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Prospective life cycle assessment of proton exchange membrane fuel cell. Comparing data from patents and papers

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ABSTRACT

The energy provided by proton exchange membrane fuel cells (PEMFC) is considered an alternative solution to fossil fuels in transportation and power generation in the future. However, to date, in life cycle assessments (LCA), PEMFCs have been modelled in reference to models already available on the market or to future development targets envisaged by government bodies. This study models PEMFCs with data extracted from patent literature and carries out the prospective LCA, comparing the resulting environmental impacts with those of studies in the literature relating to current and future PEMFCs. The result is that all the data necessary to build an inventory relating to the materials and processes constituting the membrane-electrode assembly of PEMFCs can be extracted from the patents. The impacts of the patented PEMFC are lower than those of the current PEMFC and higher than those of the future PEMFC disclosed in the literature. The variability of data in PEMFC patents is less than that of scientific papers published in international per-review journals. The same applies to the variability of the resulting impacts. Patented PEMFCs have a technology readiness level (TRL) lower than current PEMFCs and higher than future PEMFCs. In conclusion, the prospective LCA carried out on patented PEMFCs, with data extracted from the patents, can be used to analyze the environmental sustainability of prototype PEMFCs currently under development in the industry, with data deriving from experimental results.

1. Introduction

The proton exchange membrane fuel cell (PEMFC) is considered a solution for the future of electricity generation with a view to decarbonisation for several common reasons. Hydrogen, used as energy source, can buffer fluctuation in renewable energy supply, which other energy systems based on renewable energy suffer. Compared to other types of fuel cells, PEMFCs, with the same performances, have greater mechanical resistance, making them more suitable for mobile applications. Compared to batteries, PEMFCs have quicker refuelling. However, their diffusion brings some environmental problems relating to the consumption of rare materials, such as platinum, and production processes [1].

The scientific articles on life cycle assessment (LCA) of PEMFCs, which can be collected from Scopus and Google Scholar using the search query "((life W/cycle W/assessment) OR LCA) AND ((proton W/2 (fuel W/cell*)) OR PEMFC)" in title, abstract and keywords, have some limitations in providing an environmental analysis. Most studies analyze the environmental impacts of current PEMFCs (e.g., Ref. [2–4]), while only a few consider the future technological evolutions that are being proposed, which is definitely more strategic when analyzing an emerging technology such as PEMFCs.

The studies by Vargas and Seabra [5], Simons and Bauer [6], Usai et al. [7] and Thonemann et al. [8] model future PEMFCs by reducing the mass of some critical materials, such as platinum, compared to current commercial PEMFCs. This reduction is obtained by considering forecasts provided by other studies, based on learning curves relating to the increase in operating efficiency expected for these materials. In turn, these forecasts are based on the analysis of historical data relating to the use of the same materials in PEMFCs and in other technologies.

Other studies instead model future PEMFCs with direct data, obtained through experimentation on laboratory prototypes that truly express possible future developments, if they are actually realized in the future. In particular, Abejón et al. [9] and Zhao et al. [10] analyze a laboratory prototype of PEMFC in which only the membrane materials are replaced. While, Duclos et al. [11] consider a more conservative prototype close to standard PEMFCs in which the bipolar plates and the membrane have a smaller thickness and a higher conductivity through

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surface treatments during manufacturing.

To overcome the limitations of previous contributions in the literature, this study aims to obtain a life cycle inventory of future PEMFCs made up of data deriving from experimental laboratory tests of future PEMFCs currently under development. The starting point of this research is whether patents could be the source of knowledge to model future PEMFCs in prospective LCA based on the results currently obtained from industrial tests on PEMFCs in the prototype state. Accordingly, this study answers the following research questions: (i) which data can be extracted from patents to build the inventory? and (ii) How is patent data representative of future PEMFCs? To extract data from patents (RQ 1), a patent analysis was conducted using the systematic procedure of Spreafico et al. [12]. To evaluate whether the data extracted from the patents represent future PEMFCs (RQ 2), a comparative LCA was performed between the (i) patented PEMFCs and (ii) current and (iii) future PEMFCs described in literature studies.

2. Materials and methods

2.1. Life cycle assessment

The environmental impacts of the PEMFCs are quantified using the LCA methodology according to ISO 14040 [13] and ISO 14044 [14] standards. The constituting steps are the following: (i) the goal and scope of the study are defined through the identification of the technical systems to be measured, the operative scenario, the motivation for performing the assessment and all the requirements for performing it, (ii) the life cycle inventory analysis, i.e., system parts and lifecycle phases, are retrieved, (iii) the life cycle impacts are assessed, and (iv) the results are interpreted and discussed.The performed LCA is prospective [15] since we analyze future products that are not yet on the market, i.e., the patented PEMFCs and the future PEMFCs disclosed in the scientific literature are assessed along with current PEMFCs, which are marketable.

