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Review article

Additive manufacturing of solid oxide fuel cells. A comprehensive review of patent literature

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HIGHLIGHTS

- Patent analysis of Solid Oxide Fuel Cells made by additive manufacturing.
- Analysis of goals, manufacturing strategies and clusters of intersections.
- Lattice structures maximize gas diffusion and mechanical resistance of anode.
- Self-supporting thin walls and cavities improve fuel injection.
- Patenting is mainly used to protect ideas rather than industrial implementations.

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ABSTRACT

The solid oxide fuel cell (SOFC) technology has significant potential to become a large-scale, environmentally friendly solution for electricity generation, but realizing this goal hinges on advancements in performance and manufacturing. To succeed in this intent, additive manufacturing (AM) is considered a promising option. This study provides a comprehensive review of patent literature about the AM of SOFC, identifying and comparing goals, implemented AM strategies and clusters of intersections among them. Compared to previous reviews, limited to the scientific literature, some new solutions characterized by unknown goals and AM strategies have been identified. Most common clusters are: lattice structure optimization in SOFC electrodes to optimize porosity solving a compromise between gas diffusion, ionic conductivity and mechanical resistance; the printing of thin walls and self-supporting structures to build complex fuel channels; graded or 3D interface between electrolyte and electrode to improve the ionic flow. Patent bibliometrics and discussion of the results show how industrial and scientific research are patenting ideas rather than solutions ready to be implemented about the AM of the SOFC. The results of this review may be useful to industries interested in patent intelligence on the topic, as well as to researchers to understand which lines of research arouse greater economic interest.

1. Introduction

To answer the demand for an increasing clean electricity production, fuel cells are considered a promising solution for future series production [1]. The fuel cell consists of three functional layers: two electrodes, i.e., anode and cathode, and the electrolyte arranged between. The fuel, typically but not necessarily hydrogen, and the oxidant, i.e., air or oxygen, respectively spread within the porosity of the anode and the cathode. Oxygen molecules are reduced to oxygen ions at the cathode, and the ions travel through the solid electrolyte to the anode. In this latter, the oxygen ions react with the fuel, producing water, carbon dioxide (if hydrocarbons are used) and releasing electrons. The electrons flow through an external circuit, generating electricity.

Among the fuel cells, the candidates for series production are the Proton Exchange Membrane Fuel Cell (PEMFC) for the mid future term, i.e., 2035, and the Solid Oxide Fuel Cell (SOFC) for the long future term, i.e., 2050 [2]. The SOFC has the highest operating efficiency and temperature (about 600–1000 °C), for maximizing the ionic conductivity, among the fuel cell due to the constituting ceramic materials. The anode is typically made by Yttria Stability Zirconia (YSZ) and Nickel Oxide (NiO), the electrolyte by YSZ, the cathode by YSZ and Lanthanum Strontium Manganese (LSM). This choice of materials is based on their complementary properties that optimize the electrochemical processes within SOFCs. This material synergy helps achieve high efficiency,

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durability, and stability under operational conditions. In addition, the contact points between electrodes and electrolytes in SOFCs are critical for efficient operation. The choice of these materials not only affects individual layer properties but also their interactions at interfaces, influencing overall cell performance. However, to get to series production of SOFCs, some construction challenges need to be overcome. It is necessary to reduce time and costs and at the same time improve the quality of the production process in order to make SOFCs competitive, efficient in operation and resistant to mechanical, thermal and chemical wear. These requirements are most severe in transportation, where higher static and dynamic stress resistance, higher operating temperatures and reduced start-up and shutdown times are required [3]. However, all this is in contrast with the SOFC traditional production processes [4].

Additive manufacturing (AM) can accelerate the SOFC series production by increasing geometric complexity, design customization, precise control over material distribution, conductivity and durability, which are essential for operational performance and fuel efficiency. In addition, manufacturing time and costs can also be reduced and multi-materials structure can be produced. All these aspects emerge from the reviews of scientific papers available in the literature. Tai et al. [5] conducted a comprehensive comparison of the required properties and established benefits of AM of some SOFC components. Their review offers a broad overview of various requirements, including structural, operational, and production aspects, while also considering different AM strategies. However, the review's primary limitation lies in the small number of analysed sources (only nine) and not very updated. Du and Fatoba [6] analysed a relatively small sample of sources, using a less formalized approach and considering a small number of SOFC requirements. Rasaki et al. [7] specifically analyse how AM can improve fluid flow management in the SOFC. The first part of the review explores options for redesigning the fuel and oxidizer injection channel in the endplate. The second part is dedicated to the gas diffusion inside the electrodes, analysing the porosity achieved by AM. In the review by Minary-Jolandan [8] the manufacturing requirements and partly the SOFC structure are analysed. The main aspects analysed are: the reduction of manufacturing time and cost, the possible replacement or simplification of traditional processes, multi-material multilayer printing, porosity control and co-sintering. There is no specific research linking the improvements brought by AM and the implications on the functioning of SOFCs and the focus remains at a purely structural level. Affandi and Osman [9], unlike the other reviews, mainly focus on the future developments of SOFC AM, rather than on the experimental results obtained. Such developments concern both gas management, ionic conductivity, and structural strength of the cell. However, the analysis is limited to bibliometric surveys, comparing the publication trends of the various future improvements, which are not explored much beyond the level of their qualitative definition. Finally, the reviews of Cramer et al. [10] and Deepi et al. [4] summarizes the results of the other reviews on SOFC AM, relating them to other AM applications of industrial ceramic materials and traditional SOFC manufacturing methods, respectively. Their aim is to broaden the discussion and find new synergies.

Therefore, due to the limitations of the previous reviews, the objective of this study is to answer the following research questions (RQs):

RQ 1: Can patent analysis provides new solutions for using AM to build the SOFCs compared to previous review of scientific literature?
RQ 2: Which AM strategies are considered most economically promising by industrial and academic research and for which goals, AM is used to build the SOFCs?
RQ 3: Are there common paths of innovation, i.e., intersections between AM strategies and goals in patent literature?
RQ 4: What considerations on the sustainability of AM for SOFCs compared to traditional manufacturing methods can be drawn from the patent literature?

To answer the research questions, this review analyses all patents that propose and justify a way of using AM to realize SOFCs, found within the world patents database.

Compared to the existing scientific literature reviews on SOFC AM, cited before, this study introduces some novelties based on some new ideas (theoretically and experimentally):

- Patent analysis allows to collect technical solutions that have already been tested or are in the industrial prototyping phase. Because of the purpose of patents, the claimed solutions are associated with an economic value, and are often published much earlier than scientific papers, making them a more up-to-date source of information.
- The analysis is enlarged to an entire population instead of a sample related to a specific sub-topic of SOFC AM, collecting sources from the entire world patent database in a systematic way.
- The analysis is general purpose since all the goals about the manufacturing and the improving of the SOFC, faced with AM and emerging from the patents, are considered. This way, it is possible to carry out a comprehensive comparison of all trends in the SOFC AM topic.
- Finally, the classification of the solutions is carried out in a systematic way, introducing a specific ontology including the goals and the AM strategy implemented by each solution.

2. Methodology

2.1. Patent collection

The patent collection followed the PRISMA approach [11], where documents retrieved from databases using specific queries were filtered by analysing their content and applying defined eligibility criteria.

To gather all patents utilizing AM for producing the SOFC, two queries, one about the SOFC and the other about the AM, have been created and combined using the AND logical operator. Regarding the query about the SOFC, since this topic is highly circumscribed in the patent literature, it was possible to combine keywords with standardized patent classes related to SOFCs in order to increase the recall of the search [12]. The second query is related to AM and combines, in addition to the most generic names of the technology (i.e., "additive manufacturing" and "3D printing", with the related transliterations), also the current and emerging AM technologies that are used to produce SOFCs, highlighted by the previous reviews on the topic [5–9]. The search queries were intentionally constructed in a very generic way, including many classes in the first one and also generic terms related to additive manufacturing in the second one, for two reasons: to overcome the generic lexicon that patents often use to increase legal protection [13] and not to exclude emerging AM technologies that have not been considered in previous reviews. However, such generic keywords require a vast selection work of the many sources found based on the content to exclude irrelevant contributions. Both queries search within the patent title, abstract and claims and were launched in the entire global patent database using Orbit by Questel. This database was chosen primarily for its ease of use and for its continuous updates in the patent collection. To address any patent exclusions, the same queries, after appropriate syntax translations, were also launched in the Espacenet (by European Patent Office) and Patentscope (by World Intellectual Patent Office) databases and returned the same results.

Table 1 reports the used queries.

To select the patents, some eligibility criteria were established, in line with the PRISMA approach. The detailed analysis of the entire patent text, following these criteria, drastically reduced the number of considered patents. The eligibility criteria are:

- The considered SOFC is entirely or partially realized through AM. This criterium caused a drastic reduction in the number of initial patents, as many of them referred to the SOFC but not to its

Table 1
Used queries (referred to Orbit syntax).

