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Prospective life cycle assessment to support eco-design of solid oxide fuel cells

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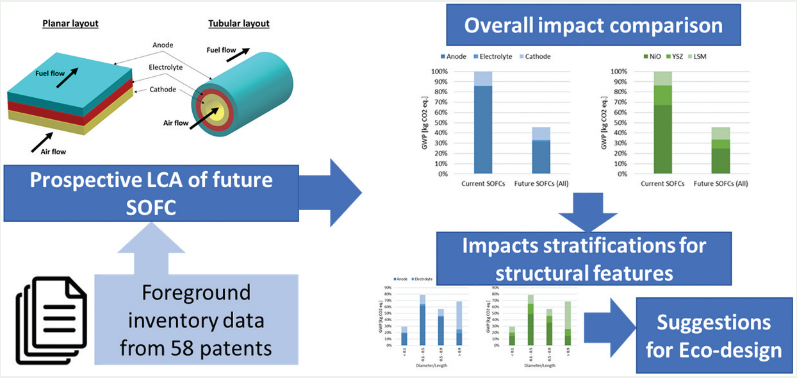
ABSTRACT

Solid oxide fuel cells (SOFCs) could have great application potential and technological development. However, there are no studies that have quantitatively and rigorously estimated the environmental impacts in the future scenario. This study fills this gap through an innovative approach consisting of patent-based technological forecasting and prospective life cycle assessment (LCA). The analysis of the 58 selected patents reveals that future SOFCs could have (on average) +53% specific power which could lead to a 56% mass reduction compared to current SOFC. The prospective LCA shows an average global warming potential (GWP) reduction of 50%. The future tubular layout is more sustainable than planar one by about 15%. GWP decreases with increasing specific power and in cells with smaller sizes and thicknesses. Finally, the ductile future SOFCs, dedicated to mobile applications and dynamic loads, have a GWP greater than future stationary SOFCs, but still equal to half of the current SOFCs. All these results therefore confirm the potential of the patented SOFC developments on environmental sustainability, arguing in favour of their industrial development and a more massive application in the future.



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Prospective LCA; solid oxide fuel cell (SOFC); patents

1. Introduction

The Solid Oxide Fuel Cell (SOFC) is a candidate solution to face the contradiction between the local production of the electricity and the elimination of fossil fuels (Peng et al. 2021; Subotić et al. 2019; Zeng et al. 2020). Their functioning is conceptually very simple: the chemical energy, deriving from the fuel, e.g. hydrogen, is converted into electrical energy directly, without the intermediate transformation into mechanical energy. For this reason, the process is remarkably efficient, more than other competing systems, including other types of fuel cells. Furthermore, the SOFCs have low noise, low emission and flexible fuel, including hydrogen (Gunaltili et al. 2022; Yasar et al. 2021).

The technology is mature and has been on the market for many years. Nevertheless, its diffusion never exploded, except for Japan, where there are various applications in the domestic field. In fact, some typical characteristics of SOFCs, including the high operating temperatures, the fragility of the constituent ceramic materials, the long transition times, have linked them to uses where the alternatives are many. Among these uses, there is mainly the generation of stationary electricity of medium-small size and decentralised. In this case, the SOFCs can also operate in combined cycle mode, exploiting the heat generated during the production of electricity for the cogeneration of heat and steam (Zhao et al. 2023). Another typical use is industrial cogeneration for the combined production of electricity and heat. In this case, the SOFCs exploit the heat produced by chemical or metallurgical processes to fuel chemical reactions or to heat process fluids (De Souza et al. 2021).

On the contrary, the interest in the developments of SOFCs is very keen both in academia and in industry, as evidenced by the trends in scientific publications (Salim et al. 2022) and patents (Fernandes et al. 2020; Han et al. 2023; Hu, Triulzi, and Sharifzadeh 2020). The most recent developments are greatly improving some aspects of the SOFCs. The efficiency has been increased, through the increase in performances. The

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materials have been reduced. While the greater ductility of the materials is making the SOFCs more resistant mechanically, thermally and chemically, for the benefit of the transportation and the reduction of the ignition and load variation transients. Consequently, new applications for the SOFCs are possible. Therefore, such developments are increasing the competitiveness of the SOFCs in reference and new application fields. Future SOFCs can be more reactive in responding to the new needs that stationary energy production poses in pursuing an increasingly dynamic grid (Affandi and Osman 2022). Furthermore, the SOFCs can be integrated with renewable energy sources (Al-Khori, Bicer, and Koç 2021), in electric-powered mobile applications (Çalışır et al. 2023; Hagen, Sun, et al. 2020), and as emergency backup systems (Joh et al. 2023).

From the analysis of the literature on LCA it emerged that there are many traditional LCA studies of SOFCs currently on the market and some prospective LCA studies, where the same SOFCs are used together with future technologies and in hypothetical scenarios (see Section 2). Therefore, both traditional LCA and prospective LCA studies on SOFCs do not allow the prospective assessment of the environmental sustainability of the technological developments of SOFCs, described in scientific publications and patents.

This study aims to answer the following research question: **What is the environmental sustainability of future SOFCs?**

To answer the research question, this study proposes comparative LCA between a current SOFC and the future SOFCs, powered by hydrogen to produce electricity. The LCA of the current SOFC is the traditional one, following ISO 14,040 (ISO 2006a) and ISO 14,044 (ISO 2006b), while that of the future SOFCs is prospective, following the method proposed by Spreafico et al. (2023). In particular, prospective LCA is defined as an LCA that models the product system at a future point in time relative to the time at which the study is conducted (Arvidsson et al. 2023). To model the system in this way, this study extracts supporting information from selected patents relating to the future SOFCs.

The research gap consists of an environmental assessment of the future SOFCs that is only possible by forecasting their technological evolutions on which the industries are developing and patenting.

More in particular, the specific novelties are:

- The evolutions of the structural characteristics of the product itself have been analysed, not those of the future operating scenario and context, as in Vargas and Seabra (2021).
- The same evolutions of the structural characteristics of the product have been described with the data extracted directly from the patents, which data have been tested experimentally on prototypes, and not simulated virtually and obtained as a result of predictions, as in Yang et al. (2022).
- The perspective of analysis of the future SOFCs is strictly linked to industrial research, since all the considered patents have been developed by industry. While the other publications have considered the data extracted from concepts also developed in the academic field to describe the developments of future SOFCs (e.g. Di Florio et al. 2021).
- Finally, this study provides a comprehensive comparison on the sustainability of all major design choices of SOFCs, which is new both for prospective LCA studies and traditional LCA studies of current SOFCs. Specifically, the environmental impacts of the future SOFCs were expressed as a function of the layout (planar or tubular), specific power, active surface area, thicknesses and cell types depending on the application of use (i.e. stationary or mobile/dynamic).

In general, this study differs quite a bit from previous perspective LCA studies on SOFCs and other systems regarding the focus and the way in which the analysis was conducted. All the other studies in the literature can in fact be attributable either to the field of sustainable energy solutions or industrial ecology. The first ones use prospective LCA to support the future choice of the most sustainable energy systems, including those based on SOFCs, among different alternatives. The second ones use prospective LCA to make the production of SOFCs or other products more sustainable. Meanwhile, this study provides prospective LCA results to actively support the eco-design of future SOFCs, suggesting the most sustainable design solutions. For this reason, in this study, prospective LCA is conducted with great attention to the definition of the inventory through product technological forecasting, rather than to the definition of the prospective scenario.

This study can be useful for drawing prospective considerations on the Environmental sustainability of future SOFCs, i.e. to understand which structural features of SOFCs are most sustainable, also in relation to the application area. Therefore, such a source of knowledge can provide the knowledge base for the eco-design of SOFCs. In addition, the particular considered application field and the in-depth investigation about the sustainability of the structural features of future products and the considerations on patent analysis, may be useful for reasoning about the development of the methods to support prospective LCA.

2. Literature background

Many studies in the literature have analysed, through LCA, the current environmental sustainability of the different SOFCs available on the market. From their analysis and comparison, the influence of different design parameters and implementation choices of a SOFC on the environmental impacts of its life cycle can be studied. Among them there are: the type of layout, e.g. planar or tubular (Di Florio et al. 2021); the size, in relation to both the power generated and the structural dimensions (e.g. Ferreira et al. 2021); the stability to changes in environmental and operating conditions (e.g. Perčić et al. 2022); the type of fuel, e.g. hydrogen or natural gas (Bicer and Khalid 2020); the adopted production processes and technologies (e.g. Kumar et al. 2022).