2.2. Compared products

The manufacturing process of a PEMFC usually begins with catalyst ink production, where the platinum powder is mixed with a PFSA binder and a solvent, typically based on isopropanol. The resulting catalyst ink is coated into the membrane through screen printing, spray coating, or slot-die coating [16]. The coated layers are dried and sintered to ensure adhesion and appropriate catalyst distribution. At the same time, the membrane is treated to enhance proton conductivity. Then, catalyst layers are applied to both sides of the membrane through hot pressing or decal transfer methods, forming the membrane electrode assembly (MEA) [17]. The gas diffusion layers are treated to make them hydrophobic, conductive, and attached to the MEA. The bipolar plates, made from graphite, metal, or composite materials, are machined to create flow channels for gas distribution, typically using CNC machining, stamping, or moulding processes. Then, the bipolar plates are coated with protective layers to improve conductivity and corrosion resistance. The gaskets are applied around the MEA to ensure gas-tight seals between the cells. Finally, the cell is stacked in series with other cells using end plates and tie rods, integrated with hydrogen supply, cooling system, humidification, and power electronics, and tested.

In this study, the environmental impacts of three types of PEMFC are assessed and compared:

- **Patented PEMFC** disclosed in patent literature.
- **Current PEMFC** disclosed in the scientific literature about LCA analysing commercial PEMFC.
- **Future PEMFC** was disclosed in the scientific literature about the prospective LCA of future PEMFC, which is currently in a prototype state and refers to future technological evolution scenarios.

The modelling and assessment of patented PEMFC is helpful in answering RQ 1 or understanding which data can be extracted from patents to build the inventory for LCA. The comparison of the impacts between the three considered products is useful to answer RQ 2 and to understand whether the patent data allows modelling PEMFCs to be more similar to current or future ones.

2.3. Goal and scope

The study aims to compare the environmental impacts arising from the manufacturing of patented PEMFCs and those disclosed in the scientific literature. The functional unit is defined in relation to producing 1 kWh of electricity through the PEMFC. The scope of the study is “cradle to gate”, considering the material extraction and manufacturing phases and excluding the use and end-of-life phases of the product. This choice was previously made by Smith et al. [18] and Spreafico [19] when analysing immature fuel cells due to the lack of reliable information about use and end-of-life. This choice is common in prospective LCA since the nature of the study is uncertain, considering the material extraction and manufacturing of which estimates are available in the patents [20].

The manufacturing and assembly of membrane, electrodes and constituting materials within the system boundaries have been considered. In membrane-electrode assembly (MEA), catalyst ink is applied to PFSA in the electrodes assembled to the membrane. In the catalyst ink production (CIP) process, the platinum powder is chemically bonded to the carbon black through isopropanol. This process follows platinum powder, carbon black and isopropanol production processes. The PFSA production process was modelled according to the production processes of its constituent materials, i.e., tetrafluoroethylene and sulfuric acid.

The use phase and the end-of-life of the products are not considered because the data extracted from the considered patents regarding the operating life of the cells are not reliable as they lack adequate experimental tests to support them. In addition, other parts of the whole system, such as the gas diffusion layer and the water control system, were not considered in the system boundary. This is because patents typically claim what is strictly necessary to obtain legal protection, or the truly innovative embodiment, leaving out the rest or at most they describe it qualitatively and without providing tests. Therefore in this study we have considered only the patents related to the functioning heart of the PEMFC, i.e., the MEA. Obviously, the fuel cell system is a complex system, and issues such as fuel and temperature and humidity have a significant impact on the lifespan. However, mixing data from different patents relating to MEA and other PEMFC components would risk being unreliable due to the lack of auxiliary information in the respective patents.

Fig. 1 graphically represents the system boundary and the phases of the PEMFC lifecycle.

2.4. Inventory

To guarantee time consistency in the analysis, all the documents collected to model the compared PEMFCs were published between 2014 and 2024.

The patents have been retrieved by using the method of Spreafico et al. [12] and Spreafico et al. [21]. The main peculiarity of this method resides in the use of a large number of patents from which to extract data for the inventory through a systematic procedure of patent analysis. The patents have been collected within the global database through Orbit by Questel. The search was carried out using the following query (referred to Orbit syntax): " ((PROTON+ 2D (FUEL+ 1D CELL+)) OR PEMFC)". The query was applied to the title, abstract and claims fields to collect patents dedicated to the topic. Only granted patents, currently alive and having published the application from 2014 to today, have been preserved to increase the reliability of testimony interest by the patent owner. This research has led to 1960 patents.

Therefore, filtering of patents was carried out, retaining only those that claim PEMFC made up of the materials described in Section 2 and produced according to the phases reported in Fig. 1. Furthermore, among them, only those patents that report all the numerical data have been kept in order to calculate the quantity of at least one of the constituent materials in relation to the functional unit, i.e., the mass of the material must be expressed in mg per kWh of electrical energy produced by the PEMFC. In some patents, this quantity is already available. In others, it was calculated as explained in Eq. (1), dividing the mass of the material normalised by the active area by the specific power, i.e., the power of electrical energy produced by the cell normalised by the active area. Both data were extracted from the patent.