Query name	Query text
SOFC query	(H01M-004/86)/CPC/IPC OR (H01M-004/9025)/CPC/IPC OR (H01M-004/905)/CPC/IPC OR (H01M-008/00)/CPC/IPC OR (Y02E-060/50)/CPC/IPC OR (C25B-011+)/CPC/IPC OR (SOFC OR ((SOLID 1D OXIDE) 1D (FUEL+ 1D CELL+)))/TI/AB/CLMS
AM query	((ADDITIV+ 1D MANUF+) OR ("3D" 1D PRINT+) OR (INKJET 1D PRINT+) OR (LITHOGRAPHY 1D PRINT+) OR ((DIGITAL 1D LIGHT) 1D PROCESSING) OR ROBOCASTING OR ((DIRECT 1D ENERGY) 1D DEPOSITION) OR ((SELECTIVE 1D LASER) 1D MELT+))/TI/AB/CLMS

realization, or claimed the use of the AM to realize another type of fuel cell (e.g., the proton exchange membrane) or another electrochemical device.
- The SOFC constituting parts, realized through AM, are: anode, electrolyte, cathode and the end-plate (EP). This criterium excluded those about the aggregation of multiple SOFCs in a stack or the production of the manifold or the heating or protective elements. Their exclusion depends on the low strategic importance of these components in the operation of the SOFC as well as on their simplicity of construction, compared to other components that must meet the more stringent requirements of: hydrogen diffusion, ionic conductivity, mechanical, thermal and chemical resistance.
- The used AM method and technology are specified and their advantages are presented in comparison with traditional SOFC manufacturing methods and technologies (e.g., extrusion or slip casting).
- The focus is on AM process, not on preparatory or subsequent activities. For this reason, patents about ceramic powders manufacturing used in SOFC AM have also not been considered.

2.2. Patent analysis

The collected patents have been analysed at bibliometric level and by extracting the solutions resulting from the use of AM. From each solution the following information have been extracted:

- **AM strategy** exploited to produce the SOFC (e.g., lattice structures, multi-materials printing).
- **SOFC component** realized through AM (e.g., anode, electrolyte), with a detail on the constituting parts (if specified) (e.g., surface, microstructure). The classification of the solutions based on the considered SOFC component has been carried out according to what is explicitly stated in the patents.
- **Goals** achieved by realizing the SOFC component through AM (e.g., increasing mechanical resistance, reducing fabricating time and cost). To rigorously classify the objectives that patented solutions claim to achieve, the function-behaviour-structure (FBS) theory [14] was used, already widely used in the analysis of patents and scientific articles (e.g., Ref. [15]). According to this ontology, the goal can be defined on different levels including the function, i.e., the objective for which a solution is designed, and the behaviour, i.e., the physical effect that is exploited to realize the function. For each solution, both the function and the behaviour have been extracted from the respective patent. The goals considered in this study are all the independent combinations of functions and behaviours. Therefore, if to fulfil the same function, e.g., "improving the ion flow in the SOFC" it is possible to implement the behaviour "Increasing ionic transport section" and the behaviour "Reducing ionic transport length", two goals deriving from the respective combinations have been considered. Both functions and behaviours were manually extracted from the patents, interpreting the content in light of the rigorous definitions of these concepts provided by Gero himself [14].
- **Application** by investigating on which type of SOFC (e.g., planar, tubular, anode supported) the solution can be implemented and with which type of AM technology it can be realized.

Consistency in data extraction across different patents has been ensured using a thesaurus of specific terms related to SOFC components and operation that has been built with the patents themselves and with previous reviews on the subject [5–9].

Subsequently, to classify the solutions, some clusters have been manually created based on the following similarities between the solutions of each cluster:

- Addressing the same goal or the same couples or triplets of goals at the same time;
- Exploiting a specific AM strategy.

This study intentionally does not critically evaluate the merits and limitations of AM strategies for SOFC applications, for two reasons. On the one hand, this has already been widely discussed in previous reviews of the scientific literature. On the other hand, the patent examination process differs from a scientific review, as it involves a more rigorous evaluation of novelty, originality, and industrial applicability of the claimed technology rather than how the experimental tests are conducted. In fact, no peer review is conducted, although the examiner has the option to reach out to an expert at their discretion (Lee, 2021). Therefore, this review aims primarily to classify patents to show in which directions industrial, and secondarily academic, research is moving through patenting.

Fig. 1 depicts the flow diagram of the procedure followed for patent collection an analysis.

3. Results

3.1. Bibliometrics

The first data to analyse regarding the bibliometric analysis is the low number of patents that specify how AM is used to realize the SOFC and that have been considered in this study (i.e., 61). This number is different compared to that typically achievable when analysing a successful emerging technology. For instance, in the same field of hydrogen-based energy systems, other promising emerging technologies count some or several hundred patents [16]. For this reason, this number may indicate that the advancement of AM technologies has not yet reached a level where it can overcome practical limitations in cost and processing quality, thereby hindering significant interest from industrial research [5]. On the other hand, the total number of generic patents on the topic (i.e., 484) suggests that there is interest, at least in exploring potential applications of AM for the production of SOFCs. At the same time, it is also conceivable that there is a current tendency to protect ideas rather than reveal technical details.

Fig. 2 reports the results of the bibliometric analysis in terms of patent trend, considering the priority year, the distribution of the legal status and patent owner type (industry vs academia) and nationality, number of patents for each owner.

The results of the bibliometric analysis (see Fig. 2) revealed that the considered patents were all filed from 2012 onwards, which makes them quite recent. The filing trend is markedly increasing starting from 2018, except for 2023–2024 that do not include all potential patents since they are not disclosed for the first 18 months. The analysis of the legal status revealed that well over half of the considered patents are still pending. This is in line with the young age of the considered patents as demonstrated by the patent trend analysis. Just over half of the patent owners are industries. This is an unusual finding compared to reviews on consolidated research topics, where almost all patents are from industries. While a strong presence of universities and research centres among patent applicants has long been associated with emerging

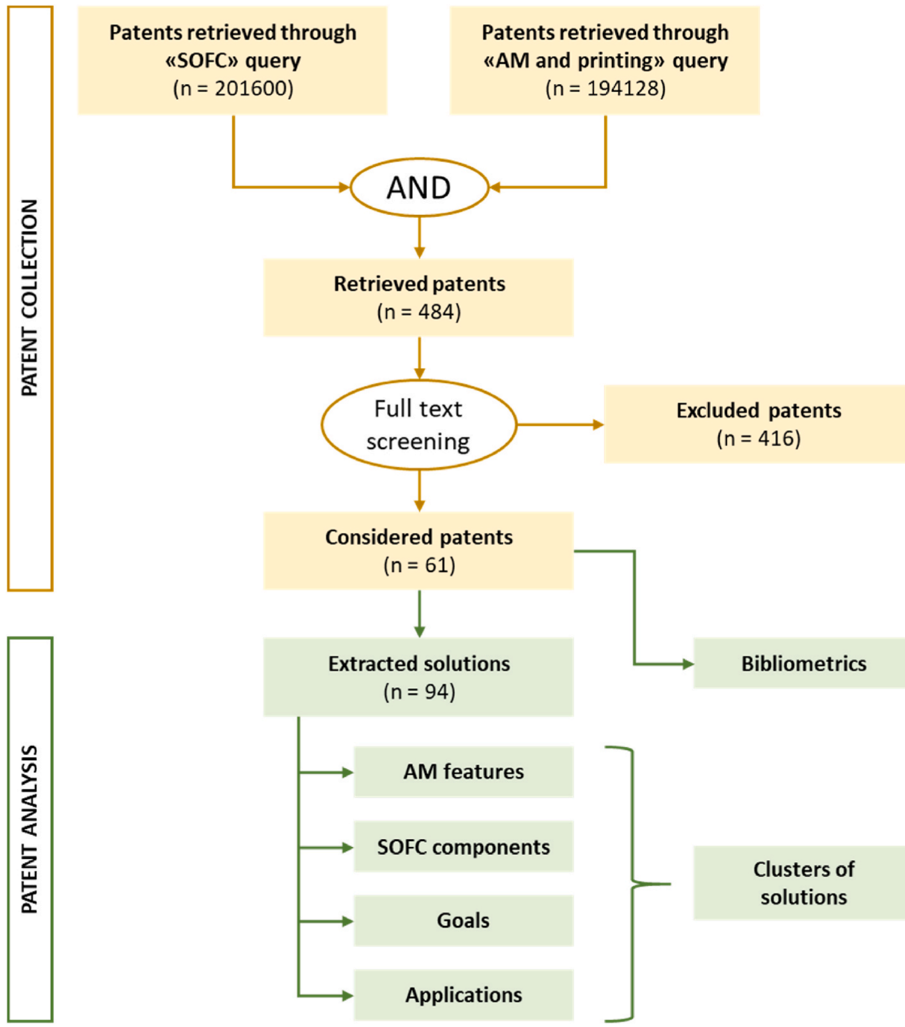

Fig. 1. Flow diagram of the systematic patent collection following PRISMA approach [11] and patent analysis.

technologies [17]. The same data can however be justified when analysing very young and cutting-edge research topics, in which the industry has not yet invested massively, patenting and purchasing patents filed by academia that still holds them, which in many cases are still pending patent [18]. About half of the patent owners are Chinese, only less than a quarter are from United States, followed by the Japanese and Europeans. This is in line with the general interest that China is showing lately in SOFCs and fuel cells in general [19]. From the analysis of the considered patents, it emerged that Chinese patents are responsible for the jump in filings from 2018 onwards. This trend could therefore be justified more by Chinese economic and political strategies towards the SOFC than by a disruptive advancement of AM technology since the same patenting trend does not occur in other countries. Furthermore, this data is also justified by the strong recent patenting of Chinese universities in cutting-edge research topics [20]. China is, after all, commonly believed to be the country that will lead the future SOFC development worldwide [21]. The fact that China is already investing more in the use of AM to produce SOFCs is perfectly aligned with the trend. The analysis of patent owners has not highlighted a reference player investing heavily on the patenting, with a heterogeneous distribution of owners, only 7 owners hold more than one patent, including universities and research centres. This fact is also another proof of the novelty of this research theme [22].

