Front. Energy
https://doi.org/10.1007/s11708-024-0945-5

REVIEW ARTICLE

Scientometric analysis of research trends on solid oxide electrolysis cells for green hydrogen and syngas production

Shimeng Kang[1], **Zehua Pan** (✉)[1], **Jinjie Guo**[1], **Yexin Zhou** (✉)[1], **Jingyi Wang** (✉)[1], **Liangdong Fan**[2], **Chunhua Zheng**[3], **Suk Won Cha**[4], **Zheng Zhong**[1]

1 School of Science, Harbin Institute of Technology, Shenzhen 518055, China
2 Department of New Energy Science and Technology, College of Chemistry and Environmental Engineering, Shenzhen University, Shenzhen 518060, China
3 Shenzhen Institute of Advanced Technology, Chinese Academy of Sciences, Shenzhen 518055, China
4 Department of Mechanical Engineering, Seoul National University, Seoul 08826, Republic of Korea

Abstract Solid oxide electrolysis cell (SOEC) is a promising water electrolysis technology that produces hydrogen or syngas through water electrolysis or water and carbon dioxide co-electrolysis. Green hydrogen or syngas can be produced by SOEC with renewable energy. Thus, SOEC has attracted continuous attention in recent years for the urgency of developing environmentally friendly energy sources and achieving carbon neutrality. Focusing on 1276 related articles retrieved from the Web of Science (WoS) database, the historical development of SOECs are depicted from 1983 to 2023 in this paper. The co-occurrence networks of the countries, source journals, and author keywords are generated. Moreover, three main clusters showing different content of the SOEC research are identified and analyzed. Furthermore, the scientometric analysis and the content of the high-cited articles of the research of different topics of SOECs: fuel electrode, air electrode, electrolyte, co-electrolysis, proton-conducting SOECs, and the modeling of SOECs are also presented. The results show that co-electrolysis and proton-conducting SOECs are two popular directions in the study of SOECs. This paper provides a straightforward reference for researchers interested in the field of SOEC research, helping them navigate the landscape of this area of study, locate potential partners, secure funding, discover influential scholars, identify leading countries, and access key research publications.

Keywords solid oxide electrolysis cell (SOEC), scientometric review, knowledge network, material development, H_2O–CO_2 co-electrolysis, modeling

1 Introduction

With the increase of the penetration of renewable electricity, the intermittent nature of the renewable energies warrants the deployment of grid-balancing technologies and short/long-term energy storage carriers. Hydrogen, as carbon-free and a promising energy carrier, is capable of interconverting with electricity and heat and serve as a foundation for a carbon-neutral and sustainable hydrogen society [1–5]. With water electrolysis, hydrogen can be produced from the abundant renewable sources such as wind, solar, geothermal, or biomass [6–10]. Hydrogen can serve as the fuel for vehicles powered by hydrogen fuel cells, as a raw material for chemical processes to produce value-added chemicals or metallurgy industry, or simply be stored. The hydrogen stored can be supplied to fuel cells, when renewable electricity cannot satisfy the demand, for combined heat and power generation [11–16]. Further, fuel cells can also serve as a non-spinning generation facility and play an essential role in renewable-energy-based energy systems and virtual power plants [17].

Solid oxide electrolysis cell (SOEC), as the latest water electrolysis technology, offers a substantial reduction in electricity consumption compared to traditional alkaline electrolysis or proton exchange membrane electrolysis [18–22], whose reaction mechanism is inverse to that of solid oxide fuel cells [23–28]. With a system capacity higher than 200 kW, the electricity-to-hydrogen

---

Received Jan. 2, 2024; accepted Mar. 14, 2024; online Apr. 30, 2024
Correspondences: Zehua Pan, panzehua@hit.edu.cn;
Yexin Zhou, zhouyexin@hit.edu.cn;
Jingyi Wang, wangjingyi@hit.edu.cn

efficiency has been independently testified by Sunfire GmbH (below 40 kWh(AC)/kg(H_2) [147] and Shanghai Institute of Applied Physics, Chinese Academy of Sciences [148] (3.16 kWh(DC)/Nm(H_2)^3). Thus, the levelized cost of hydrogen production can be substantially reduced with SOEC [29,30]. Ceres Power also plans to leverage the advantages of the steel-supported SOEC technology and to development a 1 MW-class SOEC system, aiming at enabling a path to green hydrogen production costs of < 2 \$/kg(H_2) [31], competitive to gray hydrogen costs of 0.91–2.73 \$/kg(H_2) [29]. Furthermore, the SOEC technology is capable of reversible operation; the hydrogen production and power generation can be achieved with one single device, facilitating an energy storage cycle with H_2 as the energy carrier [32]. Apart from producing H_2 by water electrolysis, the SOEC technology can also co-electrolyze CO_2 and H_2O to produce syngas or value-added chemicals such as CH_4 directly [33–36], potentially providing a more cost-saving route.

Owing to the promising perspective, SOEC is exntensively studied [34,37–40]. In the past five years, over 40 review articles have been published, shedding light on the diverse scientific advancements contributing to the evolution of SOECs. Presented in Table 1 are 20 of the review articles which are relatively more cited, more related, and published in top journal outlets. These review articles cover a variety of the hot topics in the research field of SOECs, including general developments and system-level studies [18,37,41,42], advanced materials development [43–47], degradation mechanisms [42,48–50], modeling investigations [51], electrolysis/conversion of CO_2 into CO or other types of carbon-based gaseous fuels [52–54], and other types of SOECs, such as symmetric SOECs [55,56], metal-supported SOECs [57], and proton-conducting SOECs [58–60].

