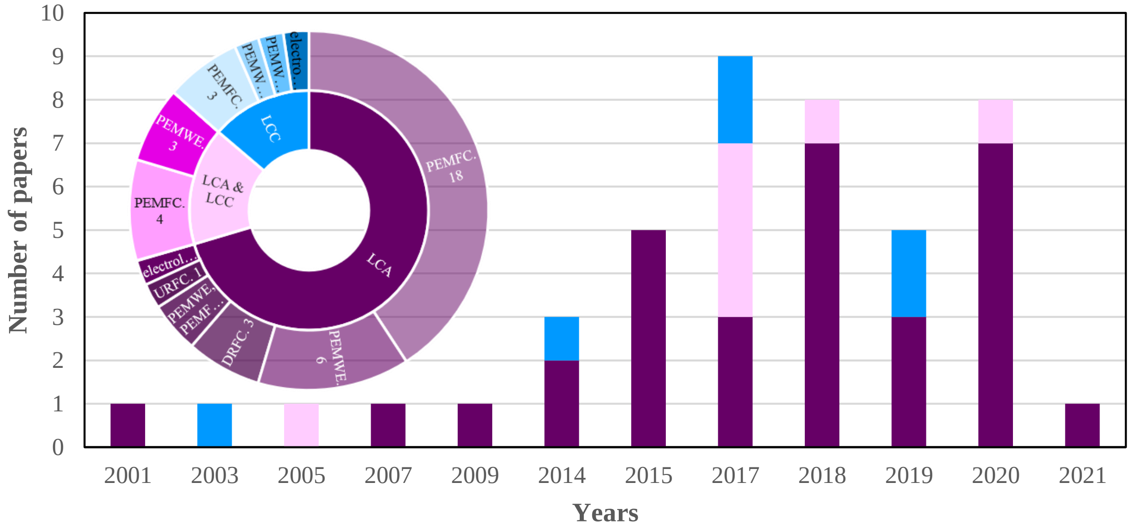

Figure 3 *Research trends of Life cycle thinking approach applied to PEM devises*

Concerning the final sample, several papers (31) applied LCA to different systems, followed by 7 papers that applied LCA and LCC to PEMFC and PEMWE. Finally, only 6 papers studied the PEM devices through LCC. Contrary to LCA (Masoni & Zamagni, 2011), standardized LCC methods or guidelines for the hydrogen sector are still missing, especially for PEM devices. As above mentioned, only one paper applied LCA to URFC. This paper aimed to evaluate the potential environmental benefits linked to a system that integrates a solar plant to the hydrogen technology of 100 kW usable for satisfying the commercial building needs (both electric and thermal loads) (Mendecka et al., 2020). In addition, the main goals of the other papers regard the evaluation of environmental and/or economic impacts, with the scope of identifying the main hot spots, optimizing the systems, and comparing the emerging technologies with conventional ones.

3.2 Main bibliometric findings

To analyse the most relevant aspects of the sample (e.g., topics, authors' collaboration, country, founding sponsor, etc.), a bibliometric and network analysis was conducted using Scopus, SciVal, and VosViewer tools. In addition, given the novelty of the technology, the temporal range accounted for this section, according to SciVal, includes the papers published from 2015 to >2020. This helps in understanding the most relevant research in the field of LCA and LCC applied on PEM devices and their main correlations. This filter limited the sample to 36 papers (82% of final sample), excluding the 8 oldest LCA and LCC studies on PEMFC.

According to the first author information of the relevant literature, more than 148 authors and 67 institutions in 24 countries or regions have invested in LCA and/or LCC of PEM devices research. The leading countries in the literature included in the Scopus database are Italy (6 papers, 16.6%), Spain (6 papers, 16.6%), Switzerland (5 papers, 13.9%), United Kingdom (5 papers, 13.9%), Slovenia (4 papers, 11.1%) and others involved for less than 9% (Figure 4).