Material mass [mg/kW] = Material mass [mg/cm^2] / Specific power [W/cm^2] * 1000 (Eq. 1)

Overall, the selection and data extraction criteria reduced the number of patents to 33.To model the current and future PEMFC, 11 articles, published in peer-review international journal were selected. Table 1 reports all the considered sources.

All the data extracted from the considered patents and articles to build the inventory of the considered products are reported in Tables S1–S3 of the supplementary material.

In the inventory of the PEMFC from patents and the PEMFC from papers, the masses of the constituent materials were obtained from the average of the masses of the same collected from each patent and each paper. The electricity consumption of CIP was determined for current PEMFC and future PEMFC from the related articles, while this data could not be collected from the patents. To determine the CIP consumption of patented PEMFC, the CIP-specific electricity consumption of the current PEMFC was used, as shown in Eq. (2).

CIP consumption $_{\text{patented PEMFC}}$ [kWh/kW] = CIP specific consumption $_{\text{current PEMFC}}$ [kWh/cm^2] / Specific power $_{\text{patented PEMFC}}$ [W/cm^2] * 1000 (Eq. 2)

The MEA consumption was retrieved only for the current PEMFC since this data was not found in the documents relating to the other products. The electricity consumption of membrane-electrode assembly for patented PEMFCs and future PEMFCs has been determined with Eq. (3) and Eq. (4).

Table 1
Source used for life cycle inventory.

Modelled product	Sources	References
Future PEMFC	Patents	WO2018/113485; CN108539218; CN110380060; CN111146447; CN111224137; KR20200123944; CN111244480; CN111193043; KR20210001097; CN113241448; CN113206275; CN113066999; CN113540481; CN112421052; CN111326773; CN109599573; CN112993349; KR102408556; CN115275235; KR20220149299; CN114094130; CN114204049; CN115020736; CN110943234; CN114614060; CN114725410; CN114079071; CN114437347; CN114300691; CN117254042; CN116845253; CN116759593
	Scientific papers	Evangelisti et al. [33]; Krishnan et al. [32]; Mori et al. [4]; Miotti et al. [31]; Notter et al. [34]; Pedersen et al. [35]; Riemer et al. [30]; Simons and Bauer [6]; Thonemann et al. [8]; Usai et al. [7]
Current PEMFC	Scientific papers	Duclos et al. [36]; Evangelisti et al. [33]; Krishnan et al. [32]; Mori et al. [4]; Miotti et al. [31]; Notter et al. [34]; Riemer et al. [30]; Simons and Bauer [6]; Usai et al. [7]

MEA consumption $_{\text{patented PEMFC}}$ [kWh/kW] = MEA specific consumption $_{\text{current PEMFC}}$ [kWh/cm^2] / Specific power $_{\text{patented PEMFC}}$ [W/cm^2] * 1000 (Eq. 3)

MEA consumption $_{\text{future PEMFC}}$ [kWh/kW] = MEA specific consumption $_{\text{current PEMFC}}$ [kWh/cm^2] / Specific power $_{\text{future PEMFC}}$ [W/cm^2] * 1000 (Eq. 4)

These approximations relating to using the same composition of the PFSA and the specific electricity consumption coefficients in both products analysed are due to the lack of such information in the PEMFC patents.

Table 2 reports the coefficients extracted from the patents and the PEMFC scientific articles used to build the inventory of the two products.

Table 3 reports the average data relating to the number of constituent materials and energy consumption, referring to the production of 1