In this paper, a holistic scientometric review is performed, which summarizes the research hotspots and provides an overview of the current status in the field of SOECs from a semantic point of view, aiming to identifying an unbiased trend in the research for SOECs. This paper can facilitate the recognition of the achievements and the identification of potential future research topics for researchers and newcomers in the field of SOECs.

Table 1 List of review artiles published within the past 5 years

Title	Authors	Year	Sourse
Water electrolysis toward elevated temperature: Advances, challenges and frontiers	Zhang et al. [41]	2023	*Chemical Reviews*
Advances and challenges in symmetric solid oxide electrolysis cells: Materials development and resource utilization	Gu et al. [55]	2023	*Materials Chemistry Frontiers*
A comprehensive review of recent progresses in cathode materials for proton-conducting SOFCs	Gao et al. [47]	2023	*Energy Reviews*
Protonic ceramic electrochemical cells for synthesizing sustainable chemicals and fuels	Liu et al. [60]	2023	*Advanced Science*
Progress and potential for symmetric solid oxide electrolysis cells	Tian et al. [56]	2022	*Matter*
A review of solid oxide steam-electrolysis cell systems: Thermodynamics and thermal integration	Min et al. [18]	2022	*Applied Energy* (*AE*)
Analysis of solid oxide fuel and electrolysis cells operated in a real-system environment: State-of-the-health diagnostic, failure modes, degradation mitigation and performance regeneration	Subotic et al. [42]	2022	*Progress in Energy and Combustion Science*
Electrochemical conversion of C1 molecules to sustainable fuels in solid oxide electrolysis cells	Lv et al. [53]	2022	*Chinese Journal of Catalysis*
Alternative and innovative solid oxide electrolysis cell materials: A short review	Nechache et al. [43]	2021	*Renewable & Sustainable Energy Reviews* (*RSER*)
A review on cathode processes and materials for electro-reduction of carbon dioxide in solid oxide electrolysis cells	Jiang et al. [44]	2021	*Journal of Power Sources* (*JPS*)
High-temperature electrocatalysis and key materials in solid oxide electrolysis cells	Ye & Xie [46]	2021	*Journal of Energy Chemistry* (*JEC*)
Air electrodes and related degradation mechanisms in solid oxide electrolysis and reversible solid oxide cells	Khan et al. [48]	2021	*RSER*
Recent advances and perspectives of fluorite and perovskite-based dual-ion conducting solid oxide fuel cells	Cao et al. [45]	2021	*JEC*
Advancing the multiscale understanding on solid oxide electrolysis cells via modeling approaches: A review	Li et al. [51]	2021	*RSER*
Recent advances in solid oxide cell technology for electrolysis	Hauch et al. [37]	2020	*Science*
Review—Electrochemical CO_2 reduction for CO production: Comparison of low- and high-temperature electrolysis technologies	Kungas [52]	2020	*Journal of the Electrochemical Society* (*JES*)
Degradation of solid oxide electrolysis cells: Phenomena, mechanisms, and emerging mitigation strategies—A review	Wang et al. [49]	2020	*Journal of Materials Science & Technology*
Surface segregation in solid oxide cell oxygen electrodes: Phenomena, mitigation strategies and electrochemical properties	Chen & Jiang [50]	2020	*Electrochemical Energy Reviews (EER)*
Progress in metal-supported solid oxide electrolysis cells: A review	Tucker [57]	2020	*International Journal of Hydrogen Energy* (*IJHE*)
High-temperature CO_2 electrolysis in solid oxide electrolysis cells: Developments, challenges, and prospects	Song et al. [54]	2019	*Advanced Materials*
Progress report on proton conducting solid oxide electrolysis cells	Lei et al. [58]	2019	*Advanced Functional Materials* (*AFM*)
Trends in research and development of protonic ceramic electrolysis cells	Medvedev [59]	2019	*IJHE*

2 Scientometric analysis

The quantitative science mapping approach enables the quantitative analysis of networks and patterns using bibliometric data [5,61–63]. Employing science mapping as a bibliometric network visualization method can proficiently unveil the trends in research collaboration networks among researchers, nations, academic journals, keywords, and so forth. It also helps identify the representations of the diverse contributions made by researchers engaged in SOEC research [64].

Various science mapping tools are currently available [65–67]. In this paper, an open-source software, VOSviewer (version 1.6.19) [67], is chosen as it is suitable for the visibility of this study, which is apparent in previously published articles [64,68,69]. The most prominent and reputable databases for indexing research in the studies related to energy are Web of Science (WoS) and Scopus. Due to the wider coverage of research articles by WoS than Scopus when searching by using the same method, this paper adopts WoS as the bibliometric database. In addition, VOSviewer supports the direct importation of bibliometric data from WoS, facilitating the analysis.

2.1 Retrieval of bibliometric data

The key strategy for obtaining extensive bibliometric data in a certain research field involves the careful selection and definition of the appropriate keyword combinations in the database. To identify research hotspots and trends, “article” was the only document type being chosen, and the database was limited in the “core selection” of WoS. The search term used to retrieve all articles about SOECs was TS = (“solid oxide electrolysis cell” OR “solid oxide electrolysis cells”), in which TS means the words that are included in the title, keywords, and abstract of an article. In total, 1276 documents were generated.