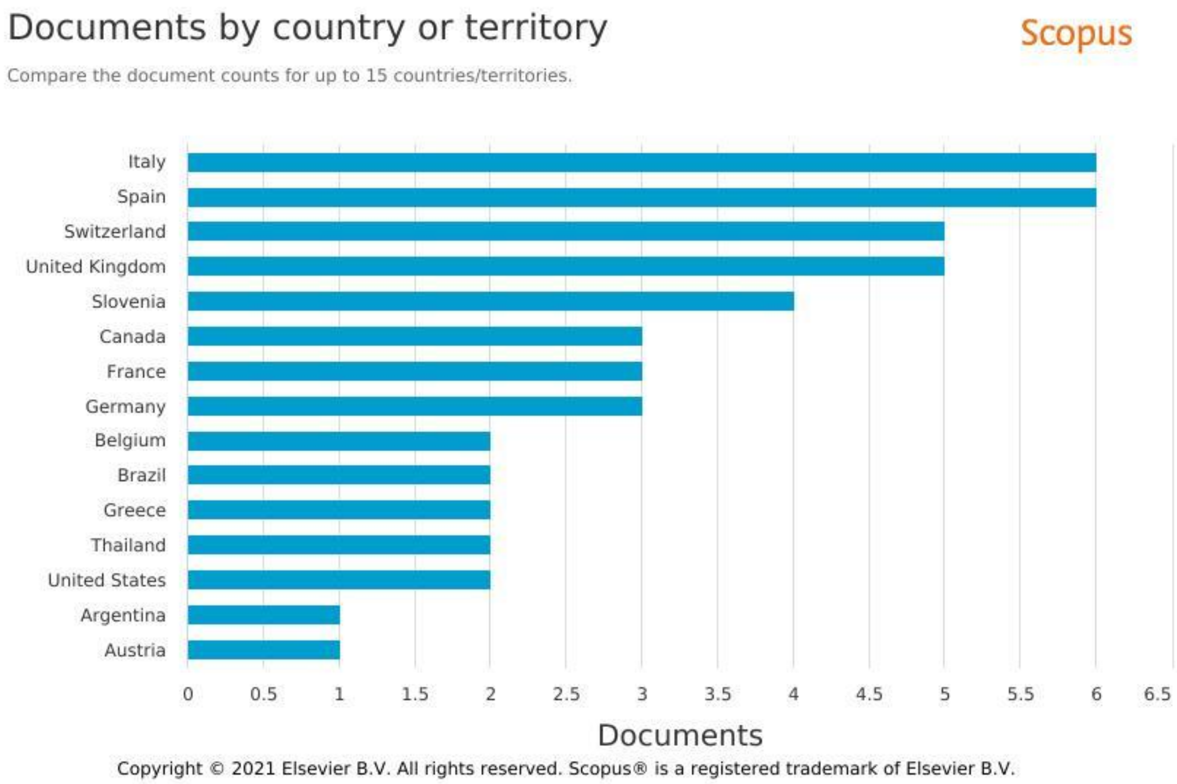

Figure 4. *Documents by top 15 countries involved in the research topic*

The documents are more than 36 because the analysis includes the affiliation country of each of the authors involved in the research collaboration. In particular, the authorship collaboration in the sample is characterized by international collaboration (44.4%); only national collaboration (33.3%); only institutional collaboration (19.4%) and 2.8% are single authorship (no collaboration) (sources: SciVal and Scopus). With VosViewer it was possible to observe the authorship collaboration from different countries. Figure 5 shows a strong collaboration between European countries, especially the United Kingdom that collaborated with Italy, Belgium, Spain, Greece, United Arab Emirates and Denmark.