However, these studies do not allow the environmental sustainability of SOFCs to be investigated prospectively, which would be significant given the particularly lively and varied interest that industry and academia are showing in the development of SOFCs (Affandi and Osman 2022; Raza et al. 2022; Salim et al. 2022). Their sensitivity analyses, when

Table 1. LCA of SOFCs in the scientific literature.

Considered SOFCs	Considered scenario	SOFC implementation	SOFC coupling	Sources
Available on the market	Current scenario	In current systems	With current fuel production technologies	Di Florio et al., 2021); Ferreira et al. (2021); Perčić et al. (2022); Bicer and Khalid (2020); Kumar et al. (2022)
Available on the market	Future scenario	In current systems	With current fuel production technologies	Vargas and Seabra (2021); Heidary et al. (2023)
Available on the market	Future scenario	In future systems	With current fuel production technologies	Liao et al. (2023)
Available on the market	Future scenario	In future systems	With future fuel production technologies	Kanchiralla et al. (2022); Scolaro and Kittner (2022); Wang et al. (2015)

present, study the repercussions on the environmental impacts of SOFCs as a result of changes in certain environmental parameters and conditions, which may also occur in the future. However, these variations have been determined arbitrarily without reference to forecast scenarios of some kind.

There are also rigorous prospective LCA studies of future SOFCs. Vargas and Seabra (2021) and Heidary et al. (2023) evaluated the impacts of SOFC vehicles, respectively, in Brazil and Iran in 2030. In these studies, the prospective scenario considered concerns the future production of hydrogen in different states, focusing on the evolution of the efficiency of production technologies. While the SFOCs and vehicles considered by both studies are current ones. The study by Liao et al. (2023) adds further perspective to this area, also considering the technological evolution of the vehicle. Kanchiralla et al. (2022), Scolaro and Kittner (2022) and Wang et al. (2015) determined the future environmental impacts of energy production systems where traditional SOFCs are coupled with new technologies for the production of the fuel that powers the SOFCs. These new technologies and their data were taken from scientific publications.

Table 1 classifies previous contributions in the literature relating to the LCA of SOFCs.

3. Compared products

3.1. Current SOFCs

The reference product is a hydrogen fuelled SOFC for the production of electricity. It is a mature product which is made on an industrial scale and which is described exhaustively in some scientific articles which have been taken as a reference to retrieve all its technical information (Al-Khori, Bicer, and Koç 2021; Di Florio et al. 2021; Smith et al. 2019). Such SOFC consists of three layers of different ceramic materials with different thicknesses: anode, electrolyte and cathode.

The reactant, i.e. hydrogen, flows inside the anode, which is porous and conductive when heated typically between 700 and 1000°C. On the cathode, also porous and conductive, and located on the opposite side of the cell, the oxygen reduction reaction takes place instead. Inside the electrolyte, which is ceramic and separates the anode and cathode, as well as the two gases, the oxygen ions transit, which, reaching the anode, oxidise the hydrogen, transforming it into water vapour which is then eliminated from the system. The electric current is created in the electrical connection between the anode and cathode in the opposite direction to the flow of ions in the electrolyte.

In the current SOFC, the anode consists of cermet, i.e. nickel oxide and yttrium-stabilised-zirconia (YSZ), in a mass ratio of 1:2. The electrolyte consists of YSZ. The cathode consists of strontium-doped lanthanum manganite (LSM) and YSZ, in a mass ratio of approximately 6.43:1.

One of the most common production processes of the current SOFC on the market, consisting of tape casting for the support and screen printing for electrolyte and cathode (Menzler et al. 2010; Minh 2004) has been considered in this study. Process energies for SOFCs manufacturing have been retrieved from Di Florio et al. (2021).

The typical mode of use of the current SOFC is the stationary one, for the production of electricity. In fact, the main limitations of this product concern the long ignition times and the fragility due to the constituent materials.

3.2. Future SOFCs

The future SOFCs considered in this study are the possible future developments of the current SOFCs, claimed in the patents. To ensure a meaningful perspective on future developments, only the future SOFCs described in the most recent patents were considered (see Section 4.1 - Life cycle inventory). While to allow the full comparability between the two considered products and to explore the impact that different design and construction choices may have on environmental sustainability, only future SOFCs of the same type (i.e. having the same components with the same materials) as the current SOFC have been considered.

In addition, the patents of the future SOFCs have been manually filtered to collect only those explicitly claiming:

- The same production process as current SOFCs, possibly considering the optimisation of the same process and/or the functioning of the same technologies, as claimed in the considered patents.
- The same application of the current SOFCs, i.e. the stationary power generation.
- A least the same performance and durability of the current SOFCs.

The choice to consider such future SOFCs, among all possible evolutions of the current SOFC can be considered a limitation for the prospective LCA. However, at the same time, this choice can ensure reliability to the analysis by ruling out considering technologies or production processes that are too fanciful and with scares chances of actually being implemented in the future. In more detail, the mass ratios of the constituent materials of the current SOFC and future SOFCs were considered the same. In terms of layout, the future SOFCs are both planar and tubular. In fact, future SOFCs differ from current SOFC in the overall size and thicknesses of anode, electrolyte, and cathode, as well as in the working efficiency.

Figure 1 schematically represents the structure of the considered current SOFCs (planar) and future SOFCs (planar and tubular) with their components.

Table 2 reports the characteristics of the current SOFC and of the future SOFCs considered in this study. In particular, the data of the future SOFCs derive from the arithmetic mean of the data extracted from all the considered patents.

4. Materials and methods

This study proposes a comparative LCA of two types of SOFC powered by hydrogen to produce energy: the current ones and the future ones. The main peculiarity lies in the use of two methodologies:

- **Traditional LCA** (ISO 14,040; ISO 14,044, Calisir et al. 2020), to assess the environmental impacts of the current SOFC;
- **Prospective LCA** (e.g. Arvidson et al., 2018), to assess the environmental impacts of the future SOFC.

Traditional LCA is one of the most diffused, appreciated and reliable methodologies to provide quantitative evaluation of the sustainability of current technologies, and to discuss the choices to implement during eco-design (Hauschild, Rosenbaum, and Olsen 2018). To do this, the methodology is articulated through the following steps, according to ISO 14,040 and ISO 14,044.

(1) Defining the goal and scope of the study, or the identification of the technical system to be measured, the operative scenario, the motivation for performing the assessment and all the requirement for performing it.
(2) Collecting all the sources of impacts, i.e. system parts and lifecycle phases, through the life cycle inventory (LCI).
(3) Assessing the impacts according to environmental indicators.
(4) Interpreting and discussing the results.

Prospective LCA allows to evaluate the environmental sustainability of eco-design solutions (i.e. ideas, prototypes, immature products, emerging technologies). To do this, prospective LCA is based on the foreground inventory, including prospective theoretical primary data arising from lab-scale tests and simulations rather than on direct measurements as in traditional LCA. In this study, the method proposed by Spreafico et al. (2023) is applied to make the prospective LCA of the future SOFC. The main peculiarity of this method resides in the use of a large mole of patents from which to extract data for the inventory through a systematic procedure of patent analysis, subordinated to the requirements of the ISO 14,040 and ISO 14,044 standards to ensure the data quality. The same data are then used to carry out the LCA according to the traditional methodology.

In the following sections, the steps followed to perform the traditional LCA of the current SOFC and the prospective LCA of the future SOFC are explained in detail.