Subsequently, the scientometric review was performed on the three different components of SOEC, fuel electrode, electrolyte, and air electrode. Further, due to the unique ability of SOEC to co-electrolyze CO_2–H_2O [34], the recent emergence of proton-conducting SOECs [70], and the importance of modeling study in the development of SOECs [71], the above three categories were also reviewed based on scientometric analysis. To ensure that the main content of the article obtained falls in the intended research field, the search was performed by searching for terms both from the TS and from the TI (TI means the searching terms included in the title of an article). For the fuel electrode, the query was (TS = (“solid oxide electrolysis cell OR “solid oxide electrolysis cells” OR “SOEC OR SOECs”)) AND (TI = (“fuel electrode” OR “hydrogen electrode” OR “cathode” OR “fuel electrodes” OR “hydrogen electrodes” OR “cathodes”)). For the air electrode, the query was “(TS = (“solid oxide electrolysis cell” OR “solid oxide electrolysis cells” OR “SOEC” OR “SOECs”)) AND (TI = (“air electrode” OR “oxygen electrode” OR “anode” OR “air electrodes” OR “oxygen electrodes” OR “anodes”)).” For the electrolyte of SOEC, the query was “(TS = (“solid oxide electrolysis cell” OR “solid oxide electrolysis cells” OR “SOEC” OR “SOECs”)) AND (TI = (electrolyte)).” In total, 222 documents focusing on the fuel electrode, 214 documents focusing on fuel electrode, and 101 documents focusing on electrolyte were generated for the study.

When analyzing the articles related to CO_2–H_2O co-electrolysis, the query was “(TS = (“solid oxide electrolysis cell” OR “solid oxide electrolysis cells” OR “SOEC” OR “SOECs”)) AND (TS = (co-electrolysis)),” and 277 documents were presented. For articles on proton-conducting, the query was “(TS = (“solid oxide electrolysis cell” OR “solid oxide electrolysis cells” OR “SOEC” OR “SOECs”)) AND (TS = (“proton-conducting” OR “protonic ceramic”)). In total, 80 documents were generated.

For articles on modeling of SOEC, the query was (TS = (“solid oxide electrolysis cell” OR “solid oxide electrolysis cells”)) AND (TS = (“modeling” OR “simulation”))” and 347 documents were generated.

Afterward, the scientometric analysis was performed using VOSviewer by importing the retrieved bibliometric data in .txt format.

2.2 Analysis of retrieved bibliometric data

In the beginning, the analyzing function provided by WoS was used to derive the publication years, publication/source titles, research areas, etc. The data was then plotted as graphs. Subsequently, the “create a map based on bibliometric data” feature in VOSviewer was employed to generate bibliographic coupling maps, providing a more direct visualization of the information. Then the keyword co-occurrence analysis was conducted to identify the main content of these documents. Afterwards, the “create a map based on text data” function was utilized to produce a co-occurrence map of textual data. This approach aims to generate a map showcasing the most frequently used terminologies in the study of SOECs. For the data generated by VOSviewer, a citation link between two documents is established if one document is cited by the other document, and the total link strength indicates all the links of the articles.

3 Results and discussion

3.1 Scientometric analysis of SOECs

3.1.1 Annual number of publication on SOECs

As shown in Fig. 1, the demonstration of SOECs was

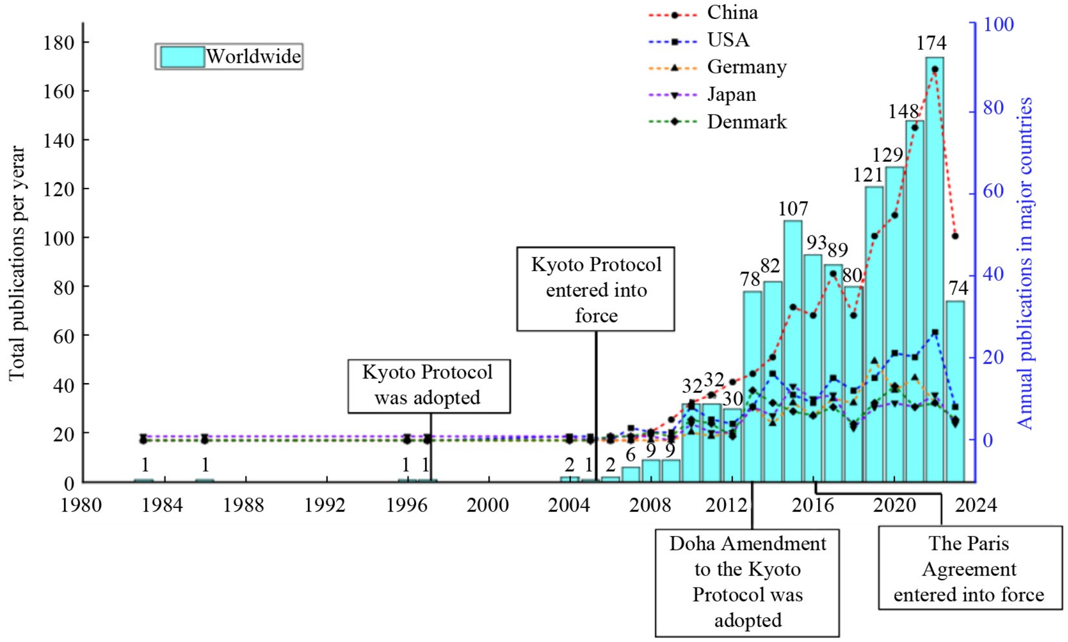


Fig. 1 Number of annual publications of research related to SOECs from the first demonstration in 1986 till date (2023).