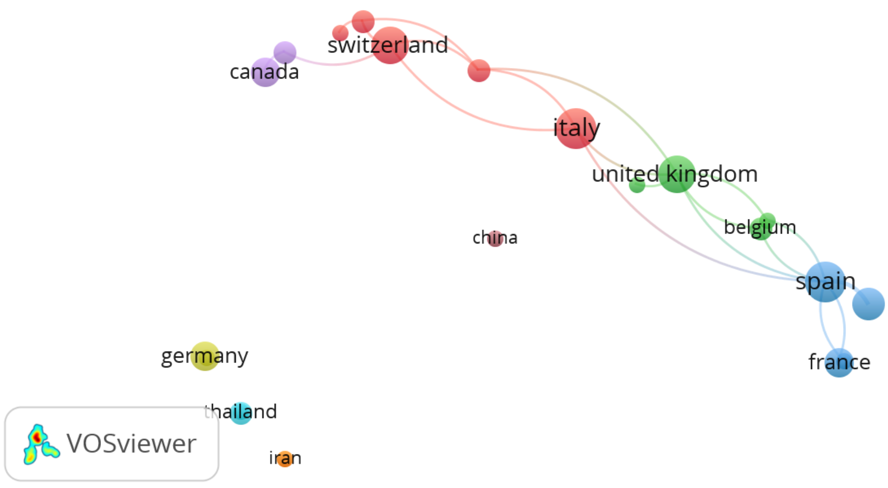

Figure 5. *Documents by the top 15 countries involved in the research topic*

Through Scopus, it was possible to observe which are the funding sponsors more interested in developing new sustainable hydrogen economy strategies and energy technologies. Figure 6 shows that the Fuel Cells and Hydrogen Joint Undertaking is the sponsor of 4 documents, followed by government agencies such as the European Commission, and ministries of the environment.

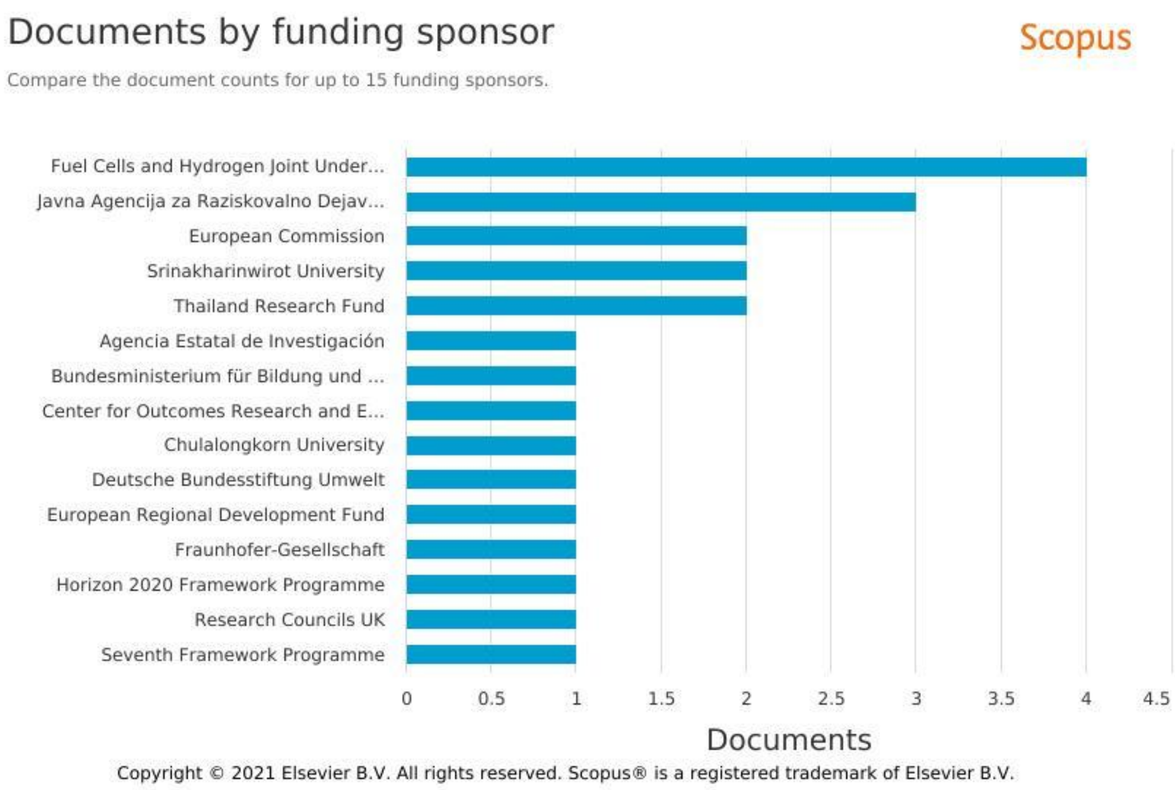

Figure 6 *Documents by founding sponsor (source: Scopus)*

The other sponsors consist of international research centres and universities. The interest of American and European authors is still increasing as shown in Figure 4, where almost 41 documents are linked to Europe and more than 8 with America. Instead, their government agencies are working to identify and develop hydrogen economy plans for reducing GHG emissions and improving the energy-environmental performances of their energy mixes by 2030.