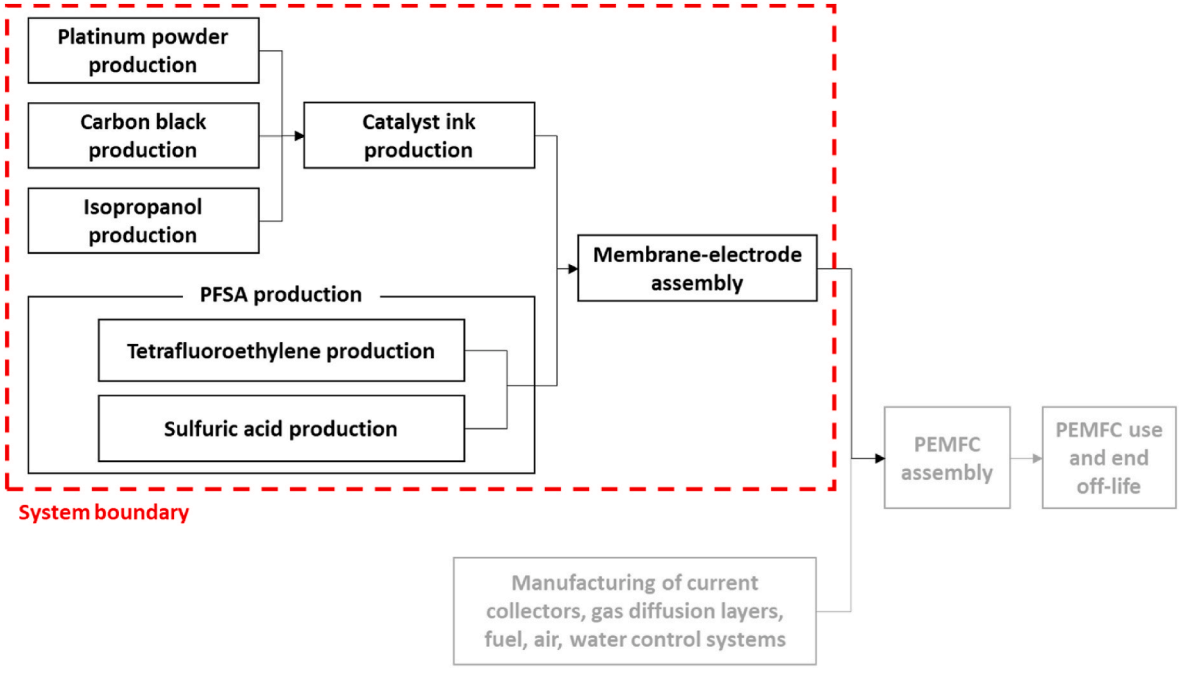

Fig. 1. System boundary.

Table 2
Coefficients used to model the compared products.

Parameter	Unit		Patented PEMFC	Current PEMFC	Future PEMFC
Specific power	W/cm^2	Average	0.95	0.82	1.62
		Standard dev.	0.42	0.18	0.52
Catalyst ink production	kWh/m^2		3.20		1.00
Membrane-electrode assembly	kWh/m^2		2.44		

Table 3
Inventory of the compared products for 1 kW_{el}.

Parameter	Unit		Patented PEMFC	Current PEMFC	Future PEMFC
Platinum mass	mg/kW	Average	444.93	599.97	168.06
		Standard dev.	279.34	457.39	108.80
Carbon black mass	mg/kW	Average	2589.53	946.56	455.69
		Standard dev.	2081.10	1238.35	332.31
PFSA mass	mg/kW	Average	32,886.04	24,235.66	26,104.46
		Standard dev.	36,488.65	31,619.01	34,227.64
Isopropanol mass	mg/kW	Average	89,466.45	49,295.06	32,067.98
		Standard dev.	126,925.31	68,075.40	86.58
Catalyst ink production - electricity	kWh/kW	Average	0.34	0.28	0.51
		Standard dev.	0.19	0.16	0.33
Membrane-electrode assembly - electricity	kWh/kW	Average	0.26	0.35	0.19
		Standard dev.	0.12	0.16	0.09

kW_{el} through the PEMFC and the used ecoinvent datasets.

The production processes of the constituent materials and generation of the electricity used in the CIP and MEA processes were modelled using the ecoinvent v3.8 datasets reported in Table 4.

2.5. Impact assessment and interpretation of the results

The impacts of the considered products have been assessed using the ReCiPe Midpoint (H) model (Goedkoop et al., 2013) (see Table 5). This does not mean that 2013 data were used to carry out the analysis but the much more recent ones present in the ecoinvent v3.8 datasets as explained in Section 2.4, organised according to the ReCiPe Midpoint (H) calculation model which is the most up-to-date to date and is used by most of the most recent prospective LCA studies. The results were interpreted by comparing the patented PEMFC, the current PEMFC and the future PEMFC in different ways.

Table 4
ecoinvent datasets were used to model the production processes of the materials and manufacturing processes considered to constitute GLO, where GLO = global and RER = Europe.

Process	Used ecoinvent dataset
Platinum production	GLO: Market for platinum
Carbon black production	GLO: Market for carbon black
PFSA production, modelled as 57.4 wt% tetrafluoroethylene production and 42.6 wt% sulfuric acid production [6].	GLO: Market for tetrafluoroethylene GLO: Market for sulfuric acid
Isopropanol production	RER: Market for isopropanol
Catalyst ink production - electricity consumption	RER: Market group for electricity, medium voltage
Assembly - electricity consumption	RER: Market group for electricity, medium voltage

The average impacts of each technology were determined using the average data of each parameter (see Table 2) and were considered to offer a comparison between the different products. In this way, having considered many sources from which to extract data, with average data and average impacts, it is possible to increase the significance of the analysis and level out specific differences. This is especially true in prospective LCA when the technologies are not mature, and the data are not forecasted [22].

A significant uncertainty analysis in a prospective LCA should consider the effect of variations in the foreground system, i.e. the design parameters of the analysed product, rather than carrying out a simple Monte-Carlo analysis aggregating parameter uncertainties [23]. Therefore, to consider the effect of the variability between the analysed PEMFCs, the standard deviations of the impacts have been assessed from the standard deviations of the inventory data relating to all the considered processes (see Table 2).