initially reported in 1983. However, there was no significant interest in this research area in the years that followed, until a mild rise in interest in 2007–2009 when the annual number of publications on SOEC reached 8. However, in 2010 and 2013, the research interest in SOEC increased significantly, with an annual number of publications reaching 32 and 74, respectively. In the following 6 years, the annual number of publications fluctuated in a small range and then surged again in 2019 to 124. Ever since then, it has continued to increase, which means SOEC is still in a rapid development phase. It is to be mentioned that hydrogen is a green and carbon-free energy carrier and the foundation for building a carbon-neutral society. The research on hydrogen-related technologies could be highly dependable on the signing of international agreements on climate change. The Kyoto Protocol was adopted on December 11, 1997 and it entered into force after a complex ratification process on February 16, 2005, possibly responsible for the gradual increase in publications starting from 2007. The Kyoto Protocol operationalizes the United Nations Framework Convention on Climate Change by committing a transition to limit and reduce greenhouse gas (GHG) emissions in accordance with agreed individual targets by industrialized countries and economies. On December 8, 2012, the Doha Amendment to the Kyoto Protocol was adopted for a second commitment period, starting in 2013 and lasting until 2020, which could be the reason for the boost in publications starting from 2013. The Paris Agreement, of which the primary goal was to hold “the increase in the global average temperature to well below 2 °C above pre-industrial levels” and spent efforts “to limit the temperature increase to 1.5 °C above pre-industrial levels” was adopted by 196 Parties at the UN Climate Change Conference (COP21) in Paris, France, on December 12, 2015 and it entered into force on November 4, 2016, promoting the research in SOECs.

3.1.2 Science mapping of source journals of SOECs

Scientific journals play a pivotal role as primary channels for disseminating high-quality research findings and discoveries to the academic community and other stakeholders with interest. These journals serve as specific platforms for categorizing research articles according to their scale, target audience, and other relevant criteria. Recognizing and identifying key journals within a specific research area is essential for methodically charting research trends in that field. Table 2 summarizes the total publications, total citations, average citations, and the total link strength of the top journals, which should have at least published 10 research articles with a minimum of 100 citations, on the development of SOECs. These parameters were established during the network generation using VOSviewer.

Figure 2 gives the ranking of the journals in terms of the average publication years and average citations per article, as well as the co-occurrence network of the journals. For Figs. 2(a) and 2(b), the areas of the circles represent the total number of publications on SOECs in each journal. The color variation in Fig. 2(a) represents the change in the average publication years, while the color variation in Fig. 2(b) represents the change in the average citations per publication. As can be seen from Fig. 2(a), *ECM* and *Journal of CO_2 Utilization* (*JCU)*

Table 2 An elaborate summary of the metrics of top influential research journals in SOECs ranked by average citations

Source journal	Documents	Citations	Avg. citations	Total link strength
JES	57	2522	44.2	994
JPS	133	5512	41.4	2030
Solid State Ionics (*SSI*)	31	1177	38.0	440
IJHE	197	6878	34.9	1880
Journal of Materials Chemistry A (*JMCA*)	46	1564	34.0	594
Energy	18	595	33.1	126
JEC	14	454	32.4	258
Applied Catalysis B-Environmental	11	353	32.1	158
Electrochemistry Communications	10	302	30.2	154
Faraday Discussions	11	296	26.9	160
ACS Applied Materials & Interfaces	15	398	26.5	252
AE	28	731	26.1	280
Electrochimica Acta	39	764	19.6	499
Chemical Engineering Journal (*CEJ*)	15	275	18.3	218
Fuel Cells	39	687	17.6	467
Journal of Alloys and Compounds	12	174	14.5	70
Energy Conversion and Management (*ECM*)	34	489	14.4	224
JCU	14	174	12.4	188
Ceramics International	29	264	9.1	184

have begun to focus on SOECs in recent years. *IJHE* (197) and *JPS* (133) have traditionally published the highest number of publications in the field of SOECs, followed by *JES* (57), *JMCA* (46), and *Electrochimica Acta* (39). The journal that has the highest average citation per article is *JES*. In addition, *IJHE* and *JPS* rank 2nd and 4th in terms of the average citations per year, which further underscores their significant contributions to the advancement of the field of SOECs.

Figure 2(c) shows the citation network among the source journals. The varying node sizes, once again, depict the overall count of articles from each journal. The connecting lines and the thicknesses of the lines illustrate the extent of cross-citation or the intensity of connections between the two journals. Evidently revealed in Fig. 2(c) and Table 2, *IJHE* and *JPS* are the two source journals exhibiting the most robust link strengths. The top five most influential journals, from a viewpoint of the total number of citations, are *IJHE* (6878), *JPS* (5512), *JES* (2522), *JMCA* (1564), and *SSI* (1177). The various colors of nodes in Fig. 2(c) indicate distinct research clusters. Research journals within the same cluster are grouped based on inter-journal citations, highlighting their thematic similarities or related topics. For instance, *IJHE, ECM, AE*, and *CEJ* belong to the green cluster, while *JMCA, JCU*, and *JEC* are part of the red cluster.

3.1.3 Active countries in the research of SOECs

This section aims to pinpoint potential collaborators and to gain insights into the countries that are actively promoting the development of SOECs. Understanding the various countries actively engaged in advancing SOECs research can assist researchers in identifying prospective collaborators to enhance their careers and contribute to the further development of SOEC technology. Figures 3(a) and 3(b) delineate the contributions of various countries to the field of SOECs and Fig. 3(c) reveals the inter-citation among different countries.