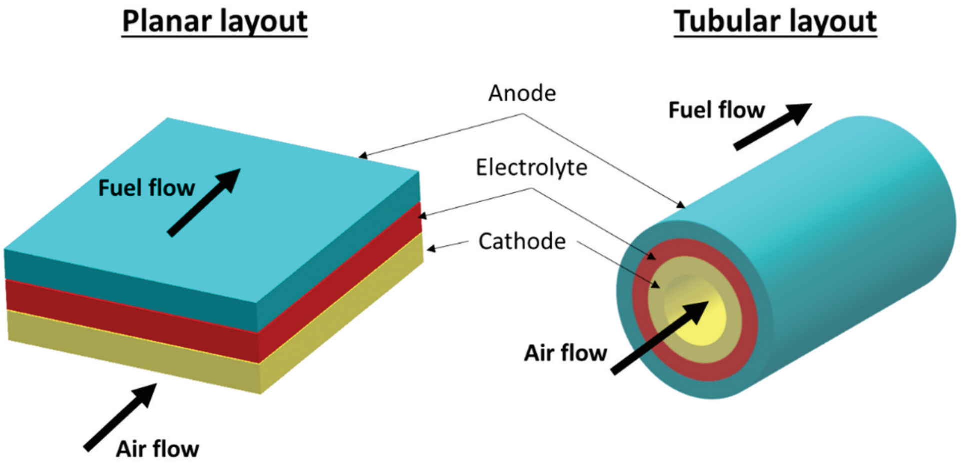

Figure 1. Structures of the considered SOFCs.

Table 2. Data referred to a single anode-supported SOFC.

Features	Units	Current SOFC	Future SOFCs	
			Average	Standard deviation
Specific power	kW/cm^2	0.28	0.43	0.28
Surface area	mm^2	29900	4196	13167
Thickness Anode	µm	700	395.95	406.18
Thickness Electrolyte	µm	10	64.87	104.01
Thickness Cathode	µm	50	66.85	135.57

4.1. Goal and scope definition

4.1.1. Functional unit and context

The objective of this study is to comprehend if the structural interventions on which the industries, who have filed the patents, are developing can reduce the environmental impacts. Therefore, this objective has been concretised in the LCA goal, such as the identification of the environmental impacts of the current SOFC and future SOFC (implementing the structural interventions) along the entire life cycle. This is because these design interventions have repercussions on all phases. A different electrical conductivity of the SOFC affects the impacts during the use phase. Different geometries and thicknesses of the SOFC affect the amount of material, to be extracted in pre-manufacturing, to be processed in manufacturing and to be disposed of in the end-of-life, as well as the duration of the cell during use.

In line with the defined goal, the functional unit concerns the production of 1 kWh of electrical energy through the SOFC and is common to both the considered products, i.e. the current SOFC and future SOFC, so as to be able to compare their environmental impacts, in line with the provisions of the comparative LCA. The parameters that define this functional unit were considered following what was done by previous studies on the LCA of SOFCs (e.g. Di Florio et al. 2021).

In order to explore the repercussions of patented design interventions on environmental sustainability, or to compare the environmental impacts of the current SOFC and future SOFCs, the same reference context was considered in both cases. All the choices and assumptions about the life cycle of the compared products refer to the current standard production techniques, use and disposal. Energy consumption for the production and disposal of the SOFCs refer to Italian context. These choices are a limitation of this work because the prospective LCA evaluates the environmental impacts of future SOFCs only in relation to the prospective changes of their structural characteristics, without considering the evolution of production technologies. On the other hand, this choice guarantees greater comparability between the two products, highlighting in particular the impacts of the structural interventions which is the objective of this study.

4.1.2. System boundaries

This study is a cradle-to-gate analysis, mainly focused on the considerations of the production of the compared products, as previously done by Smith et al., (2019) when analysing immature SOFCs, 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). Hypothesising the characteristics of the use phase and end-of-life without estimates available in the patents could make the prospective LCA insignificant (Thonemann, Schulte, and Maga 2020).

Pre-manufacturing is considered because the constituent materials of products are the same but the quantities may change. Manufacturing was considered because the energy consumption of all production steps and the amounts of auxiliary materials (e.g. water) used depend on the mass of raw materials processed and how the production technologies operate. These can also vary of the two products. In manufacturing, energy and auxiliary materials consumption of all production steps previously described (see Section 2.1.2.) were considered.

The use phase and the end-of-life of the products is 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.

Figure 2 represents the system boundaries of this study.

4.2. Inventory

Data for the current SOFCs inventory, reported in detail in Section 2.1, are collected by Di Florio et al. (2021), Al-Khori et al. (2021), Smith et al. (2019).

Data for the inventory of the future SOFCs, covering the entire life cycle, are extracted from a selected pool of patents. Patent search, selection, and analysis, as well as data extraction for LCI from these patents, were conducted by strictly following the method of Spreafico et al. (2023). This method was taken as a reference because it provides all the guidance to build a foreground inventory in order to carry out a prospective LCA, considering a large number of patents related to future products. The objective of this method is to provide a large number of relevant and reliable data. To do so, the method combines patent search and analysis techniques and guidance from ISO 14,040, ISO 14,044, and the Pedigree Matrix for LCA, to ensure the data quality requirements. In the following, all the steps followed to construct the patent pool, with reference to the considered method, are described and explained in detail.

- **Patent search**: The patent search query used is '(SOFC+ OF ((FUEL +1D CELL+) S (ZIRC+ OR YSZ+ OR OXIDE +)))/TI/AB/CLMS', which was launched in Orbit DB, within the entire world database, in the title, abstract and claims fields. This query searches for all patents related to SOFCs, where zirconium oxide is claimed to be present. As constructed, such a query is very general, which required a great deal of manual filtering work on the content. However, initial analysis revealed great heterogeneity with which the patents describe the future SOFCs considered, and only the elements considered are always present.
- **Filter on patent time relevance**: The patents obtained are then filtered by year, considering only those with early priority dates from 2018 onward, so that up-to-date data could be selected. This means considering only the patents, whose application was filed from that year.
- **Filter on reliability of patent content**: This additional filter concerns legal status. Only those patents that passed the examination are considered, so that more reliability could be ensured.
- **Filter on relevance of patent content**: In this case, the content of the title and abstract of these patents was manually analysed for relevance. Thus, all patents claiming the use of zirconium oxide not to make SOFC were discarded.

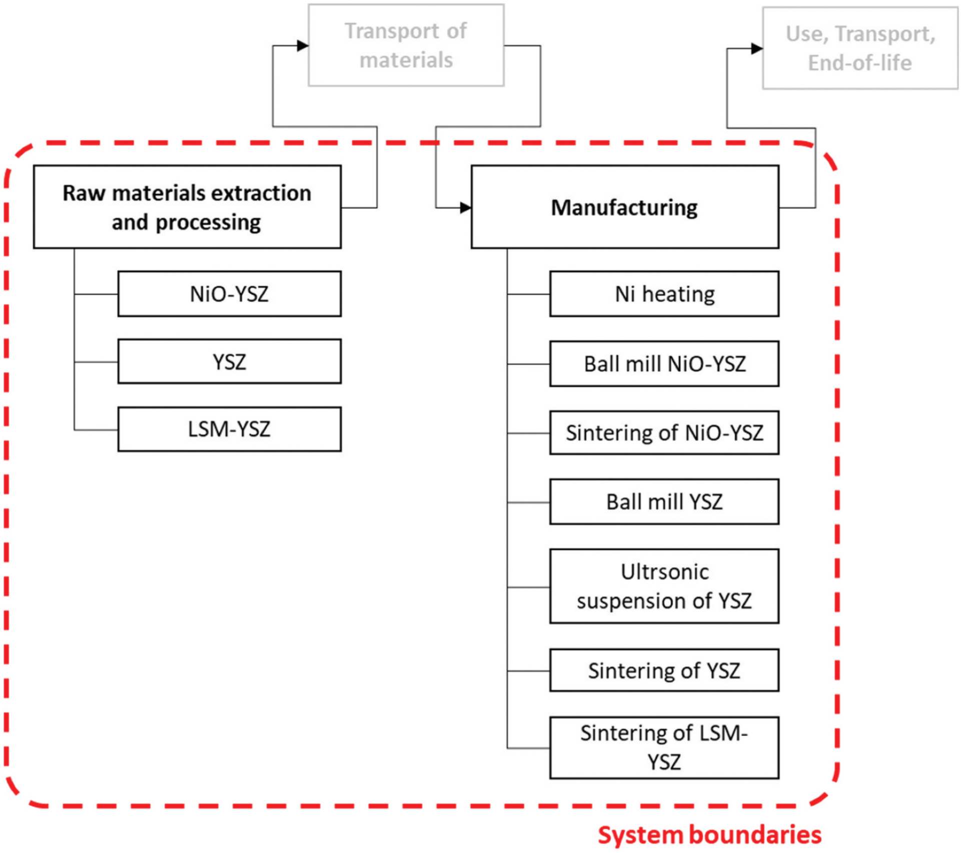

Figure 2. System boundaries.