Furthermore, the uncertainty of the results is also evaluated as a function of the Technology Readiness Level (TRL) [24] of the analysed product and processes as suggested by Cucurachi et al. [25]. To do this, the TRL of each production process, included in the system boundary, of each considered PEMFC is evaluated in relation with the data used to model it in the inventory. For example, TRL = 3 is assigned to the platinum powder production of a PEMFC modelled with a platinum load prescribed by a future target that was not tested to date, while TRL = 9 is assigned to the PFSA production process of a PEMFC including a standard PFSA membrane for PEMFC available on the market. According to the TRL definition [24], at TRL 1, the scale begins with a technology in a fundamental theoretical form and progresses to a technology proven in the operational environment at TRL 9.

3. Results an discussion

Tables S5-S7 report the average impacts and the standard deviation of the impacts of the patented PEMFC, current PEMFC and future PEMFC, while Tables S1–S3 report the TRLs associated with all the data used in the inventory.

3.1. Average impacts

Fig. 2 compares the average total impacts of the considered PEMFCs, where the total impacts are the sum of all the processes in the system boundary.

From the analysis of Tables S5–S7 and Fig. 2, it emerges that the impacts of the patented PEMFCs are lower than the current PEMFCs and greater than the future PEMFCs in all indicators except for ozone depletion, which is higher in the patented PEMFCs.

By comparing the current PEMFCs and the future PEMFCs (both disclosed in the articles), we understand that the technological process that occurs when passing from the former to the latter should reduce environmental impacts. Furthermore, the impacts of patented PEMFCs are closer to those of current PEMFCs (albeit smaller) than those of future PEMFCs. Therefore, in line with these findings, the patents provided a less optimistic representation of the environmental benefits of the technological development of PEMFCs compared to that which emerges from the scientific articles of future PEMFCs.

Fig. 3 compares the climate change of the constituent materials and manufacturing processes of the PEMFCs.

As seen from Fig. 3, the impact of platinum is the highest. Its impact in the patented PEMFC is smaller than that of the current PEMFC and larger than that of the future PEMFC, although much closer to that of the current PEMFC. The same situation occurs for the impact of the membrane-electrode assembly and with reversed parts between the current PEMFC and the future PEMFC in the catalyst ink production. In carbon black, PFSA and Isopropanol, the impact of the patented PEMFC is greater than that of the current PEMFC and the future PEMFC. Overall, the comparison of the total impact (given by the sum of the impact items

Table 5
Strtegies to decrease platinum load in the considered patents.

Patent	Platinum mass reduction compared to current PEMFC	Adopted strategy to decrease platinum load			
		Strategy 1: Platinum particles size optimization	Strategy 2: Improvement of platinum particles distruibution	Strategy 3: Reduce the thickness of the electrodes and/or the electrolyte	Strategy 4: Ensuring a more stable platinum deposition
KR20200123944	77%	✓			
CN111244480	77%		✓		
CN116759593	77%		✓		✓
KR20210001097	53%				✓
CN111326773	53%	✓			
CN110943234	53%	✓	✓		
CN114204049	46%			✓	
CN114437347	41%		✓		
KR20220149299	32%			✓	
CN108539218	30%	✓			
CN112993349	30%	✓			
CN114614060	30%		✓		
CN113066999	18%	✓			
WO2018/113485	6%		✓		✓
CN111193043	6%	✓			✓
KR102408556	6%			✓	
CN117254042	6%				✓
CN116845253	6%		✓		✓

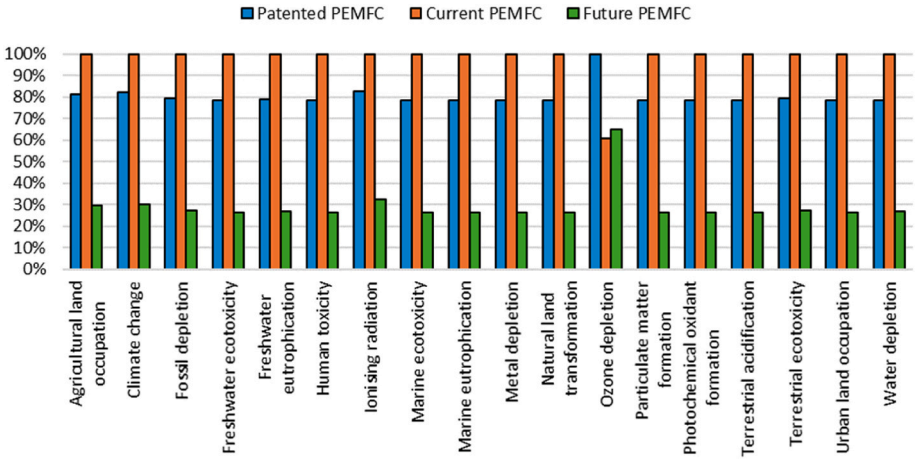

Fig. 2. Comparison of the average total impacts of the PEMFCs.