3.2. *AM strategies*

The following AM strategies have been collected from the considered patents.

Page 7: Lattice structure, i.e., intricate, repeating geometric patterns composed of interconnected struts or nodes, within a three-dimensional framework, with the microstructure of a SOFC component filled with AM. Q: I think there are some discrete cell-structure and/or factual structure which need some new and advanced formula. Also, I think that field operators should be taken into account.

- **Lattice structure**, i.e., intricate, repeating geometric patterns composed of interconnected struts or nodes, within a three-dimensional framework, with the microstructure of a SOFC component filled with AM. Some of them are: octet-truss, triply periodic minimal surface, diamond-based, body-centre, face-centre. By using lattice structures, it is possible to better control the deposition of the material inside the SOFC components, compared to the use of traditional techniques. In this way, it is possible to improve the flow of reactants and products to enhance the overall electrochemical performance, better control the size and distribution of the porosity [23] and increase the electrochemically active surface area for ionic conductivity [24]. The main limitations mainly concern the current AM technologies that may not allow achieving uniformity and control over the lattice dimensions during fabrication, compromising part of the advantages [25].

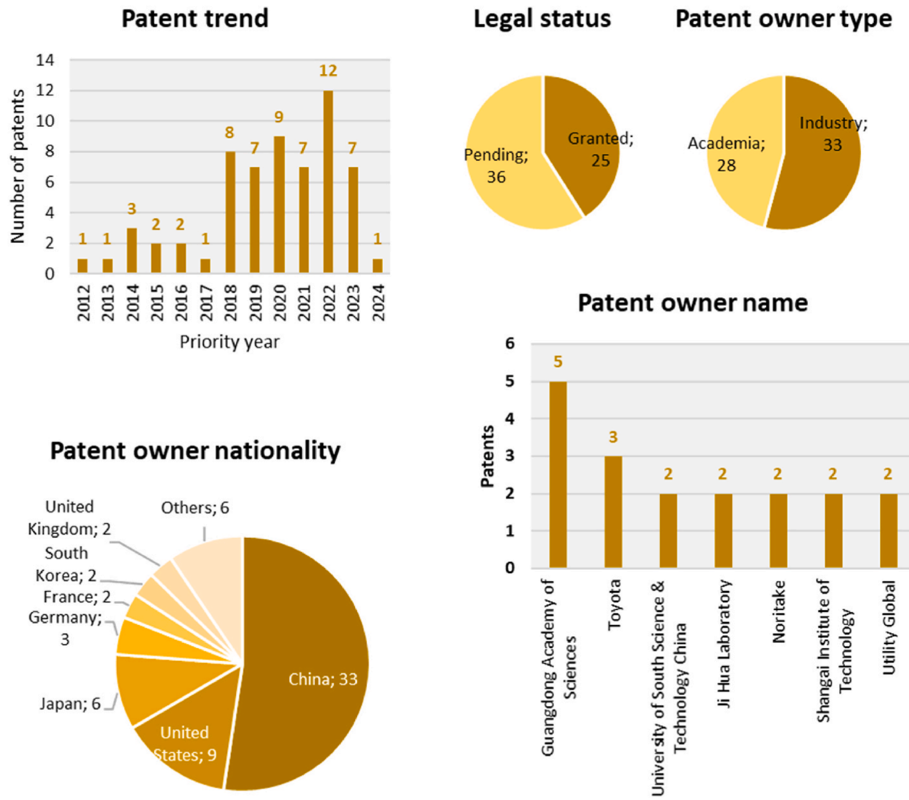

Fig. 2. Bibliometrics of the considered patents.

- **Graded lattice,** i.e., a type of lattice structure in which the geometric or material properties gradually change across the structure. The gradient can be referred to the cell size or the thickness of the struts in the cells. The advantages and disadvantages are mainly the same as the lattice structure, i.e., theoretically controlling the material deposition inside the SOFC and actually achieving it with current AM technologies [24].
- **Thin walls** refer to sections of an AM part that are designed with very small thicknesses. These thin walls can reduce the weight and maintain high flatness tolerances and constant thicknesses, while having a much greater height than the thickness, without warping or collapsing. The main advantages of this AM strategy concern the possibility of increasing the space available inside the cell for the channels in which fuel and comburent flow and improving thermal management. The technological limits seem less pressing in this case compared to lattice structures, considering the current AM technologies [26].
- **Precise material deposition** refers to the ability of AM to precisely control the placement and the mass of deposited material, creating high-quality parts with complex geometries and fine details. When, as in this case, AM is mainly used to deposit layers full of compact material, the precision and control over the thicknesses is really high, compared to traditional technologies for building SOFCs. While a limitation to overcome is still a certain mechanical fragility of such structures [8].
- **Self-supporting hollow cavity** is an empty channel within a part that do not require additional support structures during printing. AM is able to realize a hollow cavity by taking advantage of the layer-by-layer nature of the process. This AM strategy has advantages mainly on environmental and economic sustainability, reducing material waste (CN110336053).
- **Holes matrix** in which the holes have parallel axes and the height is significantly greater than the diameter. AM can realize them thanks to the possibility of producing thin, non-yielding walls. The benefits of this strategy are flow and thermal management within the SOFC, while the limits are mechanical resistance and sintering (CN112952170).
- **Sintering** of the deposited powder can be obtained through some AM technologies heating the powder below the material's melting point to bond the particles without liquefying them entirely. The main advantage is to simplify the production process, reducing times and costs, even if a complete replacement of traditional sintering with AM is still a long way off [6].
- **3D multi-materials intersection** refers to regions within a printed part where different materials meet or overlap with a clear, distinct boundary. The advantages mainly concern the possibility of better tailoring the properties, reducing production costs and improving the adhesion between layers of different materials. However, this AM strategy makes sintering more difficult, requiring greater control of the process parameters [8].
- **Graded multi-materials intersection** is characterized by a transition between different materials that is gradual rather than abrupt. This is achieved by gradually mixing the materials at the interface, creating a continuous gradient where one material slowly transitions into the other. Graded structures theoretically allow for optimization of material properties in different layers, improving ionic conductivity and reducing ohmic losses. By using materials with graded thermal expansion coefficients, the risk of mechanical failure decreases. While the mail limitations are related to current AM technologies and scalability issues, so the stability of the interface is still difficult to achieve and multi-grated-material sintering is still challenging [27].
- **Multi-materials sintering** is a technique where multiple different materials are processed simultaneously to create a single, integrated part, where particles of a material are fused together by applying heat below the melting point. The advantages are the reduction of manufacturing steps and costs and the possibility of welding complex

interfaces. However, this process leads to greater mechanical fragility interfacial stability and dimensional challenges [28].

- **Coating** with AM is used to apply a thin layer of material onto a surface of another. The main advantage is the ability to efficiently deposit the coating on 3D surfaces, as in the hydrogen inlet channel, even in the presence of undercuts, which is not possible with traditional deposition techniques. Another advantage is the possibility of controlling the coating thickness. The main limitation is the adhesion and depends on the level achieved by current AM technologies [29].
- **Filling cavities** of a substrate, made by a certain material, by depositing a different material within. The advantage is the optimization of the material, while the disadvantage is being able to control its deposition and adhesion (WO2016/008327).
- **Doped powder** to be used in AM is able to improve the physical characteristics and weldability with other particles and substrates. The advantage is the improved sintering but the disadvantage is a more complex production process (US20200014052).

Fig. 3 depicts the AM strategies exploited by the considered patents.

3.3. Components

Analysing which component, the patents claim to realize through AM, it emerged that no patent claims the realization of a complete cell with AM technology, but always one component or at most two, as previously identified also in the scientific literature by the review of Minary-Jolandan [8].

The components made by the patents with AM are the following.

- **Anode CL** is where the fuel, typically hydrogen or a hydrocarbon like methane, reacts with oxygen ions (O^{2-}) that have been carried through the solid oxide electrolyte from the cathode.
- **Anode gas diffusion layer (GDL) structure** is a porous structure distributing the fuel to the anode CL, ensuring that the gases reach all parts of the catalyst, optimizing the electrochemical reaction. In addition, the anode GDL material allows the electrons generated at the anode CL during the reaction to flow to the external circuit.
- **Anode GDL surface** refers to the surface where the fuel enters into the anode GDL and is on the opposite side to the anode CL.
- **Cathode CL** is where the oxygen reduction reaction takes place, facilitating the reaction of oxygen molecules with electrons and ions to form oxygen ions (O^{2-}), which are then transported through the electrolyte to the anode.
- **Cathode GDL structure** is the equivalent of the anode GDL structure with the difference that the oxidizer enters it instead of the fuel.
- **Cathode GDL surface** refers to the surface through which the oxidant enters the cathode GDL structure.
- **Electrolyte structure** is a solid, non-porous material that conducts only oxygen ions (O^{2-}), while being impermeable to electrons and gases, ensuring separation between fuel and oxidizer.
- **Electrolyte-anode interface** is responsible for facilitating the electrochemical reaction between the fuel (typically hydrogen or a hydrocarbon) and oxygen ions (O^{2-}) that have migrated through the electrolyte from the cathode side.
- **Electrolyte-cathode interface** is where oxygen molecules from the air are reduced and converted into oxygen ions (O^{2-}), which are then transported through the electrolyte to the anode side.
- **EP structure** provides mechanical support and ensures uniform compression of the cell stack to maintain adequate seal and contact.
- **EP flow channel** supplies fuel to the anode and removes reaction products, such as water vapor or carbon dioxide, if incorporated into the EP on the anode side, or oxidant to the cathode, if in the EP on the cathode side.
- **EP cooling channel** allows the circulation of a cooling fluid, such as air, water, or coolant, to absorb and dissipate heat generated during SOFC operation.
- **Diffusion layer** is a porous layer, typically metallic, positioned between the fuel or oxidizer source and the anode CL or cathode CL, in addition to or instead of the anode GDL and cathode GDL. Unlike the GDLs, there is no ionic or electrical conduction within it.