- **Filters on the quality of the data extracted**: Of all these patents, only those that present numerical data relating to the parameters to be considered for the inventory were therefore selected. Among all the data, only those supported by documented experimental evidence, which were conducted according to standard methods and procedures, were retained.

The data of the current SOFC and those of the future SOFCs, collected from the patents, are described in detail in the following sections. In the same, are also reported further hypotheses, with respect to those of the method of Spreafico et al. (2023), introduced ad hoc for this study to allow the comparison between the two considered products.

4.2.1. Raw material extraction

The flows of the raw materials of the current SOFCs and future SOFCs are modelled using Ecoinvent v3.6 database, using same datasets used by the studies referenced for the current SOFC (i.e. Al-Khori, Bicer, and Koç 2021; Di Florio et al. 2021; Smith et al. 2019). In this regard, all current SOFCs mass datasets, which in turn are dependent on geometry and thicknesses (see Table 1), are retrieved from those studies. Instead, data for the same parameters of future SOFCs were extracted from the selected patents. In this case, since patents usually claim a range of values for a given parameter, rather than a precise value, so as to increase protection, in almost every patent considered, the minimum and maximum value of the reported range were extracted for each parameter. Then for the parameters of future SOFCs, the values derived from the arithmetic mean of all the data collected from the different patents were considered (see Table 2).

4.2.2. Manufacturing

All technologies used in the different stages of the production process of current SOFCs and future SOFCs are electrically powered. The same auxiliary materials used in the manufacturing of current SOFCs were also considered for the manufacturing of future SOFCs. The energy consumption of the manufacturing process and auxiliary materials depends almost exclusively on the mass of the SOFC, even as the adopted temperature curve varies (Scataglini et al. 2017). In line with this assumption, in this study, these fluxes for future SOFCs, were scaled from those of current SOFCs, relative to mass.

Following the systematic selection of documents and data and all hypotheses considered, 58 patents were considered. These patents and all the data extracted from them and used in the foreground inventory are reported in Table A1 in the Appendix.

Table 3 reports all the inventory data, relating to materials, auxiliary materials and energy consumption, where those of the current SOFCs derive from Smith et al. (2019). This data also includes the wastes.

All the flows reported in Table 3 were modelled using ‘market for’ datasets from Ecoinvent v.3.9.

Table 3. Inventory of the current and future SOFCs.

			Future SOFCs	
Flows	Units	Current SOFCs	Average	Standard deviation
NiO	kg	0.68	0.25	0.33
YSZ	kg	0.57	0.21	0.27
Ethanol solvent	kg	0.44	0.29	0.10
Trichloroethylene	kg	0.43	0.16	0.21
Isopropanol	kg	0.28	0.10	0.14
Ethylene	kg	0.11	0.03	0.05
Polyvinyl alcohol	Kg	0.09	0.03	0.04
Methyl methacrylate	kg	0.06	0.02	0.03
Lanthanum oxide	kg	0.03	0.02	0.00
Water	kg	0.03	0.02	0.00
Strontium nitrate	kg	0.02	0.01	0.00
Zirconium dioxide	kg	0.01	0.04	0.01
Manganese oxide	kg	0.01	0.00	0.00
Polyethylene glycol plasticizer	kg	0.01	0.04	0.01
Electricity consumption	kWh	0.34	0.13	0.15

4.3. *Impact assessment*

The impact assessment of current SOFCs and future SOFCs has been performed by means of the LCA software SimaPro 9 and Ecoinvent v 3.9 using the midpoint ReCiPe (H) model (Goedkoop et al., 2013) and IPCC 2013 GWP 100a method (Stocker et al. 2013). In line with what is typically done in prospective LCA (Arvidsson et al. 2018), the environmental impacts of future SOFCs were expressed as a function of mean and standard deviation. These results relate to the total impact and stratified between the components (i.e. anode, electrolyte, and cathode) and the constituent materials (i.e. NiO, YSZ, and LSM).

In order to provide useful guidance for the design of SOFCs, the results were first reported in general terms by determining the GWP of current SOFCs and future SOFCs. Then, the GWP of future SOFCs was stratified in order to investigate the relationships between environmental sustainability and the following features of interest of SOFCs.

- **Layout**, by comparing the future SOFCs with planar and tubular structure and these latter in relation with the diameter-to-length ratio. In this way, the prospective results of this study can be easily compared with those of the current SOFCs described in other studies in the literature, since the comparison between planar and tubular geometry is usually performed (e.g. Singh, Zappa, and Comini 2021; Vargas and Seabra 2021).
- **Specific power**, by comparing GWP as a function of variation in SOFC specific power, as done in some comparative LCAs of current SOFCs (e.g. Ferreira et al. 2021).
- **Surface**, comparing the GWP to the active surface of the SOFC changes to understand the most sustainable size, as done in LCA comparatives of current SOFCs that have this objective (e.g. Lai and Adams II, 2023).
- **Thickness**, comparing GWP as anode, electrolyte and cathode thicknesses vary, as in some comparative LCA of current SOFCs that aim to offer guidance for sustainable sizing of SOFCs (e.g. Longo et al. 2019).
- **Application fields**, comparing the GWP according to the intended use of the SOFC, i.e. stationary or mobile and more dynamic, and thus the different design choices that are made on the SOFCs to ensure their application in these fields. This stratification was performed by classifying the patents, based on what is explicitly stated. The purpose of this stratification is to respond, with considerations of environmental sustainability, to the open debate about the sustainability in general of new developments in SOFCs. Indeed, much speculation exists in the scientific and patent literature about the possibility of developing SOFCs for new areas, competing with other fuel cell types or energy production technologies. In particular, a certain interest is on two applications, both of which are analysed in this study. On the one hand, future SOFCs were considered for mobile applications, where greater ductility is required (e.g. Hagen, Sun, et al. 2020; Zeng et al. 2020). On the other hand, future SOFCs were considered for using microgrids and with variable loads, where greater dynamism in SOFCs operation and reduction of start-up transients is required (e.g. Jiang et al. 2022; Malfuzi et al. 2020).

5. Results and discussion

5.1. *Overall results*

The more general result of this study concerns the comparison of the environmental impacts of current SOFCs and future SOFCs.

Table 4 reports the environmental impacts of the components and materials of current SOFCs and future SOFCs.

Table 5 classifies the impacts of the compared SOFCs between the material extraction and manufacturing phases.

Figure 3 graphically compares the environmental impacts of the components and materials of current SOFCs and future SOFCs. To facilitate the comparison, in Figure 3 (left) the sum of the impacts of the components of the current SOFCs has been set equal to 100%, while in Figure 3 (right) the sum of the impacts of the materials of the current SOFCs has been set equal to 100%.

Table 2 and Figure 3 show that the future SOFCs claimed in the patents are more sustainable than the current SOFCs, as regards the GWP. The overall GWP reduction is

Table 4. GWP impacts [kg CO_2 eq.] of components and materials of current SOFCs and future SOFCs.

GWP impacts [kg CO_2 eq.]			Future SOFCs	
Component	Material	Current SOFCs	Average	Standard deviation
Anode	**NiO**	15.34	5.56	7.42
	YSZ	4.14	1.50	2.00
Electrolyte	**YSZ**	0.09	0.36	0.12
Cathode	**YSZ**	0.06	0.04	0.01
	LSM	3.15	2.07	0.75

Table 5. GWP impacts [kg CO_2 eq.] of material extraction and manufacturing of current SOFCs and future SOFCs.