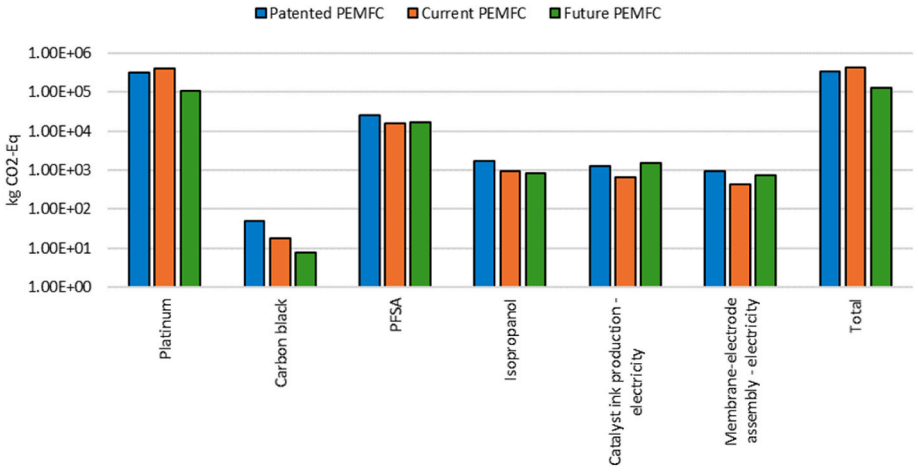

Fig. 3. Climate change comparison of constituting materials and manufacturing processes in the PEMFCs.

shown in Fig. 3) in the different PEMFCs follows the comparison between the impacts of platinum. This is due to the predominant impact of platinum on the total.

These proportions between the impacts follow the proportions between the mass or electricity values associated with the same items appreciated in the inventory (see Table 2). Therefore, the technological evolution of PEMFCs, which is responsible for the lower impact of future PEMFCs compared to current PEMFCs, is mainly due to the reduction of the used platinum. Concerning the use of platinum, the patents, therefore, photograph a PEMFC that uses less platinum and therefore has less impact than current PEMFCs, but not as little as the future PEMFCs disclosed in the articles. Yet, the reduction of platinum in patented PEMFCs compared to current PEMFCs, whose main function is electrical conductivity in the calla, does not reduce the specific power, which in patented PEMFCs is still 16% greater than in current PEMFCs (see Table 2).

To understand which strategies the patented PEMFCs have adopted to reduce the quantity of platinum, the text of the patents claiming a smaller quantity than the average of the current PEMFCs, i.e., 599.97 kW/kg (see Table 3) was analysed. The strategies identified are the following:

- Platinum particles size optimization (strategy 1), to enhance the surface area available for catalytic reactions, improve the dispersion, increase the catalyst durability [26].
- Improvement of platinum particles distruibution sugli elettrodi (strategy 2), realizzandoli controllando maggiormente la loro porosità superficiale [27].
- Reduce the thickness of the electrodes and/or the electrolyte (strategy 3) to reduce the electrical resistance, increase the efficiency of the cell and, consequently, reduce the quantity of platinum [28].
- Ensuring a more stable platinum deposition (strategy 4), by controlling the drying and reduction steps of the platinum and better securing it with the carbon support in ordert to reduce the electrical resistance at the interface [29].

Table 4 reports for each patent, the platinum load reduction compared to the average value of the current PEMFC and the strategy implemented to decrease it.

Finally, the analysis of the strategies implemented in the patents, shown in Table 4, allows us to determine the effectiveness of each strategy based on the average reduction of the platinum load in the patented PEMFCs. In fact, it emerges from Table 4 that the strategy allowing the platinum load to be reduced the most is Strategy 2 (i.e., 41%, implemented in 7 patents), followed by Strategy 1 (i.e., 38%, implemented in 7 patents), from strategy 3 (i.e., 28%, implemented in 3 patents) and from Strategy (i.e., 26%, implemented in 6 patents).

While the reasons for the reduction of environmental impacts of future PEMFCs have been identified by analyzing the structural solutions adopted, in the considered sources.

The most widespread solution [4,7,30] consists in reducing the primary platinum load to be inserted into the electrodes during manufacturing, up to a target of 0.125 mg/cm^2 against the current average of 2 mg/cm^2. To do this, platinum recycling up to 95% from spent membrane catalysts has been introduced and manufacturing processes are optimized, making them more precise in platinum deposition in order to reduce waste.

Another solution consists in reducing the mass of the platinum through an optimized spatial deposition in the hosting carbon matrix of the electrodes that has a better organization of the microstructure [4, 31].