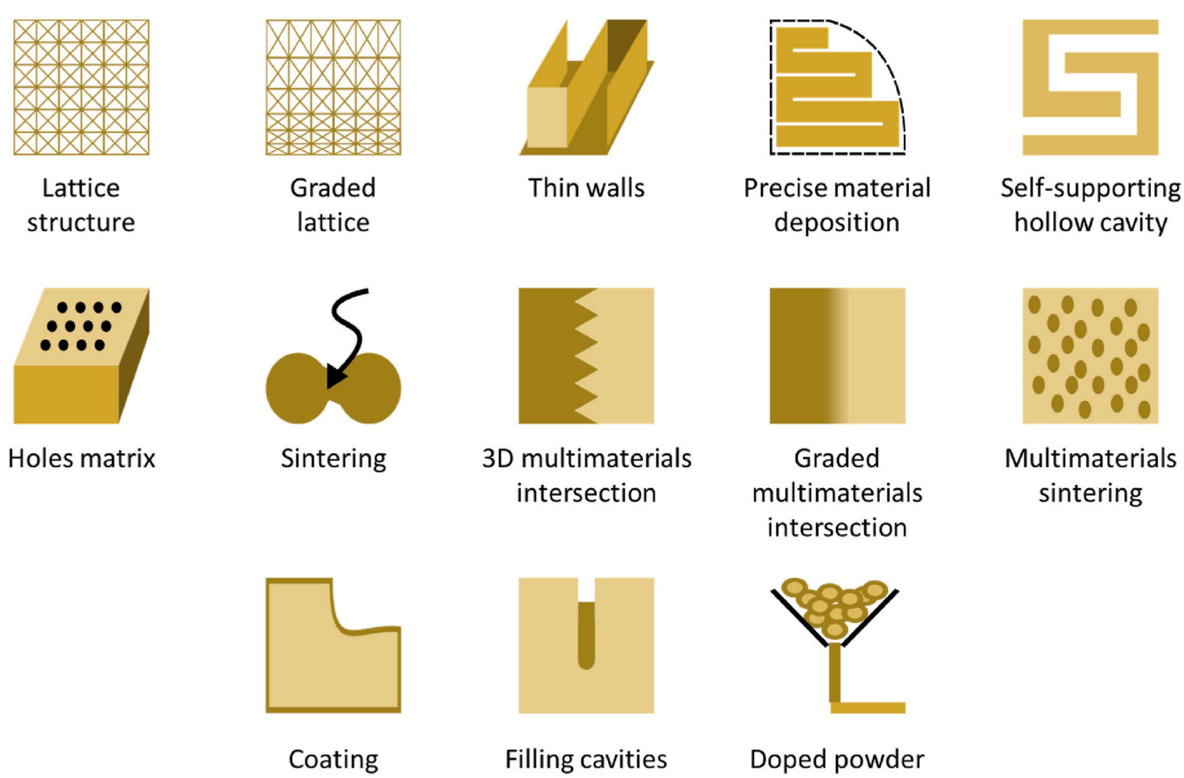

Fig. 3. AM strategies collected from the considered patents.

- **Insulating layer** is a non-conductive layer that separates the high temperature components (GDL or diffusion layer) from the EP, preventing heat loss, gas leakage and corrosion of sensitive parts.

Fig. 4 represents the SOFC components and parts on which AM solutions have been identified in the considered patents, referring for simplicity to the planar layout.

3.4. Goals

The goals for which AM has been used to produce the SOFCs in the considered patents are different and concern almost specific aspects of operation and production to be improved compared to SOFCs produced with traditional techniques.

- **Increasing flow rate** of the fuel or oxygen/air, respectively supplied at the anode and cathode side, by increasing the SOFC's ability to accommodate such gases, e.g., by optimizing the porosity in GDL through lattice structure (CN109545579).
- **Increasing flow contact surface** between the fuel and the anode GDL surface or the oxidizer and the cathode GDL surface, e.g., printing thin walls in flow channel to increase contact surface (CN112234223).
- **Avoiding gas leakage** flowing within the EP flow channel or anode GDL porosity or cathode GDL porosity, e.g., by improving the adhesion at the interface of different materials by printing graded multi-materials intersection (CN117613333).
- **Increasing gas diffusion volume** passing through the GDL anode or GDL cathode and participating in the reaction, or to ensure that the porosity of the GDL can accommodate a greater amount of gas, e.g., by optimizing the porosity in GDL through lattice structure (CN109545579).
- **Reducing gas diffusion resistance** during the entry into the GDLs or during diffusion within them, e.g., by realizing a porosity with increasing density to reduce pressure losses, through graded lattice structure (CN105047947).
- **Increasing ionic transport section** leaving more space for ions to transit in order to increase their flow through the SOFC, e.g., by printing lattice structure within the microstructure to increase internal surface where ions move (CN110845232).
- **Reducing ionic transport length** in order to decrease the resistance to the transit of ions and increase the flow, e.g., by optimizing material deposition within electrolyte to reduce thickness while preserving mechanical strength (CN110845232).
- **Improving ionic conductivity** of the SOFC constituent materials for improving the transit.

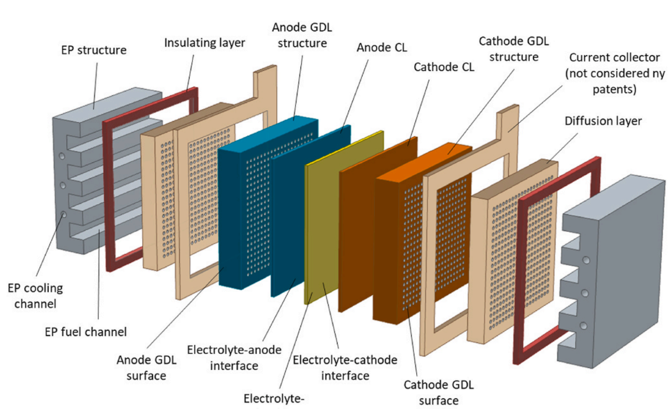

Fig. 4. SOFC components and parts on which AM solutions have been identified in the considered patents.

- **Improving electrical conductivity** of the materials constituting the anode and cathode so as to remove the electrons released during the reaction more rapidly, e.g., by introducing dopants of more conductive material (WO2016/008327).
- **Improving electrical insulation** to avoid short circuits within the SOFC, by printing thin and cohesive coating (CN112751055).
- **Improving mechanical resistance** by avoiding the formation of internal cracks, e.g., printing lattice structure to optimize material disposition within the microstructure to better distribute the tensions (CN109545579), and the detachment of components, through graded intersection between different materials (CN116423822).
- **Improving thermal resistance** reducing the thermal expansion of a material or at the interface between two materials and consequently the mechanical stresses and structural damage that result, e.g., through graded multi-materials intersection.
- **Improving chemical resistance** to hydrogen and oxygen corrosion and contamination resulting from the release of particles between components of different materials, by printing thin and cohesive coating.
- **Reducing fabricating time and cost** by exploiting more efficient dynamics of material use and aggregation and reducing material waste, by realizing self-supporting hollow cavities.

3.5. Applications

The solutions provided by the collected patents are intended to be implemented in SOFCs with different layouts as explicitly stated by the considered patents. Regarding the shape layout, both planar and tubular SOFCs are considered. Regarding the structural layout, the patents claim four types of SOFCs as possible applications. (1) Anode-supported SOFC, where a thick anode (~500 μm) supports the structure with a thin electrolyte (~5–20 μm) and enables intermediate temperatures (600–800 °C) and high-power density. (2) Cathode-supported SOFC, where a thick cathode supports the structure with a thin electrolyte, operating at intermediate or high temperatures (~800–1000 °C) and offering performances similar to anode-supported SOFCs. (3) Electrolyte-supported SOFCs have a thick electrolyte (~100–500 μm) providing support and require high operating temperatures (~900–1000 °C), resulting in lower power density but easier fabrication. (4) Metal-supported SOFCs have a thin ceramic layer on a metal backbone that enables high mechanical robustness and lower temperatures (500–700 °C) with good power density and thermal cycling life.

Nine AM technologies claimed by patents to realize the proposed solutions have been found. (1) Selective laser melting, where a laser fully melts metal powder to create solid parts layer by layer. (2) Laser photocuring, where a laser is used to solidify photosensitive resin layer by layer. (3) Stereolithography that exploits an ultraviolet laser to cure layers of photosensitive resin where ceramic particles are suspended. (4) Digital light processing that uses a digital light projector to cure layers of resin where a slurry of ceramic particles is suspended. (5) Inkjet printing, where droplets of material are deposited. (6) Electron beam melting, where an electron beam is used to fully melt the powder in a vacuum to produce high-density parts. (7) Binder jetting is a process where a liquid binder selectively binds powder particles together to form a part. (8) Fused deposition modelling is a process where a ceramic filament is melted and extruded layer by layer. (9) Fused filament fabrication, where a ceramic filament is melted and extruded layer by layer.

Fig. 5 reports and compares the number of solutions, collected from the considered patents, referring to each AM strategy, component, goal, shape layout, shape structure and AM technology.