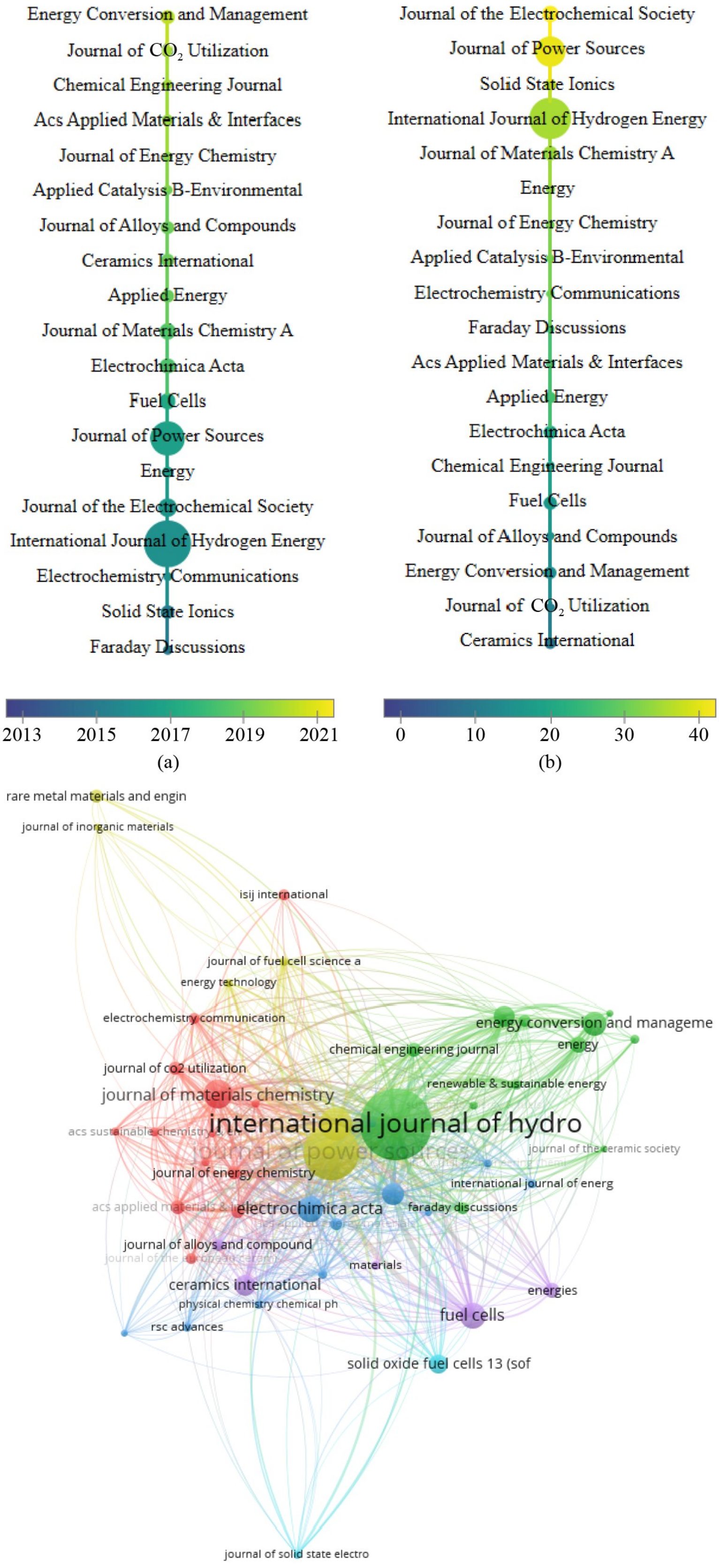
Figures 3(a) and 3(b) reveal variations in rankings when considering average publication years and citations separately. The size of the nodes illustrates the contributions of each individual country to the development of SOECs. For instance, China, with 508 publications and a total citation count of 10424, significantly dominates the research in this area based on the research output, surpassing all other countries by a wide margin. Following China, by assessing research output, the top contributors include the United States (182), Germany (108), Denmark (103), and Japan (103). On the other hand, when looking at average citations per publication, Denmark leads the list with an average citation of 61, followed by Saudi Arabia (58), England (52), Scotland (42), and Spain (41). The network exhibits the emergence of several distinct clusters, each having a strong and interconnected relationship with China.

3.1.4 Research areas of SOECs

Figure 4 depicts the contributions in various subject areas related to SOECs, derived from the bibliometric data. The primary contributing research area is *Energy & Fuels*, accounting for approximately 1010 research documents. *Engineering* follows closely, with a cumulative total of 842 research documents. The remaining subject areas constituting the top five domains include *Chemistry* (898), *Electrochemistry* (870), and *Materials Science* (549). These areas exert the great influence on SOEC research. The top-cited articles in different areas are shown in Table S1.

3.1.5 Co-occurrence network of keywords

Keywords play a pivotal role as essential index terms, offering a succinct summary of research content. Consequently, mapping keywords within a specific research direction can facilitate the swift retrieval of relevant information, thereby helping achieve various research objectives. In the VOSviewer software, the “co-occurrence” was chosen as the analysis type and the “fractional counting” method was used for counting. The “unit of analysis” was selected for “Author keywords.”