The highest number of papers were published in scientific journals that focus on energy (37.5%), environmental science (20%), engineering (16.3%), and physics (13.8%) disciplines. In particular, the International Journal of Hydrogen Energy is the journal with the highest number of papers (10 papers) on LCA and LCC of PEM devices, followed by Applied energy (5) and Journal of Cleaner Production (3). Figure 7 shows a shift of the thematic of the 36 papers (in comparison to Figure 2) towards life cycle assessment, functional unit, and materials flow topics (second biggest green bubble).

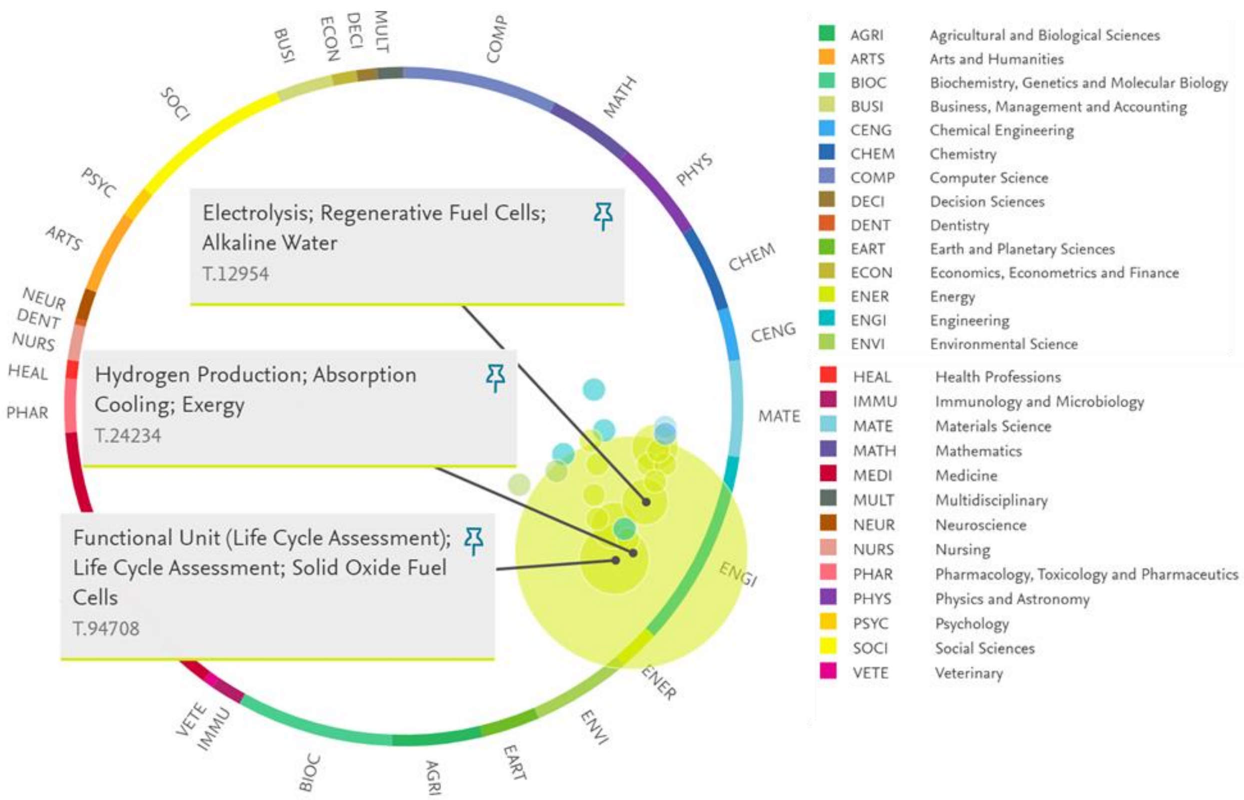

Figure 7 *Topics analysis of 36 articles - Year range: 2015 to 2021 Data source: Scopus, up to 19 May 2021*