From the analysis of Fig. 5, an interest emerges which, although highlighting some preferences, is very heterogeneous between AM strategies, components and goals. This could mean that industry and academia have not yet decided what to concretely focus on for industrial development, patenting sparingly to keep open several possible options.

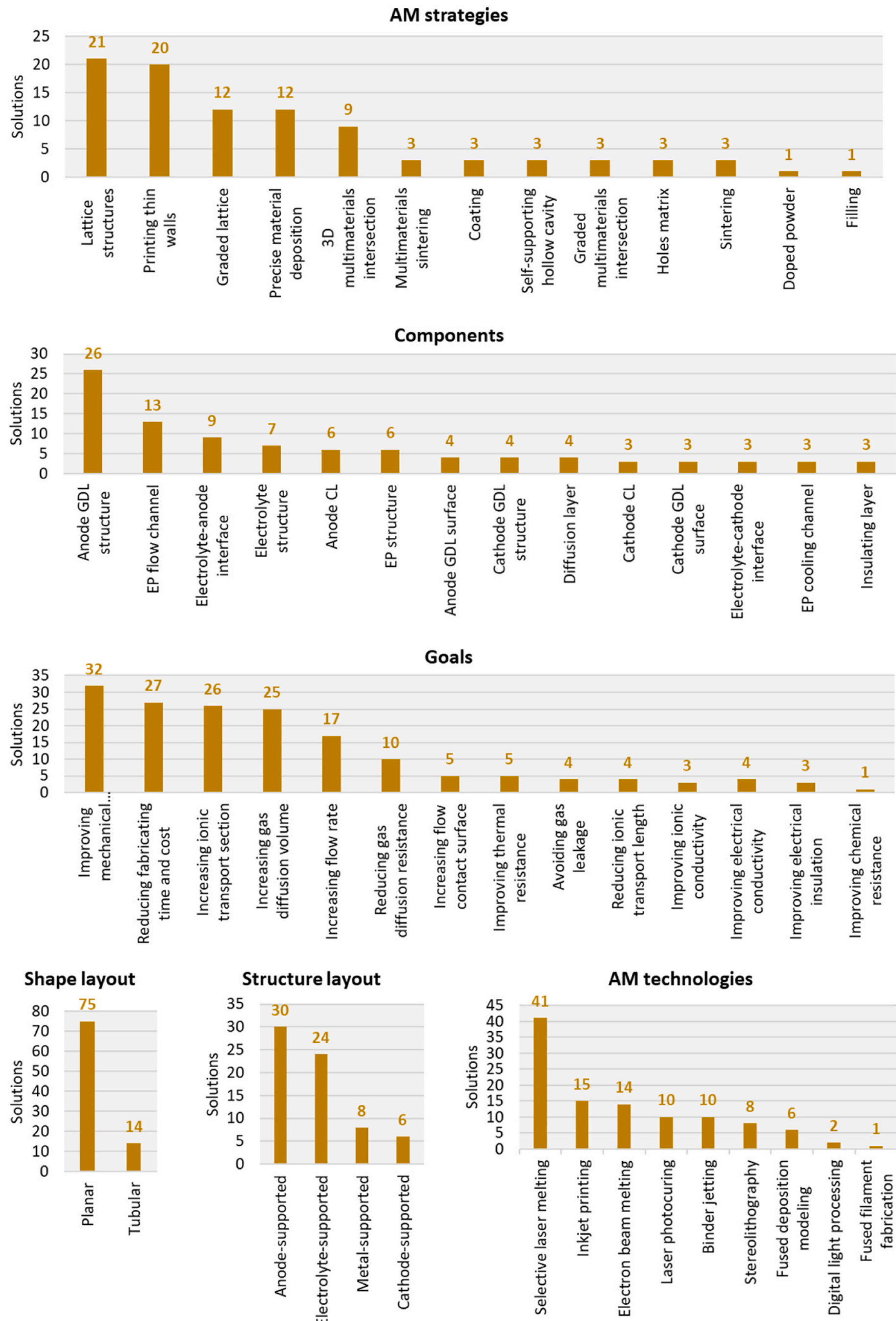

Fig. 5. Number of solutions referred to AM strategies, components, goals, shape layout, structures layouts and AM technologies.

The cause can be immature industrial research and/or an undefined market [30].

The most exploited AM strategies are the lattice structure, the use of thin walls, graded lattice and precise material deposition. These strategies are aligned with the current efforts of the scientific community in the AM of ceramic and micrometre-sized materials [31].

The SOFC components on which the patented solutions focus most are the anode GDL structure and the EP flow channel. The highlighted distribution is substantially aligned with what emerges from the previous review of the scientific literature by Rasaki et al. [7], almost confirming that industrial development is actually focusing on the components on which scientific research has already worked. This alignment between scientific literature and patents can be understood as a confirmation of promising research directions by industry and also demonstrates that academia sees an economic interest in developing its research through patenting. This is due to the large percentage of universities and research centres among the applicants of the considered patents.

The most popular goals are the improvement of mechanical resistance, the reduction of fabricating time and cost and the increasing of the ionic transport section and the gas diffusion volume. The heterogeneous distribution of goals and the rather comparable interest towards the first four is substantially aligned with the general future development goals of SOFCs, mainly realized with traditional non-AM methods, highlighted by the review of [9]. This means then, that at least in terms of intent, with AM it is possible to work to answer the development requests of SOFCs.

The most used shape layout is clearly the planar one, while the most

Table 2
Number of solutions having implementing the same AM strategy on the same components, for achieving the same goals.

AM strategy	Components	Solutions	Goals													
			Increasing flow rate	Increasing flow contact surface	Reducing gas diffusion resistance	Avoiding gas leakage	Increasing gas diffusion volume	Improving ionic conductivity	Increasing ionic transport section	Reducing ionic transport length	Improving electrical conductivity	Improving electrical insulation	Improving mechanical resistance	Improving thermal resistance	Improving chemical resistance	Reducing fabricating time and cost
Lattice structure	Anode GDL structure	14					14		9			1	12			1
	Cathode GDL structure	3					3		3			1	3			
	Electrolyte structure	2							2							
	Diffusion layer	2					2						2			
Graded lattice	Anode GDL structure	9			7		3						1			1
	Diffusion layer	2			2								1			
	Cathode GDL structure	1			1											
Thin walls	EP flow channel	13	11	4									3	1		1
	Anode GDL surface	4	3	1												1
	Cathode GDL surface	3	3													
Precise material deposition	Anode CL	4											1			3
	Cathode CL	3											2			2
	EP structure	3														3
	Electrolyte structure	2											1			1
Self-supporting hollow cavity	EP cooling channel	3												3		
Holes matrix	Anode GDL structure	3					3						3			
Sintering	EP structure	2				1					1		2			2
	Electrolyte structure	1											1			
3D multimaterials intersection	Electrolyte-anode interface	8							8		1					3
	Electrolyte-cathode interface	1							1		1					1
Graded multimaterials intersection	Electrolyte-cathode interface	2							2							2
	Electrolyte-anode interface	1							1					1		1
Multimaterials sintering	Electrolyte structure	2						2								
	Anode CL	1						1								
Coating	Insulating layer	3				3						1			1	

(*continued on next page*)

Table 2 (*continued*)

AM strategy	Components	Solutions	Goals													
			Increasing flow rate	Increasing flow contact surface	Reducing gas diffusion resistance	Avoiding gas leakage	Increasing gas diffusion volume	Improving ionic conductivity	Increasing ionic transport section	Reducing ionic transport length	Improving electrical conductivity	Improving electrical insulation	Improving mechanical resistance	Improving thermal resistance	Improving chemical resistance	Reducing fabricating time and cost
Filling cavities	EP structure	1									1					1
Doped powder	Anode CL	1														1

considered structure layout is the anode-supported one, followed by the electrolyte-supported one. The predominance of these structures for SOFC can be attributed to some factors [32]: Ease of manufacture and assembly in stacks compared to tubular models (this can also be an advantage to reduce costs at the laboratory level where the patents are developed); High specific volumetric power due to their close packing in stacks minimizes ohmic losses on interconnects; Better thermal stability and mechanical strength for long-term duration.

The most exploited AM technology is clearly the selective laser melting. Looking at the numbers of solutions referring to the structure layout and the AM technology, however, it can be noticed that their sum is lower than the total number of solutions found. This is because not all solutions claim the structure layout and the AM technology. The disparity of information collected on strategies, components, AM objectives on one side and applications on the other can be justified by the novelty of the topic emerging from the bibliometric analysis (see Section 3.1). This can mean that a precise direction of application of AM on SOFCs has not yet been undertaken by industrial research.

Table 2 shows and compares the intersections between AM features, components and goals.

As can be seen from Table 2, the intersections between the AM features and the multi-solution components are the lattice structure for the anode GDL structure, the use of thin walls to realize the EP flow channel, and the 3D multilateral intersection to realize the electrolyte-anode interface. In turn, the first intersection is mainly used to increase the gas diffusion volume, improve the mechanical strength, and increase the ion transport section. The second intersection is used to increase the flow rate, and the third intersection is used to increase the ionic transport section.

The heterogeneity of the results in Table 2 shows that there are so many patents filed despite the apparent lack of a clear, initiated direction in industrial research. This can be related to the evidence previously found on the Chinese situation, namely a strong interest in the development of SOFCs in general, and AM in second place. Therefore, this and also the large presence of Chinese universities and research centres among the applicants is evidence that this trend is absolutely new and the goal, for the moment, is still to identify a specific trend to undertake at an industrial level. Patenting aimed more at protecting development ideas rather than solutions to do business immediately therefore testifies to a long-term strategy of China that could therefore, in the future, launch SOFCs at a global level and become the reference player in the sector.