		Future SOFCs	
GWP impacts [kg CO_2 eq.]	Current SOFCs	Average	Standard deviation
Material extraction	22.57	9.44	10.20
Manufacturing	0.21	0.08	0.09

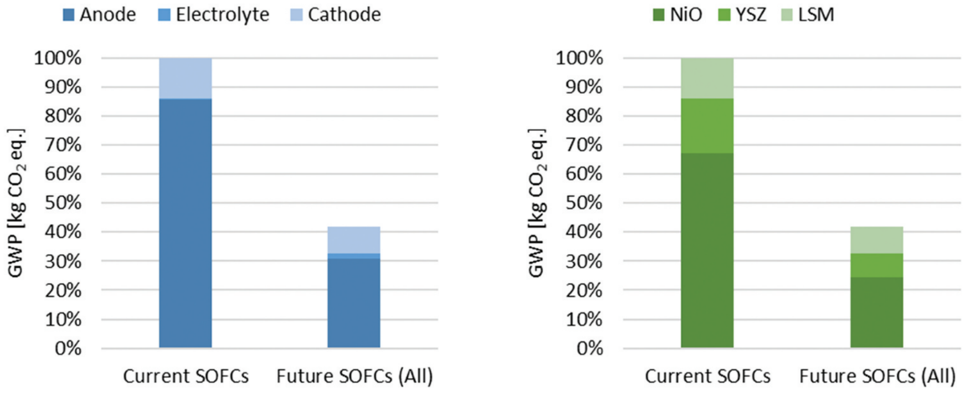

Figure 3. GWP impacts comparison of components and materials of current SOFCs and future SOFCs.

greater than 50%. At the level of the individual components, the greatest GWP reduction occurs on the anode (−54%), while the impact of the cathode decreases by only 2% and that of the electrolyte even increases by 2%. The impacts of all the constituent materials decrease passing from the current SOFCs to the future SOFCs: the GWP NiO by 42%, that of the YSZ by 10% and that of the LSM by 2%. These results demonstrate that the major interventions on the patented SOFC concern the anode and its materials which by mass is definitely the most present and impactful component.

In fact, justifications for these results can be drawn if the masses of the components and materials of the current SOFCs and future SOFCs are compared. The masses of NiO and YSZ in the anode are both reduced by 63%, that of YSM in the electrolyte increases fourfold, while those of LSM and YSZ in the cathode are both reduced by 12.4%. In turn, these mass differences of the components and materials in the current SOFCs and in the future SOFCs depend on the differences of their thicknesses and mainly in the significant reduction of that of the anode (see Table 1) and the reduction of the overall effective surface of the SOFCs. In fact, to generate 1 kWh of electricity, according to what is established in the functional unit, the overall effective surface of the future SOFCs is 34% lower than that of the current SOFCs. This is possible thanks to the greater specific power of the future SOFCs compared to the current SOFCs (+52% on average) (see Table 1).

The detailed analysis of the considered patents provides design strategies to reduce the impacts by guaranteeing the increased conductivity:

- Reduce the internal porosity by optimising the distribution (e.g. WO2021/025050). At a physical level, this is justified by the less tortuous transit of electrons through the SOFC (Andersson et al. 2016) that lead to a greater ionic conductivity of anode and cathode (Araujo et al. 2018 and Zhang and Hu 2023).
- Optimize the particle size of raw material powders (e.g. JP2020071987) and the dosage of raw materials (e.g. US20190123362). This leads to an increase in the electrical conductivity of the SOFC which improves its performances, reducing consumption and to a greater stability of the surfaces of the SOFC in contact with the fuel and therefore to a longer life of the SOFC (Sugihara et al. 2014). Both of these factors have a positive influence on the reduction of GWP. This control can be achieved through the optimisation of the temperature curve in the firing and drying of materials obtained thanks to a different and more precise control of the electric oven (e.g. CN109638325). Another option is the optimisation of the arrangement and distribution of the material during firing, for example by better controlling the rolling pressure (e.g. CN108417872). These precautions in production allow the porosity inside the SOFC to be reduced, eliminating voids and blowholes in a widespread and constant way (Kuterbekov et al. 2024). Consequently, the performances of the SOFC following the reduction of the ohmic resistance which occurs in the most homogeneous material.

Therefore, to understand which design choices, described in the considered patents, improve SOFCs sustainability the most, in the following sections, the environmental impacts of future SOFCs have been appropriately stratified. All the results are compared with the GWP of the current SOFCs, which was set equal to 100%, as in Figure 3.

5.2. Layout comparison

To explore the repercussions of the SOFC layout on the GWP reduction, in Figure 4, the overall results have been stratified into two categories: planar future SOFCs vs tubular future SOFCs.

Figure 4 clearly shows the greater sustainability of future SOFCs with tubular layout, which obtained a GWP lower than 28% compared to the planar future SOFCs. In particular, the greatest GWP reduction was obtained on the LSM of the cathode (9%). While, in order to understand which type of tubular layout is the most sustainable, Figure 5 graphically compares the environmental impacts of the components and materials of the tubular future SOFCs having different ratio of diameter to length.

Figure 5 clearly shows that the smallest diameter-to-length ratio (<0.1) is the most sustainable. The trend of the overall GWP with the highest ratios cannot be correlated to a particular trend. The GWP of the anode is significantly reduced, while that of the cathode increases.

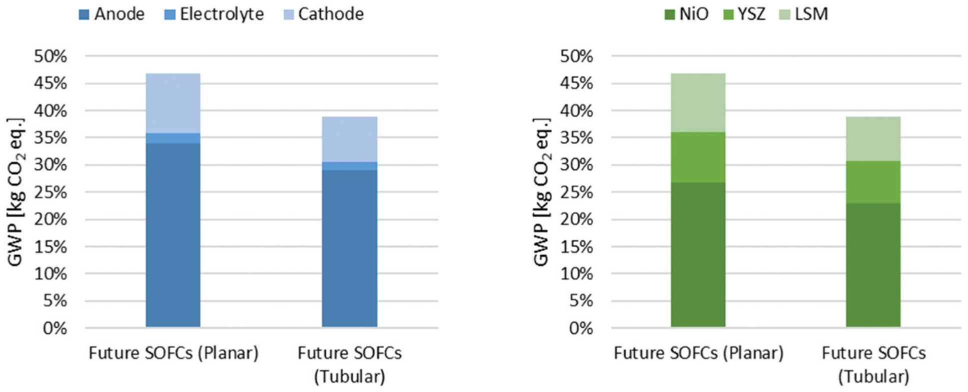

Figure 4. GWP impacts comparison of components and materials of future SOFCs with planar and tubular layout (where 100% is the GWP of current SOFCs).

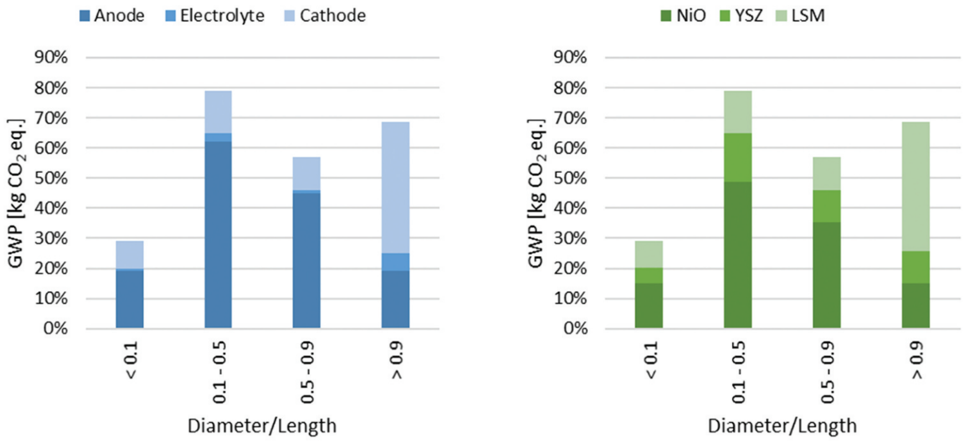

Figure 5. GWP impacts comparison of components and materials of tubular future SOFCs with different diameter to length ratio (where 100% is the GWP of current SOFCs).

The analysis of the scientific literature can extend the validity of the results also to the use phase which was not considered in this study. This is because, according to Perčić et al. (2022), tubular SOFCs are more sustainable due to their greater mechanical strength and therefore their greater stability during use, which increases their efficiency over long time spans. While according to Salim et al., (2022) and Gandiglio et al., (2019), the greater environmental sustainability of microtubular SOFCs, which have very low diameter to length ratios, compared to tubular SOFCs, is due to their easier manufacture, with the consequence reduction of the energy consumption.

5.3. Specific power comparison

Figure 6 graphically compares the environmental impacts of the components and materials of future SOFCs with different specific power.