Still another solution, described in Krishnan et al. [32] consists in an advanced design where the electrodes are over pressed against the membrane to achieve a zero gap in order to significantly lower ohmic resistance and helps facilitate operation at a higher current density of 1.3 A/cm^2 when compared to state-of-the-art densities of 0.245 A/cm^2.

3.2. Evaluation of uncertainty

Fig. 4, for each PEMFC, compares the standard deviation of the impacts.

From Fig. 4, the standard deviations of the impacts of the patented PEMFCs are lower than those of the current PEMFCs and greater than those of the future PEMFCs. Therefore, the comparisons about the standard deviation argue in favour of using PEMFC patents, rather than articles, as a source for the inventory to obtain more precise and less dispersed total impacts.

To understand how the standard deviations of the impacts of the constituting materials and production processes concur to the standard deviation of the total impacts, Fig. 5 compares, as an example, the standard deviation of the climate change of each process between the different PEMFCs.

Fig. 5 shows a rather variable comparison between the standard deviations of the climate change of the different PEMFCs in relation to the flow. Unless, in the case of platinum, the standard deviation of the patented PEMFC is no less than that of the current PEMFCs or future PEMFCs. In particular, in the case of platinum, the low standard deviation of the impact of future PEMFCs is because almost all related articles consider the platinum mass defined by the achievement of the goal defined by the US Department of Energy. Despite the different distributions of the standard deviation of climate change across different processes, the total climate change substantially follows that of platinum due to the strong influence that platinum has on the total impact. This also applies to other impact categories (see Tables S5–S7).

Fig. 6 compares the average TRLs of the production processes of the considered PEMFCs.

From Fig. 6, it emerges that the associated average TRL of patented PEMFCs is lower than that of current PEMFCs for platinum, carbon black, PFSA, isopropanol production processes, while it is the same in catalyst ink production and membrane-electrode assembly. The same TRL is greater than that of the future PEMFCs in all flows except for the isopropanol, which is lower, and that of the membrane-electrode assembly, in which it is the same. Furthermore, for platinum, whose weight on impacts is much higher than other flows, the difference between the TRL of the processes constituting the patented PEMFCs and that of future PEMFCs is one of the highest. Entering into the meaning of the TRL, it emerges that the patented PEMFC data are taken from systems that have a value between 6 and 9; that is, they have been demonstrated at least in an industrially relevant environment. The data of future PEMFCs have instead TRLs referring more to expert opinions. This is the consequence of the vast use of target values, which are used by the articles to model the inventory of future PEMFCs [2].

4. Conclusions

This study presented a prospective LCA of current and future PEMFCs using a systematic approach that integrated data from structured analyses of patents and scientific literature. It successfully addressed two key research questions: identifying extractable data from patents and assessing the environmental relevance of such data for future PEMFC technologies. For the processes considered—specifically material extraction and the manufacturing of the membrane-electrode assembly—patents provided sufficient data to build the inventory, thereby affirming the validity of RQ 1. Meanwhile, the results of the prospective LCA enabled a detailed response to RQ 2.

Key findings include strategies in patented PEMFCs to reduce platinum load through innovations like particle size optimization, improved distribution, reduced electrode thickness, and stable deposition techniques. These advancements significantly decreased environmental impacts compared to current PEMFCs, with patented designs showing a 26%–41% reduction in platinum usage. However, the platinum efficiency in patented PEMFCs remains lower than that of future PEMFCs described in scientific literature.

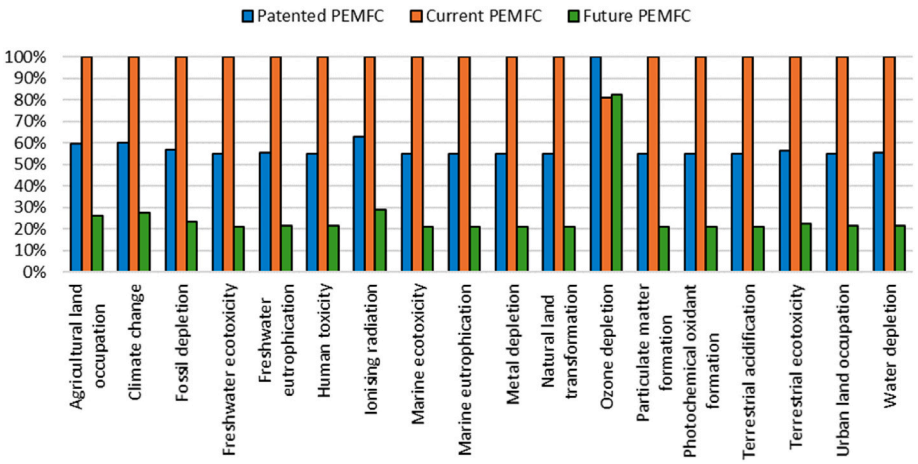

Fig. 4. Comparison of the standard deviation of the impacts for each PEMFC.