3.6. *Clusters of solutions*

By comparing the solutions based on the commonality of the implemented AM strategy, considered SOFC components and achieved goals, 14 clusters have been isolated. Fig. 6 shows the distribution of solutions in clusters and in relation to AM strategies, components and goals. For each solution, the patent number has been reported.

Table 3 reports for each cluster a brief description, the number of solutions and the respective patents.

The comparison of the different clusters (see Table 3) shows that there are some shared working directions regarding the use of AM to realize SOFCs, such as clusters that have a greater number of solutions, i.e., 1, 4, 7, 9, and other solutions that point in more independent directions.

In the following sections, the identified clusters are presented and discussed in detail.

3.6.1. *Cluster 1*

Cluster 1 solutions, aiming to increase the gas diffusion volume and the ionic transport section and/or the mechanical resistance, solve a contradiction of the GDL and the diffusion layer. In fact, increasing the gas diffusion volume requires increasing the porosity, while increasing the ionic transport section and/or the mechanical resistance requires its

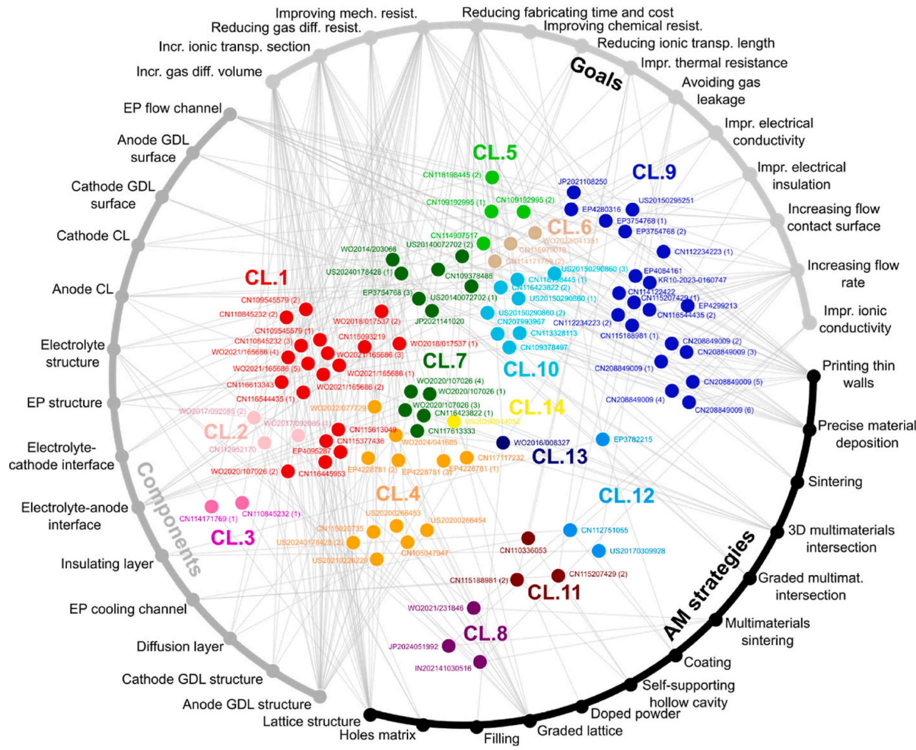

Fig. 6. Graphical representation of the clusters of solutions based on common AM strategies, components and goals.

reduction, ensuring a larger material volume. All the solutions of cluster 1 use optimized lattice structures to solve this contradiction. The analysis of the patents did not reveal a lattice structure that is more used than the others, but some options are possible. Some examples of lattice structures are: triply periodic minimal surface lattice (CN110845232, WO2021/165686), honeycomb (EP4095287), diamond-based lattice shape, face-centre lattice shape, octet-truss lattice shape (WO2021/165686).

According to the patents (e.g., CN115377436), the lattice structures, compared to traditional manufacturing methods, can ensure a porosity in the GDL/diffusion layer with a more constant size and distribution. An optimized porosity size and distribution improves gas diffusion, mechanical strength, and the overall electrochemical performance of the SOF [33]. While traditional methods for fabricating porous structures in SOFC, such as tape casting or impregnation, often lead to inconsistent pore size and distribution due to limited control over the microstructure during sintering [34]. On the ability to create such porosity with the considered AM technologies, scientific literature provides only some sporadic confirmations aimed at the GDL of SOFCs made with the required ceramic powders. Many other contributions refer to metal powders and millimetre scales not suitable for SOFCs [35].

Compared to traditional production, the considered patents claim to create, through AM, lattice structures having porosities with a more complex shape (WO2021/165686). This is particularly useful to increase the space available for ionic transport and ensure better elimination of water vapor in the GDL anode, which could otherwise occlude the porosity [36]. It remains to be seen, however, how reliably such complex structures can be realized in SOFCs without encountering manufacturing problems such as cell occlusion. In fact, in the considered patents there are very few microscopic images and they are not significant enough to demonstrate their actual feasibility. While in the scientific literature some recent examples have been presented, adequately tested, although limited to certain geometries [37]. Consequently, the Technology Readiness Level (TRL) of current solutions utilizing AM technologies to create lattice structures in GDL, to achieve the declared purposes, is generally assessed to be around TRL 4 to TRL 5, since further validation in operational conditions is necessary before commercialization [38]. Future developments of this AM strategy and technologies could also occur thanks to synergies with other sectors that are interested in this, albeit to satisfy other functions, while still working with similar scales. Examples of this are the applications of micro or nano-scale lattice models for the left-hand structure [39] and dipole matrix for the dielectric function [40].

As regards the parameters to quantify the performances of the lattice structure in relation to gas diffusion, none of the patents considered reports the values of the diffusion coefficient, the Scattering Coefficient or the Ballistic Transport Coefficient. While in the scientific literature, some values are found but they refer only to simulations with virtual models and not to laboratory tests obtained with real structures [41].

Fig. 7 reports examples of lattice structure used to increase gas diffusion volume, ionic transport section and mechanical resistance from the considered patents.

3.6.2. Cluster 4

All the solutions in cluster 4 aim to reduce the gas diffusion resistance by realizing a graded lattice structure with AM, to achieve graded porosity in the GDL. In all patents, the obtained porosity has a specific layer-by-layer thickening direction that is perpendicular to the maximum surface of the GDL. Inside the GDL, the porosity size is largest at the gas inlet (e.g., end plate side) and gradually thickens towards the catalyst layer. In this way, the larger pores near the outer surface facilitate rapid gas entry, while the smaller pores near the catalyst layer improve the uniform distribution of the reactants and enhance their interaction with the catalyst. This gradation reduces bottlenecks in the gas flow, minimizes diffusion paths, and allows for more efficient transport of oxygen or fuel to the reaction sites, thereby reducing overall gas diffusion resistance and improving fuel cell performance [42].

In some of the patents considered, the shape of the lattice cell is constant and only its size changes, which gradually decreases (e.g., CN117117232). While in other patents, cells with different shapes and sizes are combined, optimizing the geometry in relation with the dimension (e.g., EP4228781). Both in the considered patents and in the

Table 3
Clusters description, number of solutions and patents.

Cluster	Description	Solutions	Patents
1	Using lattice structure in GDL/diffusion layer to optimize between the increase of gas diffusion volume and the increase of ionic transport section or mechanical resistance	19	CN109545579, CN110845232, CN115093219, CN115613049, CN116445953, CN116544435, CN116613343, EP4095287, WO2020/107026, WO2021/165686, WO2018/017537, CN115377436
2	Using holes matrix in GDL to increase both the diffusion volume and the mechanical resistance	3	CN112952170, WO2017/092085
3	Using lattice structure in electrolyte to increase ionic transport section	2	CN110845232, CN114171769
4	Using graded lattice in GDL/Diffusion layer to reduce gas diffusion resistance	12	CN105047947, CN115020735, CN117117232, EP4228781, US20200266453, US20200266454, US20210226229, US20240178428, WO2022/077729, WO2024/041685
5	Using precise material deposition in Electrolyte/CL to reduce ionic transport length when improving mechanical resistance	4	CN109192995, CN114907517, CN118198445
6	Using sintering in electrolyte/EP structure to improve mechanical resistance	3	CN114171769, CN116979078, WO2022/041351
7	Using graded or 3D multi-materials intersection at the electrolyte interface to increase the ionic transport section	12	CN116423822, CN117613333, EP3754768, JP2021141020, US20140072702, WO2020/107026, CN109378488, US20240178428, WO2014/203066
8	Using multi-materials sintering in electrolyte/CL/GDL to improve ionic conductivity	3	IN202141030516, JP2024051992, WO2021/231846
9	Printing thin walls in flow channel/GDL surface to increase flow rate/flow contact surface	20	CN112234223, CN114122422, CN115188981, CN115207429, CN116544435, CN208849009, EP3754768. EP4084161, EP4280316, EP4299213, JP2021108250, KR10-2023-0160747, US20150295251
10	Use precise material deposition to reduce fabricating time and costs	8	CN109378497, CN113328113, CN116423822, CN118198445, CN207993967, US20150290860
11	Using self-supporting hollow cavity for EP cooling channel to improve thermal resistance	3	CN110336053, CN115188981, CN115207429
12	Using coating for insulating layer to avoid gas leakage and improving chemical resistance	3	CN112751055, EP3782215, US20170309928
13	Using filling in EP structure to improve electrical conductivity	1	WO2016/008327
14	Using doped powder in CL to reduce fabricating time and cost	1	US20200014052

scientific literature, the demonstration of the effectiveness of the graded lattice for this purpose is mainly carried out at the level of theoretical simulation. Therefore, further practical tests are needed to understand with what degree of reliability, such structures can be realized with the current AM technologies claimed in the patents and reference documents [43].