Figure 6 shows a linear correlation emerged between the increase in specific power and the reduction in GWP, whose trend is associated with an R^2 equal to 0.93. This is mainly due to the reduction of the GWP of the anode, which is also linear. The GWP of the electrolyte also decreases, although not linearly, while nothing can be said about the trend of the GWP of the cathode. At the material level, both the GWP of NiO and the GWP of YSZ decrease more or less linearly.

Going into the merits of the considered patents, the reasons for this reduction in GWP following the increase in specific power can be understood.

- Reduction of the dimensions of the SOFC and therefore of the materials for the same generated power (e.g. US20190123362).
- Reduction of the quantity and/or temperatures of the fuel used for the same generated power, or increase in the power of the SOFC for the same input (e.g. IN202121045468).

The first evidence is useful to strengthen the projections of Micoli et al. (2023) on the future of the SOFC, who hypothesise an increase in environmental sustainability following the reduction of their dimensions, possibly precisely thanks to the increase in efficiency. In regard to the second case, the obtained trend of the GWP vs specific power is useful for quantifying the observations previously made by Zhong et al. (2021). In fact, these authors stated that the environmental impacts deriving from the greater cooling demand, to maintain the integrity of a more powerful SOFC, are in any case largely compensated by the reduction of the impacts deriving

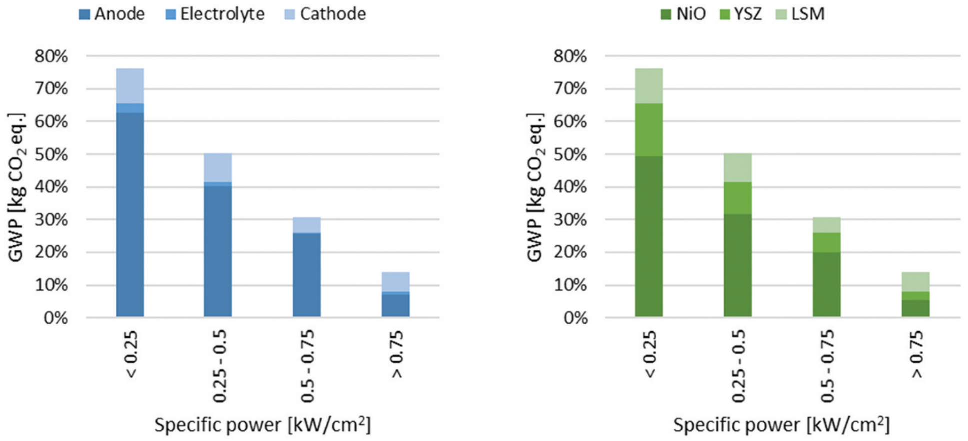

Figure 6. GWP impacts comparison of components and materials of future SOFCs with different specific power (where 100% is the GWP of current SOFCs).

from the increase in the efficiency of the SOFC. However, this evidence had been obtained on the basis of a few experimental observations, in which the specific power varied in a more limited way than shown in this study.

5.4. Surface comparison

Figure 7 graphically compares the environmental impacts of the components and materials of future SOFCs with different active surface.

Figure 7 shows that the most sustainable future SOFCs are the smaller and larger ones, although the former is better than the latter. The main reason for this trend concerns the impacts of the anode and in particular of NiO. The analysis of the considered patents provides justification for this, showing the reduction of the overall mass of future SOFCs and the increase of the active surfaces. This in turn is due to the decrease in thickness of the anode, cathode and electrolyte in these cases.

These data are useful to deepen the considerations already made on the environmental and economic sustainability of SOFCs of different sizes by Naeini et al. (2022), albeit limited to the manufacturing phase. In line with this study, the authors state that as the size of the SOFC decreases, the environmental sustainability increases. Meanwhile, according to the authors, economic sustainability exists for both small and large SOFCs, due to different reasons. Small SOFCs are easier to implement and benefit from the scale factor, while large SOFCs allow for reductions in connection and frame costs.

In addition, these results are also useful at a more general level, to provide new evidence to various studies in the literature that carry out the LCA of SOFCs, combining them with other plants for cogeneration purposes (e.g. Gandiglio et al. 2019; Tanveer et al. 2021; Yang et al. 2022). In these cases, the trend is in fact to consider only medium-size SOFCs and to investigate their environmental performance in relation to the variation of the operating conditions, rather than the structural aspects and in particular the dimensions.

5.5. Thickness comparison

Figure 8 graphically compares instead the environmental impacts of the components and materials of future SOFCs with different thicknesses of anode, electrolyte and cathode.

Figure 8 shows exponential correlations between the increase in thickness of the anode, electrolyte and cathode and the GWP increase. These trends are mainly due to the explosion of the GWP when the thicknesses become very large. With contained thicknesses, the trend is instead mostly linear and with a slight slope. Going into more detail of the obtained

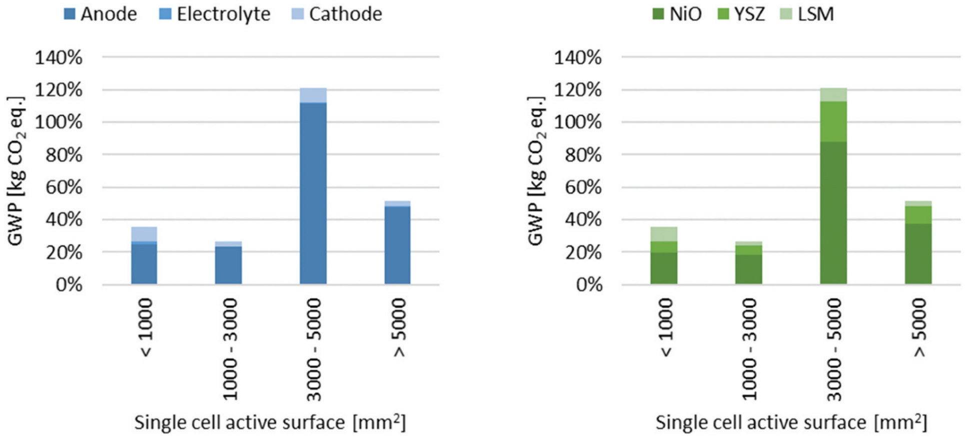

Figure 7. GWP impacts comparison of components and materials of future SOFCs with different active surface (where 100% is the GWP of current SOFCs).

Figure 8. GWP impacts comparison of components and materials of future SOFCs with different thickness of anode, electrolyte and cathode (where 100% is the GWP of current SOFCs).

results, the motivation of this GWP explosion with large thicknesses can be studied. At the component level, the responsible for this trend is in fact the GWP above all of the cathode which increases exponentially. In turn, this is due to the exponential increase in the GWP of the LSM. Moreover, even by observing the individual growth trends of the GWP, as the thickness of the anode, electrolyte and cathode varies, it can be seen that the increase in the thickness of the cathode is what causes the greatest growth in the GWP.

These results confirm the results of several articles regarding the increase in SOFCs sustainability with decreasing thickness (e.g. Duan et al. 2017; Hong et al. 2017; Ji et al. 2015). This argument is rather followed in the scientific literature due to the recent investigation on the recent advances in the manufacturing processes that allowed to consistently achieve nano-to-submicron level thicknesses for various SOFC components. However, all of these studies report experimental data obtained in purely academic contexts. For this reason, the results of this study also broaden the perspective to the patent literature, exclusively related to industry in the considered patents.

The justification for the reduction in GWP following the reduction in thickness can be found by comparing the results of Li et al., (2006) and those of Section 5.4. According to the authors, the reduction of the YSZ electrolyte thickness from 100 μm to 40 μm led to the increase of the maximum output power density from 0.47 W/cm^2 to 0.76 W/cm^2, which in turn is beneficial for the reduction of the GWP (see Figure 6). The physical justification lies in the reduction of the electrolyte ohmic loss. Since the latter is proportional to the thickness, it follows that this reasoning can also be extended to the anode and the cathode, where the polarisation resistance also decreases (Lyu et al. 2021).

5.6. Application fields comparison

Figure 9 compares the GWP of the future SOFCs used for stationary and mobile and more dynamic applications.

Figure 9 shows that future SOFCs used in stationary applications have a lower GWP than those used in mobile and dynamic applications. The main reason lies in the considerably higher impact of the cathode and in particular of the LSM, while that of the anode, and in particular of the NiO is even lower.