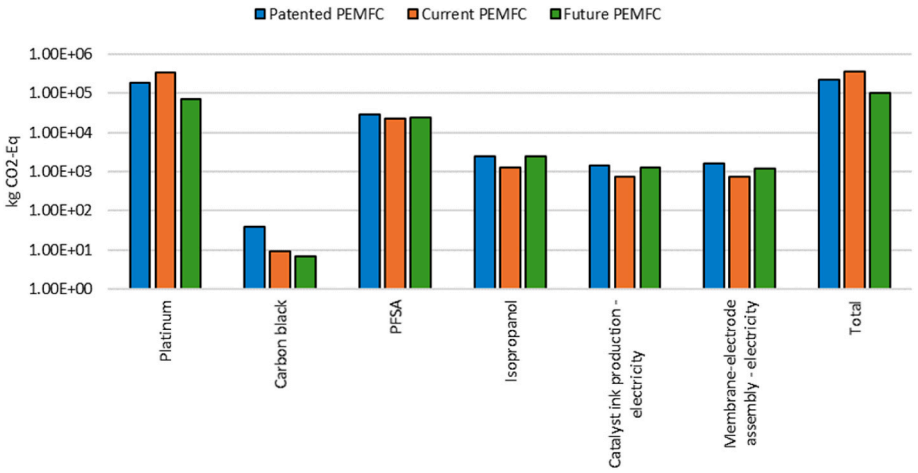

Fig. 5. Comparison of the standard deviation of the climate change for each process.

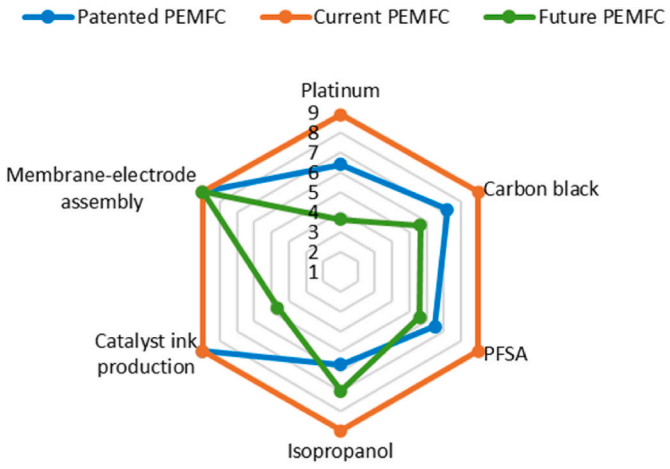

Fig. 6. TRL comparison of the constituting processes of the considered PEMFCs.

From a data-driven perspective, the study revealed that the impact comparison between patented PEMFC and current PEMFC disclosed in scientific articles about LCA referred to the current scenario, and future PEMFC referred to the future scenario, which has photographed an intermediate situation of the patented PEMFC. In particular, patented PEMFCs achieve a 16% higher specific power compared to current PEMFCs while using less platinum. Environmental impacts of patented PEMFCs are consistently lower than those of current PEMFCs but higher than those of future PEMFCs in all categories except ozone depletion. Patented PEMFCs provide more precise impact estimations with lower standard deviations than current PEMFCs, attributed to the reliability of industrial data underlying patent claims.

The standard deviation of the impacts of patented PEMFC is lower than that of current PEMFC, and higher than that of future PEMFCs.

Patent data used in the inventory refer to technologies having a higher TRL than those disclosed in articles of prospective LCA of future PEMFC. Patented PEMFC refers to prototypes tested in an industrial environment, while future PEMFC disclosed in articles are modelled mainly using target values. This is especially true for the amount of platinum, which is responsible for most of the impacts. However, the data from the LCA articles about current PEMFC practically always refer to products available on the market and do not offer a prospective vision of the impacts of future PEMFC developments.

In conclusion, this research fills a crucial gap in prospective LCA studies on PEMFCs by leveraging patent data to model future technologies based on industrial prototype testing rather than hypothetical targets. This approach provides a more realistic vision of future PEMFC impacts and demonstrates the environmental benefits of ongoing technological advancements in the industry. The lower variability in patented PEMFC impact data compared to current designs underscores the robustness of industrial insights, while the narrower range in future

PEMFC estimates reflects reliance on idealized projections rather than real-world testing. Crucially, the availability of such results during the pre-market phase of patented PEMFCs facilitates eco-design strategies to minimize environmental impacts before commercialization.

This study highlights the practical potential of patented PEMFCs as a transitional technology that balances environmental performance and industrial feasibility. While less optimistic than future scientific projections, patented designs reflect achievable advancements in industrial contexts. These findings emphasize the importance of reducing platinum dependency and improving environmental sustainability, paving the way for future innovations in hydrogen energy systems.

CRediT authorship contribution statement

Christian Spreafico: Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Nils Thonemann:** Validation, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary material

All supplementary material is provided in an MS Excel datasheet "DB_PEMFC_supplementary.xls".

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2024.12.211.

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