In particular, graded lattice structure in electrode GDL, facilitating better gas flow and diffusion to the active sites of the electrode, is crucial for maximizing the electrochemical reactions at the triple phase boundaries where the electrolyte, electrode, and gas meet [28]. The complexity of graded structures allows to increase surface area to enhances reaction kinetics, while maintaining a compact volume [44]. However, the fabrication of graded lattice structures can be complex, requiring advanced AM techniques and precise control over printing parameters to ensure quality [8]. In addition, during the sintering process, graded structures can have densification or warping and their mechanical integrity and performance can be compromised [45]. These solutions remain in various stages of development with TRLs typically around 4 to 5. Ongoing research should overcome current challenges related to scale and quality of graded lattice in GDL to allow for increasing TRL [38].

Fig. 8 reports examples of graded lattice structures realized through AM in GDL to reduce gas diffusion resistance.

3.6.3. Cluster 7

In the cluster 7 patents, graded or 3D interfaces between the electrolyte and the electrode are designed to facilitate ion transport and reduce interfacial resistance. This is done by increasing the active surface area by creating multiple contact points across the interface and reducing abrupt changes in material properties. In particular, according to US20240178428, both the interfaces are used to increase the effective length of the triple phase boundary, which refers to the region where the electrolyte, electrode, and gas phase simultaneously meet in the SOFC and electrochemical reactions take place. Consequently, increasing this area provides a larger reaction volume and thus higher power density and efficiency [46].

The 3D interfaces in the patents are obtained with thin ridges (CN117613333, JP2021141020), corrugated surfaces (EP3754768), or separate prismatic bodies with a pyramidal or cylindrical shape (WO2020/107026). All these patents do not add new geometries to the literature studies that have already tested different types of interfaces between electrolyte and electrodes in SOFCs [47]. Therefore, the presence of such patents is a confirmation that the industrial research is investing in the same directions as the scientific research in this theme.

Graded interfaces increase the length of the triple phase boundary, improving reaction kinetics and overall cell efficiency by providing more active sites for electrochemical reactions. The use of graded structures can mitigate issues related to thermal expansion mismatches between electrode and electrolyte, thereby enhancing ionic transport and mechanical stability [28]. On the contrary, the manufacturing processes for creating graded or 3D interfaces to guarantee these properties, cannot be obtained by many of the current AM technologies [48]. The behaviour of graded interfaces under operational conditions is not fully understood, particularly regarding degradation mechanisms over time. This lack of knowledge can hinder the development of reliable long-term solutions [49]. Finally, high-temperature during functioning can lead to degradation of the interface with large gradients, creating stress concentrations [48].

While technologies for creating graded or 3D interfaces between electrolytes and electrodes in SOFCs are advancing, they remain in various stages of development with TRLs typically around 4 to 5. Ongoing research will be essential to overcome challenges related to scale and quality, ultimately leading to improved performance and commercial viability of SOFC systems [50].

Fig. 9 reports examples of graded and 3D interfaces between the electrolyte and the electrode.

3.6.4. Cluster 9

Cluster 9 collects solutions in which the flow channels in the EP or GDL surface are printed with a dense network of thin walls that have the purpose of increasing the flow rate or the flow contact surface. Thin walls are used to accommodate more gas in the duct, increasing its overall length, creating intricate labyrinths (KR10-2023-0160747). Another option is to use thin walls to conduct the flow more gradually,

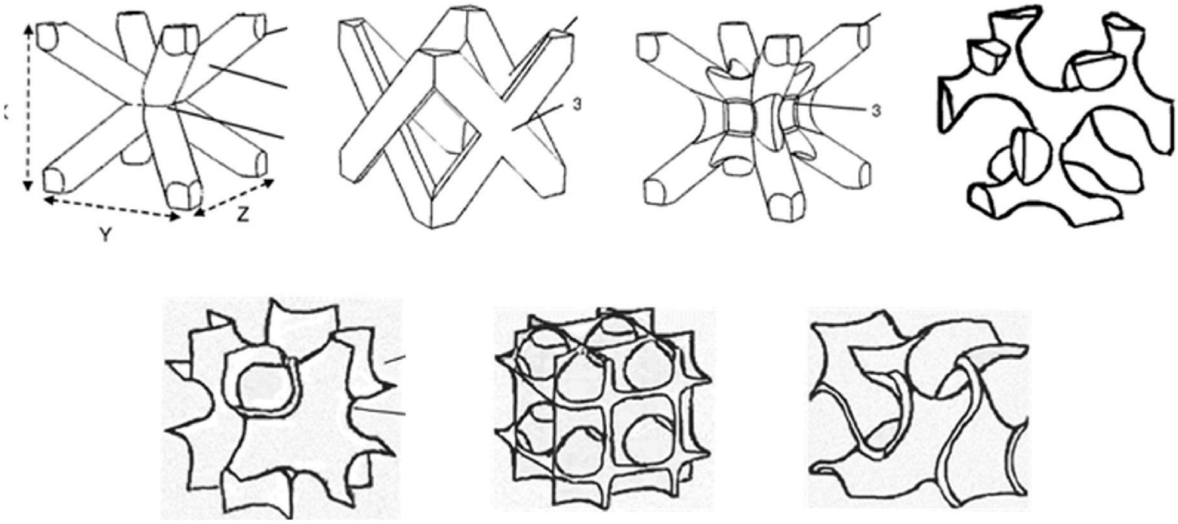

Fig. 7. Examples of lattice structures used to increase gas diffusion volume, ionic transport section and mechanical resistance in GDL (WO2021/165686).

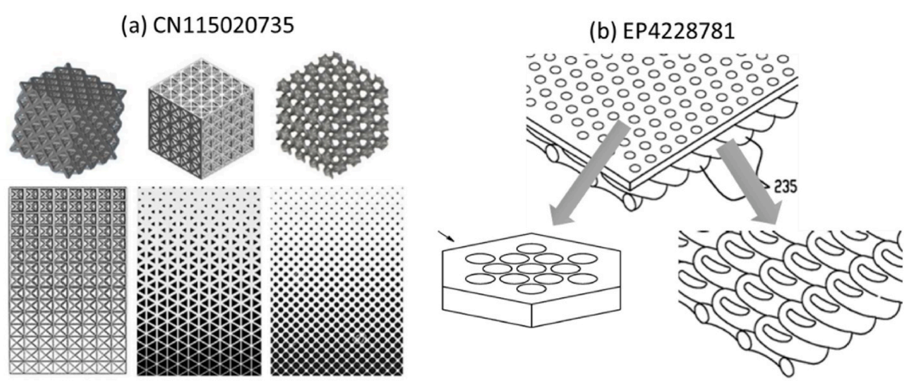

Fig. 8. Examples of examples of graded lattice structures realized through AM in GDL to reduce gas diffusion resistance: (a) with the same lattice cell geometry and decreasing dimension and (b) with different lattice cell geometry and dimension.

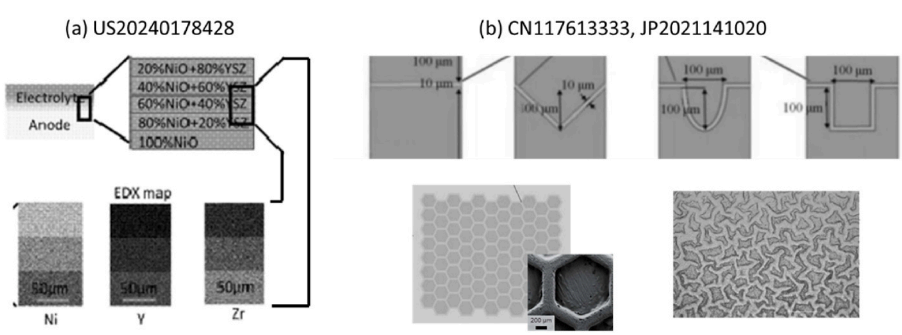

Fig. 9. Examples of interfaces between electrolyte and electrode of the type (a) graded and (b) 3D (side view - above - and top view – below -).

for example through a spiral path, in order to avoid congestion that causes blockage of the flow and therefore accommodate more gas (EP4299213). Thin walls are also used to disrupt flow, reducing surface bonding to the channel (EP4084161) and concentrated turbulence (CN208849009). When thin walls create converging ducts, they increase flow velocity (CN112234223). Finally, thin walls are also used to disperse heat spots that negatively affect the fluid dynamics of the flow (CN112234223). In all these cases it is necessary to obtain thin structures characterized by high precision that current AM technologies are easily able to obtain both with the metal powders that constitute the EP and with the ceramic ones of the electrodes, when the thin walls are made on the surface. This is demonstrated by the experimental results reported in the same patents and confirmed by scientific literature [51].