From the analysis of the patents of the two categories it is possible to understand the reasons for this difference. The future SOFCs for stationary applications and for mobile and dynamic applications have in fact an average-specific power, respectively, of 0.44 kW/cm^2 and 0.39 kW/cm^2, the average thickness of the anode of 0.42 mm and 0.32 mm, the average thickness of the electrolyte of 0.04 mm and 0.09 mm and the average thickness of the cathode of 0.02 mm and 0.09 mm. By virtue of these differences, future SOFCs for mobile and dynamic applications need a greater surface area to generate the same electrical power and, consequently, greater volumes (and masses) of the electrolyte and the cathode.

Anyway, both these categories of future SOFCs are still more sustainable than current SOFCs. The greater sustainability of SOFCs for stationary applications can be justified by their design optimisation which started much earlier than that of future SOFCs for mobile and dynamic applications, which are a more recent topic of study (Singh, Zappa, and Comini 2021). The results of the latter are, however, encouraging in the comparison with other energy production technologies, e.g. other fuel cells, which are already working in these application areas (Longo et al. 2019; Ramadhani et al. 2022).

5.7. Overall discussion: implications, limitations and future developments

The obtained results could be useful to those involved in the research and development of SOFCs in industry and academia and to those who are prospectively evaluating the use of SOFCs in future applications. This investigation could be carried out, on a general level, to understand the influence of interventions on different design parameters on environmental sustainability. On a more specific level, it is possible to get an idea of the quantitative extent of the change to be made to the most strategic design parameter. Although far from a structured eco-design framework in terms of organisation and quantity of information, the results provided could serve as the basis for its definition. For example, along the lines of what was done by Papurello et al. (2022) for current SOFCs, the indications provided for design intervention and component could be systematised.

This study can also serve as an example of an innovative application of the prospective LCA methodology, as it is based on a systematic patent analysis to build the prospective inventory and considers a large number of patents from which to extract the data. The prospective LCA community has in fact been asking for integration with patents in these terms for some time (Adrianto et al. 2021; Arvidsson et al. 2018). In this regard, the study is also an advancement compared to the method of Spreafico et al. (2023) which proposes an integration only at a theoretical level.

The obtained results must be read in light of several limitations. First of all, the patents from which the data were extracted are only 58. The meaning of this number is twofold. To ensure the significance of the results, the number is low, in fact there are definitely many more patents relating to possible future technological developments of SOFCs on which companies are working, not to mention the scientific publications. On the other hand, this number is consistently higher than that used in the majority of prospective LCA studies of different applications, published in prestigious journals (Spreafico, Landi, and Russo

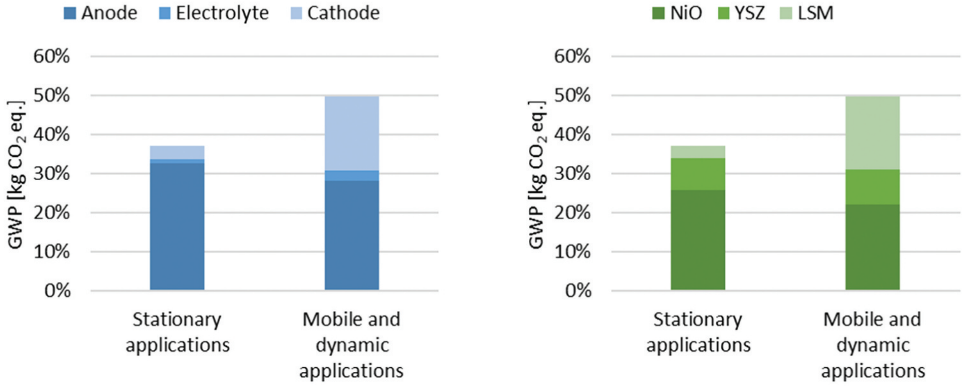

Figure 9. GWP impacts comparison of components and materials of future SOFCs used for stationary and mobile and more dynamic applications (where 100% is the GWP of current SOFCs).

2023). To overcome this limitation, some filters used for patent selection (see Section 4.3) could be removed, but this would affect the quality and reliability of the analysis.

In addition, the criteria by which the data were filtered were always those of keeping the most representative future SOFCs for future mass developments, eventually sacrificing the developments with fewer chances to be implemented. While the geographical distribution of the considered patents is decidedly unbalanced towards China (see Table 5 in the Appendix). Moreover, China is working hard on the development of SOFCs, but it is also a country that patents much more than others in every area, also thanks to less rigorous examination procedures (Bian 2020). Therefore, it is difficult to say whether the distribution found is truly significant.

Another limitation of the study concerns the time consistency and scale-up of the results. It is in fact difficult to say when and how the results extracted from the patents will actually be implemented at an industrial level (Dunn 2011). The solution to this problem could be sought in the patents themselves, which have already been used in the past to collect information to support predictions on development times, at a general level (Liu et al. 2021) and on industrial scalability in prospective LCA studies (Thonemann, Schulte, and Maga 2020). That is, to verify the results of the analysis, and at the same time enrich it with new evidence, in the future the real implementations of what is claimed in the patents considered could be monitored. To this end, to ensure correspondence between the patents and their developments, control could be on the patent applicants and on the possible transfer to others and on the companies that will create the SOFCs in the future.

Future developments of this study could also involve the prospective comparison of the results obtained with future energy production technologies and prospective insights into about the future context of use in order to draw broader considerations for environmental sustainability. In this regard, as a starting point, one could consider many of the patents discarded in this study, which claim future developments of SOFCs, although not quantifying them, coupled with other future technologies for energy production. This step is fundamental to extend the evaluation domain and obtain more complete considerations on the environmental sustainability of energy systems based on SOFCs. The usefulness of this study is in fact limited to SOFCs only. However, eco-design seen more broadly could clash with some of the results obtained to promote the sustainability of other aspects, such as the duration of the entire system (Raza et al. 2022).

Highlights

- Prospective LCA of SOFCs with inventory data extracted from patents.
- GWP of future SOFCs is less than 50% of that of current SOFCs.
- Impact of the anode counts for about 80%, while that of nickel oxide counting for almost 70%.
- Tubular SOFCs with diameter-to-length ratios (<0.1) are the most sustainable.
- GWP decreases with specific power and in cells with smaller sizes and thicknesses.

6. Conclusions

In this study, the environmental impacts (limited to the GWP) of current SOFCs and future SOFCs were determined and compared based on a prospective LCA. The main peculiarity lies in having followed a systematic procedure to conduct the prospective LCA, i.e. to construct a foreground inventory for the future SOFCs. This kind of inventory consists of patent data related to the structural characteristics of future SOFCs. Both the large number of considered patents and the criteria for their selection and data extraction, in line with ISO 14,040 and 14,044 standards for LCA, are new to this study.

Apart from the limitations, this study brings the following conclusions.

- The average GWP of future SOFCs is lower than that of current SOFCs, due mainly to the reduction in the GWP of the cathode, and in particular the LSM. This is mainly due to the increase in specific power in future SOFCs and thus the reduction in active surface for the same energy generated, rather than the thicknesses, which in future SOFCs decrease only in the anode.
- The future SOFCs with tubular layout are more sustainable than the planar future SOFCs. In particular, among the tubular ones, those having a low ratio of diameter to length have a lower GWP.
- At the size level, the GWP of future SOFCs decreases as the specific power increases, with a direct proportionality. The patented future SOFCs having the low GWP are those with an active surface comprised between 1000 and 3000 mm^2. In addition, GWP decreases almost linearly as anode, electrolyte, and cathode thicknesses decrease.
- Regarding, the stratification of future SOFCs according to application fields, it was found that those dedicated to mobile or more dynamic applications are less sustainable than stationary ones. However, the impacts of the former are still significantly lower than current SOFCs, applied for stationary uses, and bode well for their diffusion towards such new areas.

Nomenclature

GWP	global warming potential
LCA	life cycle assessment
LCI	life cycle inventory
LSM	strontium-doped lanthanum manganite
NiO	nickel oxide
SOFC	solid oxide fuel cell
YSZ	yttrium-stabilised-zirconia

Disclosure statement

No potential conflict of interest was reported by the author(s).