Whit reference to the most relevant papers into the field, the SciVal calculated that the top 5 publications in the sample by the number of citations are: Parra et al. (2017) (cited 128 times); Zhang et al. (2015) (88); Simons & Bauer (2015) (67); Evangelisti et al. (2017) (56); Miotti et al. (2017) (53). These papers are the most cited because they report complete life cycle inventory data that are then used in other literature studies for PEMFC and PEMWE. The fuel cell and electrolyzer have been several analysed in the literature, but the URFC systems have reached only an early stage of technology development.

3.3 Main modelled features of PEM devices

Concerning the main features of PEM devices, only 19 documents (published between 2009 and 2020) report detailed information on life cycle inventory and resource flows. Thus, it was possible to underline the main components of PEM devices as well as their main critical phases or rare materials. Except for the bifunctional cell, that is not yet thoroughly studied, the common components accounted for URFC systems and other PEM devices are: balance of plant, bipolar plates, gasket, gas diffusion layer, catalyst, membrane, and stacks. In addition to them, a storage system is required when hydrogen fuel is produced. Generally, the membrane is realized in Naftion, and the catalyst is commonly prepared in the form of an ink characterized by platinum and iridium. The storage instead is realized in steel and the gas diffusion layer in carbon fiber. The whole life cycle of PEM devices accounts for several phases (Figure 8): fuel/electricity production, manufacturing, assembly, market/distribution, operation & maintenance, end-of-life, and recycling/recovery.

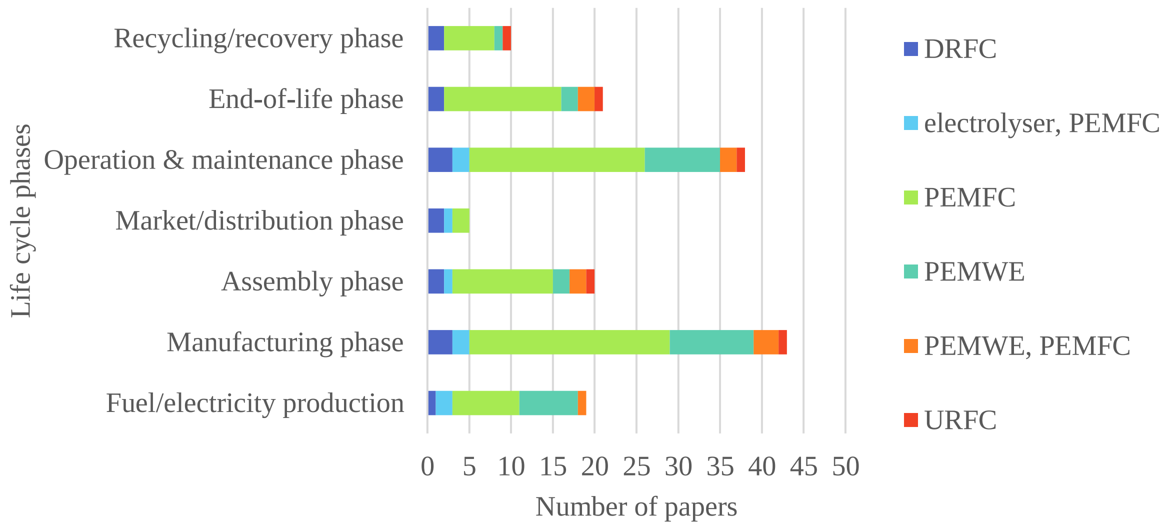

Figure 8. *Life cycle phases analysed for objects of studies*

Figure 7 shows that the most common phases studied are manufacturing (43/44) and operation and maintenance (38/44). To account for the potential recycling and recovery of rare materials, this phase has been accounted for in 10 papers. Furthermore, only 5 papers accounted for the economic and environmental effects connected to the transport, distribution, and marketing of PEM devices.