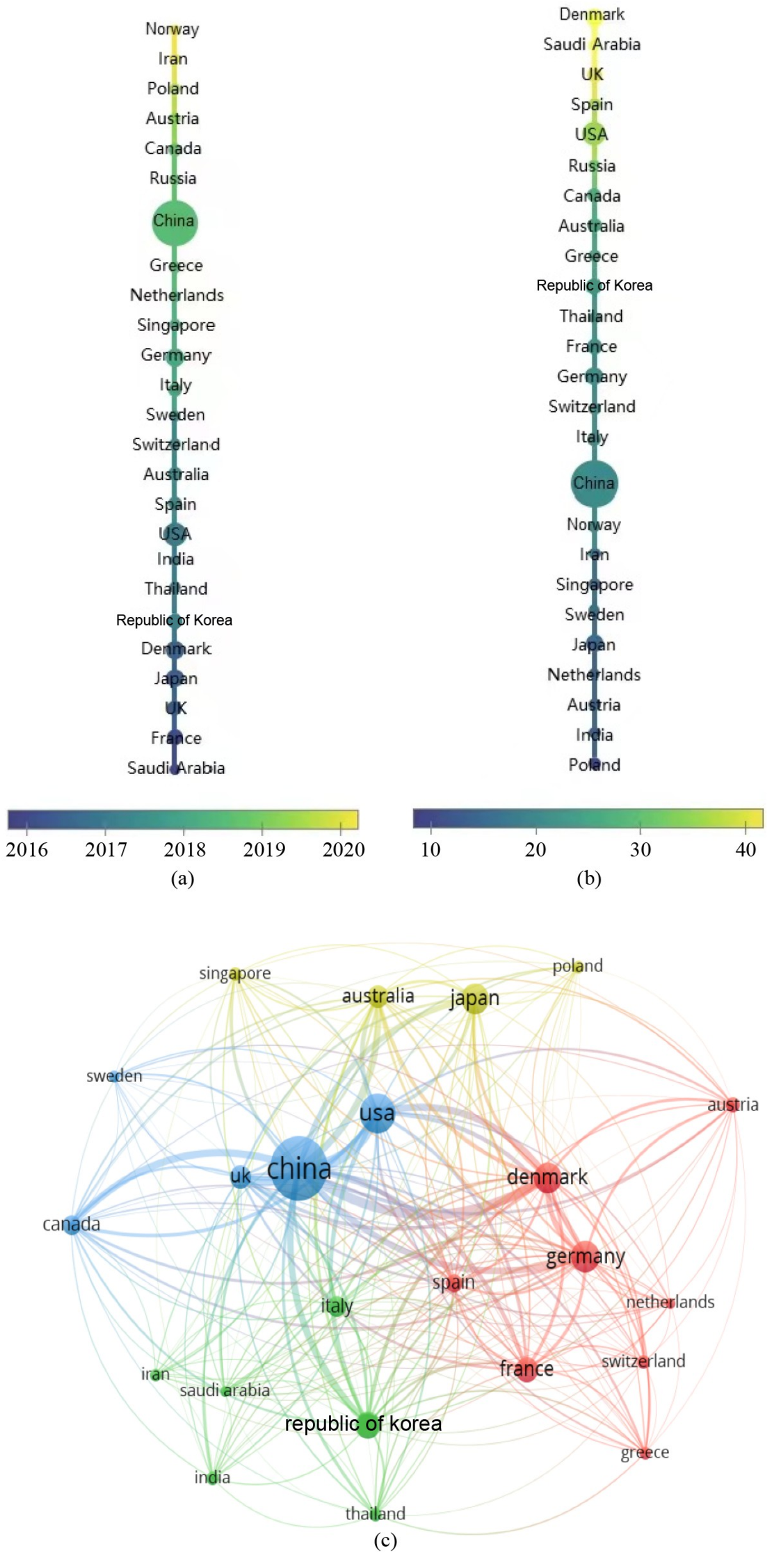


(a)

(b)

(c)

Fig. 2 Analyses of source journals in the field of SOECs.
(a) Ranked by average publication year; (b) Ranked by average citations; (c) Co-occurrence network.



(a) (b)

(c)

Fig. 3 Analyses of countries in the field of SOECs.
(a) Ranked by average publication year; (b) Ranked by average citations; (c) Co-occurrence network.

Among the 2313 keywords identified from the 1276 articles, only 126 surpassed the threshold of appearing at least 5 times. Table 3 showcases the foremost 20 frequently employed author keywords in articles on SOECs, detailing their frequency and total link strengths. Furthermore, keywords that exhibit close associations are

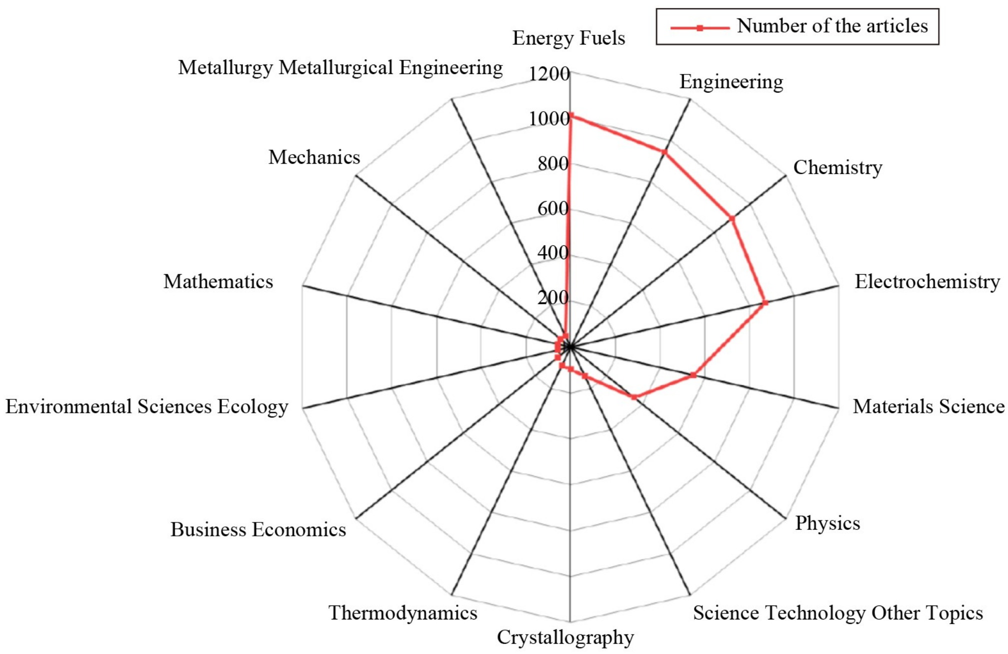


Fig. 4 Subject areas of SOECs.