Notes on contributor

Christian Spreafico is assistant professor at the University of Bergamo. He has a PhD in industrial engineering and an MSc in mechanical engineering. His main research interest deals with eco-design, paying particular attention to patent analysis and prospective LCA to evaluate the sustainability of emerging technologies. He is the inventor of six patents.

Data availability statement

Data derived from public domain resources.

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Appendix

Table A1. Considered patents about the future SOFCs and data extracted from them (where Stat = stationary, Mob = mobile/dynamic).

Patent	Year	Layout	Application field	Diameter [mm]	Length [mm]	Surface [mm^2]	Electrolyte thickness [mm]	Anode thickness [mm]	Cathode thickness [mm]	Power [W/cm^2]
CN109638325	2018	Tubular	Stat.	10–12	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
CN109650873	2018	Planar	Stat.	13	n.a.	n.a.	n.a.	1	n.a.	n.a.
US20190097243	2018	Planar	Stat.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0.3–0.4
CN108417872	2018	Tubular	Stat.	0.5–1	2.26	3.55–7.100	0.15	n.a.	n.a.	n.a.
CN109378488	2018	Tubular	Mob.	n.a.	n.a.	n.a.	0.001–0.05	n.a.	n.a.	n.a.
WO2019/205855	2018	Tubular	Stat.	1	2	6.283	0.001–0.02	0.005–0.02	0.005–0.02	0.22
JP2018067416	2018	Tubular	Mob.	5	50	785.398	0.01	0.05–0.4	0.01	n.a.
CN108736051	2018	Planar	Stat.	n.a.	n.a.	n.a.	n.a.	1.2	n.a.	n.a.
JP2020071987	2018	Tubular	Stat.	20	20	1256.637	0.005	0.5	0.005	0.5
CN109818021	2018	Tubular	Stat.	13	26	1061.858	n.a.	n.a.	n.a.	0.26–0.53
KR10–2020–0026411	2018	Planar	Stat.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0.05–0.15
KR10–2019–0024749	2018	Planar	Mob.	6–12	150	2827.433–5654.867	0.035–0.04	n.a.	n.a.	0.3
CN109244514	2018	Planar	Stat.	n.a.	n.a.	45	n.a.	n.a.	n.a.	0.4–0.88
CN210861803	2018	Planar	Mob.	n.a.	n.a.	225	n.a.	0.025–0.1	n.a.	0.3
KR10–2019–0092873	2018	Planar	Stat.	n.a.	n.a.	2500	n.a.	n.a.	n.a.	n.a.
CN109888303	2019	Planar	Stat.	n.a.	n.a.	n.a.	n.a.	0.01–0.03	0.01–0.03	0.433–0.79
CN110981527	2019	Planar	Stat.	n.a.	n.a.	n.a.	n.a.	0.2–1.6	n.a.	n.a.
JP2019220454	2019	Planar	Stat.	n.a.	n.a.	n.a.	n.a.	0.1–0.5	0.01	n.a.
WO2019/167811	2019	Tubular	Stat.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0.5
WO2020/208861	2019	Planar, Tubular	Stat.	n.a.	n.a.	n.a.	0.01	n.a.	n.a.	0.075–0.5225
CN109808042	2019	Tubular	Mob.	1–13	7–10	21.991–408.407	0.200–0.300	0.307–0.500	0.200–0.300	0.319–0.762
US20190123362	2019	Tubular	Stat.	2	25	157.080	0.01–0.05	0.1–0.5	0.01–0.05	0.38
CN110534781	2019	Tubular	Stat.	n.a.	n.a.	2100	0.02	0.2	0.02	0.093
WO2020/191829	2019	Tubular	Stat.	n.a.	n.a.	n.a.	0.005–0.01	0.3–0.7	0.02–0.04	0.52
JP2019212642	2019	Tubular	Stat.	11	95	3282.964	0.005–0.01	0.3	0.01	0.092
JP2019212643	2019	Tubular	Stat.	11	95	3282.964	0.005–0.01	0.3	0.01	0.092
CN110600779	2019	Planar	Stat.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0.86–0.96
CN109638325	2019	Tubular	Stat.	12	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
KR10–2015123	2019	Planar	Stat.	n.a.	n.a.	50	n.a.	n.a.	n.a.	0.35–0.375
WO2021/005810	2019	Planar	Stat.	n.a.	n.a.	n.a.	0.01	n.a.	n.a.	0.075
CN109817997	2019	Tubular	Stat.	15	n.a.	n.a.	n.a.	n.a.	n.a.	0.27–0.84
CN111370713	2020	Planar	Mob.	n.a.	n.a.	n.a.	n.a.	0.5–0.8	0.4–0.6	n.a.
CN110890571	2020	Tubular	Mob.	n.a.	n.a.	n.a.	0.1–0.2	n.a.	n.a.	n.a.
CN111029596	2020	Planar	Mob.	n.a.	n.a.	n.a.	0.02–0.2	n.a.	0.005–0.05	0.102–0.123
CN111403763	2020	Tubular	Mob.	3–12	50–500	471.239–18849.556	0.05	0.25	0.050	n.a.
CN111403764	2020	Tubular	Mob.	3–12	10	94.248–376.991	0.05	0.25	0.050	n.a.
CN112072137	2020	Planar, Tubular	Mob.	2–7	n.a.	62.832–219.911	0.05	0.4	0.05	0.371–0.528
WO2022/041466	2020	Tubular	Mob.	7	10	62.832–219.911	0.011	0.4	0.011	0.371–0.528
JP2020071987	2020	Tubular	Mob.	1	10	31.416	0.001–0.01	0.5	0.001–0.01	n.a.
WO2021/025050	2020	Planar	Stat.	n.a.	n.a.	n.a.	0.09–0.2	n.a.	n.a.	n.a.
CN110828873	2020	Tubular	Stat.	12	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
KR10–2022–0035730	2020	Planar	Stat.	n.a.	n.a.	2000–90000	n.a.	0.1–2	n.a.	n.a.
KR10–2021–0135154	2020	Planar, Tubular	Stat.	20.000	n.a.	225–400	0.15	n.a.	n.a.	n.a.
EP3916136	2020	Planar	Stat.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0.07
CN113140745	2021	Tubular	Stat.	n.a.	300–1000	n.a.	n.a.	n.a.	n.a.	n.a.
CN113381049	2021	Tubular	Stat.	20	n.a.	13500–45000	n.a.	n.a.	n.a.	0.12–0.4
CN113381050	2021	Tubular	Stat.	n.a.	n.a.	2644.444	n.a.	0.4	n.a.	0.3
CN112909311	2021	Tubular	Stat.	9.5–10	18–21	537.212–659.734	0.01–0.09	0.9–1	0.01–0.09	0.465
IN202121045468	2021	Tubular	Mob.	20	20	1256.637	0.015–0.02	0.1–0.2	0.015–0.020	0.36–0.61
CN113285084	2021	Planar	Stat.	n.a.	n.a.	n.a.	0.01	0.35	0.04	0.43

(*Continued*)

Table A1. (Continued).

Patent	Year	Layout	Application field	Diameter [mm]	Length [mm]	Surface [mm^2]	Electrolyte thickness [mm]	Anode thickness [mm]	Cathode thickness [mm]	Power [W/cm^2]
KR10–2021–0066214	2021	Planar	Stat.	n.a.	n.a.	n.a.	0.001–0.005	0.001–0.3	0.001–0.005	n.a.
CN113800571	2021	Planar	Stat.	n.a.	n.a.	n.a.	0.01	0.4	0.01	0.338–1.079
CN114335640	2021	Planar	Stat.	n.a.	n.a.	10000	0.01–0.02	0.3–1.5	0.01–0.02	0.35–0.43
CN114230330	2021	Planar	Stat.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	1.015–1.278
CN217303697	2022	Planar	Stat.	n.a.	n.a.	600.000	n.a.	n.a.	n.a.	n.a.
TWI783307	2022	Tubular	Stat.	0.8	60	150.796	0.005–0.01	0.005–0.03	0.02–0.06	n.a.
CN115084614	2022	Planar	Stat.	n.a.	n.a.	8060–7200	0.007–0.009	0.004–0.006	0.01	0.9
KR10–2022–0006372	2022	Planar	Stat.	n.a.	n.a.	n.a.	0.01	0.01	0.001	n.a.