However, hydrogen technologies could be used for reducing CO_2 emissions in different sectors (European Commission, 2019). This generates greater variability in modelling the case studies. In fact, given the object of analysis, it was possible to cluster the sector of applications of the case studies in industry (14 papers), power (6 papers), transport (12 papers), building (6 papers), and multi-sectors (6 papers). The papers included in the same categories are characterized by similar functions: e.g., hydrogen produced at a large scale for the industry sector, electricity generation for the power sector, or thermal and electric energy generation for satisfying the building loads, etc. The sector selected is also reflected in the assumptions made by authors on the operation phase, nominal power, and life span of the technologies. Concerning the latter, it was noticed that the life span was assumed to equal 30 years for the URFC system, instead it assumed in a range of 7.5-20 years for the PEMFC and PEMWE. Furthermore, when the PEMFC is used in the transport sector, its lifespan has been measured in kilometres (from 150000 to 300000 km) that change based on vehicle properties as well as life cycles of use. Concerning to whole life cycle modelling of URFC systems, reliable assumptions on co-products allocation, optimal functional unit, reliable economic and environmental datasets should be analysed in deep.

With reference to the environmental and economic impacts, the authors identify that the greater contributes are associated with the manufacturing and operation phase, including the electricity use for water electrolysis. Also, the highest impacts in manufacturing processes are linked to membrane assembly production processes and the raw materials such as platinum, although its small amount is used. Hydrogen production is an environmentally friendly process only if it is produced using renewable energy. However in 2019, about 75% of the annual global hydrogen was still produced by reforming natural gas (International Energy Agency, 2019), this process is considered in several papers that accounted for the hydrogen production in life cycle of fuel cell systems.

Furthermore, to provide additional information on technical variables and applied a multi-parameters analysis, 43% of the sample integrated the LCA and LCC with additional analysis, such as energy analysis, economic analysis, and environmental analysis that does not cover the whole life cycle of the technologies, but allow to estimate the features of their components, the energy efficiency, the energy consumed during the use phase, the environmental burdens, and other relevant data for the case studies. Integrating LCA and economic analysis is essential in some cases for economic allocation of the environmental impacts, especially when physical allocation is not representative of the environmental burdens of elements or co-products (e.g., the case of platinum recycled that represents less than 1% in weight of the technology) (Hank et al., 2019). When energy analysis is accomplished to LCA or LCC, only 4/13 papers report detailed inventory data. Instead, the others limited the data presentation to parameters set as input into the energy simulation tool.

4 Conclusions

This study comprehensively analysed the LCA and LCC of PEM-URFC related literature based on the Scopus database and bibliometric platforms (Scopus analysis of the results, SciVal, and VosViewer), which present research trends in terms of the number of reports, distribution of countries, institutions, research topics and network between keywords used. Furthermore, a discussion of the technical data was conducted to highlight the main knowledge and research gaps on features and modelling approaches of PEM devices. The articles were selected applying a systemic protocol for avoiding bias and selecting English peer-reviewed papers. The additional eligibility criteria include papers that carried out complete LCA and LCC studies on PEM devices.

The preliminary research on URFC systems reveals that the researchers and developers are still focusing on the optimization of energy performances of the technologies, neglecting the analysis of potential environmental and economic benefits associated with their whole life cycle in comparison to the original plants.

Although guidelines on LCA for fuel cell and electrolyzer were proposed to harmonize the results, it is not still possible identifying guidelines for modelling LCC and LCA of URFC system based on literature knowledge. Although the information on some resources could be assimilated to that of other PEM devices, the life cycle assumptions and modelling aspects should be evaluated in deep with a focus on the URFC systems and their use in different sectors. In addition, during the operation stage, the electrochemical cell produces both hydrogen and oxygen or electricity. The oxygen produced e.g., could be stored, and then used for the inverse electrolyze mode or emitted in the environment. Given the limited number of research, no reliable assumptions, modelling approach or datasets are available for URFC. Future research in this field should focus on critical discussion of the methodological aspects of life cycle studies on the unitized regenerative fuel cell, pointing out the main reliable literature data and available environmental and economic datasets on treatment and manufacturing processes for this type of technology as well as well as identifying the good practices and critical issues.

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