Table 3 Predominantly utilized used keywords in the research of SOECs

Keyword	Occurrences	Total link strength	Cluster
Clussolid oxide electrolysis cell	616	535	Yellow
Solid oxide fuel cell	139	128	Brown
Hydrogen production	110	106	Red
Electrolysis	60	56	Red
Co-electrolysis	52	49	Brown
CO_2 electrolysis	50	44	Orange
Degradation	49	48	Dark blue
Steam electrolysis	43	39	Green
Oxygen electrode	40	40	Green
Hydrogen	36	35	Red
Carbon dioxide	34	33	Purple
Perovskite	33	29	Light blue
High temperature electrolysis	31	30	Brown
CO_2 reduction	29	27	Purple
Electrochemical performance	29	27	Yellow
Cathode	28	27	Yellow
Stability	28	28	Green
High temperature steam electrolysis	26	25	Red
Stack	24	23	Dark blue
Solid oxide electrolyser	23	22	Red

organized into clusters, as visually depicted in Fig. 5, in which the 126 keywords are classified into 11 clusters. Articles cite each other more frequently if these keywords appear in the same cluster, which means there may be more similarities in the content of these articles.

Three main categories of study can be identified from the 12 clusters shown in Fig. 5. In the red and pink clusters (enlarged in Fig. 6(a)), except for some words that may occur in all kinds of articles related to SOECs, like “hydrogen” and “electrolysis”, the keywords such as “energy storage”, “power to gas”, “gasification”, “efficiency”, “exergy analysis”, “co-electrolysis”, and “renewable energy” frequently co-occurred. Hence, this kind of documents focus more on the macroscopic performance at the system level and are related to the energy conversion from electricity to various kinds of products, H_2 or CO, using SOECs.

As enlarged in Fig. 6(b), the keywords in the yellow, green, and purple clusters have similar characteristics. Keywords such as “carbon dioxide”, “CO_2 reduction”, “carbon monoxide”, “zirconia”, “ceria”, and “carbon recycling” often co-occurred in the green cluster; keywords such as “CO_2 electrolysis”, “perovskite”, “cathode”, “microstructure”, “air electrode”, and “*in situ* exsolution” often co-occurred in the yellow cluster; and keywords such as “stability”, “syngas production”, “electrochemical performance”, and “electrolyte” co-occurred in the purple cluster. These keywords are related to the electrolysis of CO_2. The related research covers a variety of aspects of CO_2 electrolysis, including the fundamental mechanism investigation of CO_2 reduction, the development of high-performance electrodes, the stability of SOEC during CO_2 electrolysis, and the cell-level macro evaluations.

In the dark and light blue clusters (enlarged in Fig. 6(c)), the keywords that co-occurred with the

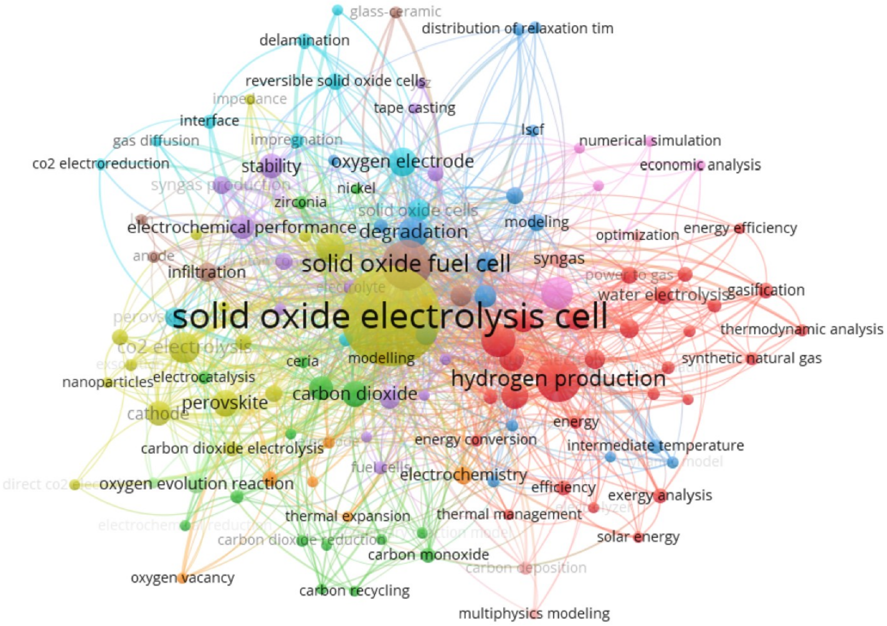


Fig. 5 Co-occurrence network of frequently used keywords in articles related to SOECs.

most-frequently-emerged keyword, “degradation” are “electrochemical impedance spectroscopy”, “durability”, “modeling”, “oxygen electrode”, “delamination”, etc. Further, “oxygen electrode” has a close relationship with “delamination”, indicating one of the key degradation phenomena during electrolysis operation. It can be seen that the articles in this cluster are more about the durability and relative modeling of SOECs.