Improved flow channel designs, introducing thin walls, is beneficial for providing better gas distribution, mitigating gas flow stagnation and improving mass transport properties to allow for higher flow rates and better fuel efficiency [52]. Thin walls can also facilitate better heat transfer within the channel, by maintaining optimal operating temperatures and improving SOFC durability [53]. The customization of the channel, obtained through intricated thin walls allows to enable tailored designs of the channel, for optimizing gas flow trajectories as well as power density and efficiency [48]. However, manufacturing is more

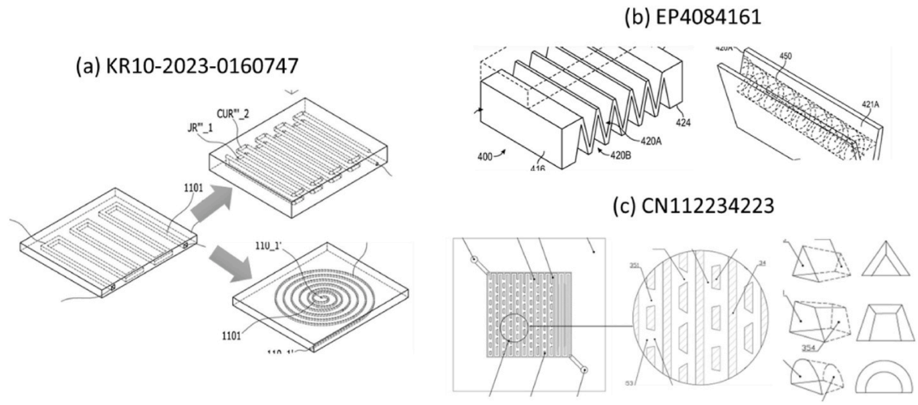

Fig. 10. Examples of EP flow channels realized through AM by exploiting thin walls, used for: (a) increasing the length of the duct and taper it to accommodate more gas; (b) breaking the turbulence and pressure drops of the flow; (c) increasing flow velocity by creating ducts with converging geometries.

complex and difficult to be obtained through traditional AM technologies [52]. Thin-walled structures may be more susceptible to mechanical failure under high temperatures [53]. Additional flow resistance can be introduced if the channel is not accurately designed in relation with the complex fluid dynamics governing the process of hydrogen diffusion, also considering the high temperatures and the formation of water vapor [49].

At a manufacturing level, the necessary quality at the required scale remains a significant challenge. Recent studies have demonstrated the feasibility of using AM techniques to fabricate thin-walled components for SOFCs, e.g., of the microtubular type. The fabrication processes for these components often involve co-sintering and careful control of material properties to ensure reliability [32].

Fig. 10 provides some solutions, claimed in the considered patents, of EP flow channels realized through AM by exploiting thin walls.

3.6.5. Other clusters

Cluster 10 is much more generic than all the others, combining the advantages of precise material deposition of AM with the reduction of fabricating time and costs. This depends on a more rational use of materials and the reduction of waste (CN116423822). Cluster 5 is also related to the use of precise deposition of the material in electrolyte/CL, but to reduce the ionic transport length, improving the mechanical resistance and therefore reducing the thickness. For this reason, the solutions of this cluster are particularly interesting for mobile SOFC applications, especially automotive, where it is necessary to reduce the operating temperature to reduce the start-up transients, which is possible by reducing the ionic resistance [54,55]. This cluster represents a novelty with respect to the scientific literature since it shows that the reduction of the thickness of a functional layer can be achieved by directly optimizing its microstructure and not necessarily by optimizing the external mechanical supports [8]. In this way, the load distribution as well as the mechanical resistance of the SOFC are improved compared to conventional external supports that may introduce points of weakness or stress concentration [32]. The ongoing research about ultra-thin SOFC electrolytes suggest that while advancements are being made, the technology is still in a developmental phase, consistent with TRL 5.

Clusters 6 and 8 collect solutions where laser sintering of one or more materials simultaneously, in conjunction with additive manufacturing, is used in the electrolyte, cathode and anode, to increase mechanical strength and ionic conductivity. With more precise heat transfer via laser sintering, it is possible to better control the structural features to improve the mechanical strength (CN116979078) and dopant distribution to improve the ionic conductivity (WO2021/231846). These solutions could effectively reduce manufacturing time and cost while ensuring the requirements of such a cluster. However, the main limitation is the reduction of the microstructure quality and the resulting increase in the risk of thermal stress and cracks [56]. Experimental test about laser sintering have been conducted on some SOFCs showing initial interesting results which however still require further evaluations [57].

Clusters 2, 3 and 11 use AM strategies characterized by structural strength and thin thicknesses, i.e., lattice, holes matrix and self-supporting hollow cavities to improve gas diffusion, ion transport, mechanical and thermal resistance. These solutions are similar to those of other clusters already presented although not identical for the combination of the considered elements. Also in this case, as for the solutions of cluster 1, the main issue is the manufacturing quality, in relation to the scale required for SOFCs, achievable with current AM technologies [35]. To date, testing at this dimensional scale is confined to the laboratory level only [58].

Clusters 12 and 13 present rather cutting-edge solutions, with few patents and also few scientific publications to support them. The possibility of printing coatings on 3D surfaces (cluster 12) is known in AM even if used in products that work at lower temperatures than SOFCs [59]. The use of conductive metal filling, deposited in the EP structure with AM, must be evaluated with respect to interface expansions, which compromise adhesion and conduction, given the high operating temperatures that could represent a limit in this sense [60]. This option to join multiple parts (e.g., the end plate and the conductive layer) is new in SOFC AM, where it is typically done layer by layer [8]. The coatings printed on 3D surfaces of an insulating layer can be uniformly applied across complex geometries, providing a better seal and reducing the risk of defects such as pinholes, which can lead to gas diffusion or leakage. Moreover, AM allows for more precise control over the thickness and consistency of the layer, for improving the integrity of the gas separation barrier and thus operational efficiency and longevity of the SOFC [57]. Hybrid 3D inkjet printing method shows promise for fabricating coatings on 3D surfaces of SOFC components but requires further validation in operational environments (TRL 4) [61].

Finally, cluster 14 is about the use of doped powder in CL to reduce fabrication time and cost was included in the study because it is specifically dedicated to the production of SOFCs with AM (US20200014052). The use of doped powders can influence the sintering behaviour during manufacturing since doping can help control grain size and distribution, leading to improved mechanical stability and structural integrity [57]. To date, spark plasma sintering has demonstrated its effectiveness in sintering doped powders at laboratory scale (TRL 4), highlighting improvements in relative density and microstructure [62].

3.7. Sustainability assessment

The different AM solutions for SOFCs can bring some advantages in terms of environmental and economic sustainability compared to traditional manufacturing methods, in terms of energy consumption, material waste, and lifecycle impact.

Lattices and graded lattice structures are typically used for lightweight design, i.e., to reduce the mass of the component and therefore the consumption of raw material. In general, this is not the main objective of this strategy in this field, which is instead aimed at controlling the porosity to improve the diffusion of the gas and increase the surface in which the ions move. However, there are studies that have worked with lattice structures in SOFCs also to reduce the use of material and in particular of YSZ which has a significant impact on the environment and costs. The result is the search for lattice cells that, while ensuring mechanical resistance and ionic diffusivity, are specifically designed to reduce the amount of YSZ [63].

Self-supporting hollow cavity as well as precise material deposition allow the elimination of supports and excess materials, reducing material waste and avoiding subsequent operations to remove them. This is an undoubted advantage, especially since the waste material is typically YSZ. Currently, some recycling technologies for YSZ wastes have been proposed, e.g., thermal spray waste recycling and hydrothermal recovery. However, their level of development is mostly experimental and recycled YSZ can only be partially reused and in rather niche electrochemical applications [64].

The use of AM to also perform sintering could instead be a very promising solution on an environmental level to reduce the impacts of sintering which is a very energy-intensive process. The potential to fully substitute traditional sintering with AM exists, particularly as advancements in AM technologies continue to evolve. Microwave-assisted sintering and electric current-assisted sintering have shown that lower temperatures and shorter processing times, in order to reduce environmental and economic impacts, can achieve similar or improved material properties compared to conventional methods [58].

A quantitative and more structured analysis on the environmental sustainability of such AM strategies in the SOFC implementation could be conducted by applying the method of Spreafico et al. [65] to perform a patent-based prospective life cycle assessment. However, in order to perform a reliable and rigorous analysis it would be necessary to wait for other patents to be filed, in order to expand the database size. While, given the low TRL of the patented solutions, tests in an industrially relevant environment would undoubtedly be useful to increase the quality and significance of the data.

4. Conclusions

The proposed review identified in the patents several solutions characterized by many different goals, AM strategies, and some clusters of intersection between goals and AM strategies that are common to different solutions. The analysis of the patented solutions allows to answer the research questions.

- RQ 1: Compared to the reviews in the scientific literature, some new solutions have emerged, showing how AM strategies can be deployed in new ways to achieve new goals. The bibliometric analysis and the discussion of the results have shown that the patent literature on the topic is mostly aimed at claiming ideas still far from practical applications. The topic of SOFC AM is identified as very new and niche.
- RQ 2: The comparison of the number or goals, AM strategies and their intersections has contributed to highlight those with the greatest economic interest by industrial and academic researches.
- RQ 3: Cluster analysis has allowed to assign some innovation paths. The most followed are: topological optimization of the lattice structure to optimize the porosity in the GDL in order to find a compromise between Diffusion Gas, Ionic Conduction and Mechanical Resistance; Printing of thin walls and self-supporting structures to build complex fuel, air and coolant channels; 3D or graded multi-material interface between electrolyte and electrode to improve the ion flow.

All the results of this review are explicitly stated by the considered patents, which explicitly refer to SOFC AM. However, there may be patents that, although relevant, do not explicitly state it. This could be the case, for example, of a patent on AM powder that could be used to realize a SOFC. Another limitation concerns the poor proposal of patents to describe information on possible AM applications and technologies. Furthermore, this is consistent with all those patents aimed at claiming an idea that with technologies with low level of technological readiness, as in this study, can be the majority of them. To overcome the limitations of this study, future developments are planned to broaden the analysis of patents by interpreting those that do not explicitly state the application of AM to SOFC.

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.

Data availability

The DB is attached in supplementary material

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