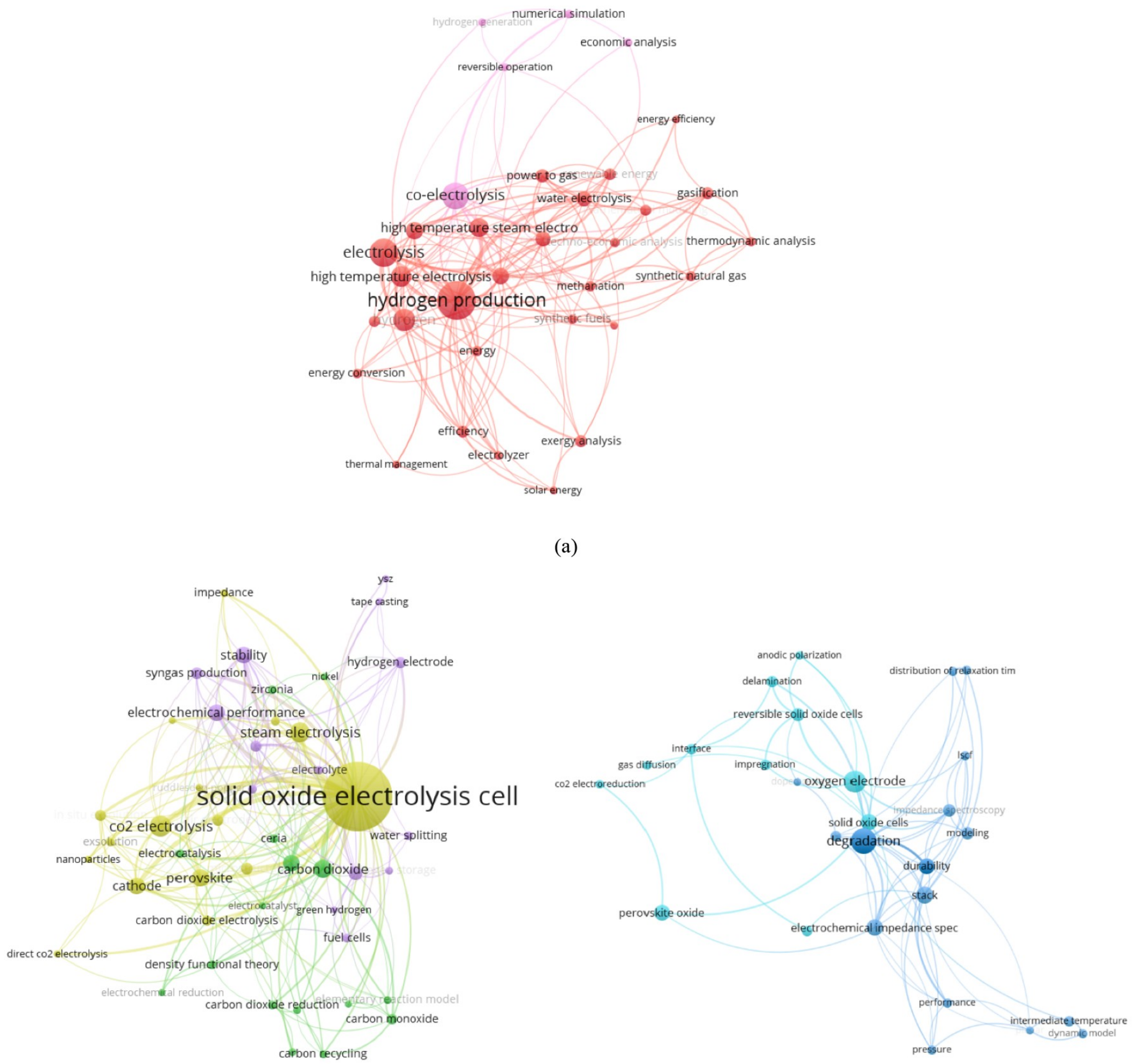
The average publication year of the keywords can also be generated by VOSviewer, which is shown in Fig. 7. The lighter the color, the more recent the average publication year of the keyword is. It is evident that the keywords related to “CO_2 electrolysis” are updated, while those ralted to “hydrogen production” are not, which means that compared with the traditional role of SOECs to produce hydrogen, researchers started to pay more attention to the electrolysis of CO_2 recently. Moreover, the publication year of the keywords such as “energy efficiency”, “solar energy”, and “exergy analysis” are also closer, indicating that the research on SOEC has steered from the material/cell level to the system level. This could be a sign of technology maturity and the SOEC technology is around the corner of commercialization.

3.1.6 Highly-cited articles

Extracted from the WoS database, the top 20 highly-cited articles in terms of the annual average citations per article in the field of SOECs are listed in Table 4. Clearly, at the cell level, two primary research topics emerge, i.e., the degradation of SOEC [72–78] and the development of fuel electrodes [79–85]. The degradation study focuses on water electrolysis. Specifically, Tietz et al. [75] and Knibbe et al. [74] investigated the degradation mechanisms. Graves et al. [72] proposed and validated experimentally that carefully tuning the reverse operation pattern could eliminate the degradation during electrolysis operation. Hauch et al. [77,78] focused on the optimization of fuel electrode to improve stability. In comparison, the electrode development is mainly for CO_2 electrolysis. Especially, the *in situ* exsolution of metal catalysts, such as Fe–Ni alloy nanospheres, and Ru−Fe alloy nanoparticles, is a major direction pursued to improve the catalytic activity toward CO_2 reduction and to retain a higher resistance to the carbon deposition and to the particle growth. On the system level, the SOEC was mainly suggested for integration with renewable energy sources, such as solar and biomass energy, aiming to enhance energy efficiency.

3.2 Focus assessments on different research fields of SOECs

To determine the parameters commonly discussed in research articles on SOECs, a bibliometric data-driven co-occurrence analysis was undertaken from all 1276 high-quality research articles. This approach is essential for studying research trends in a specific field, as mentioned by Su and Lee [92]. Keywords often serve as indicators of the emphasis and substance of a research theme. While the above co-occurrence network focused on keywords, the current analysis covers essential terms found in the titles and abstracts of articles. To accomplish this, the binary counting method was chosen in the VOSviewer, with the minimum number of occurrences set to 5–10 based on the number of the search results.



(a)

(b)

(c)

Fig. 6 Different clusters in co-occurrence network of keywords.

(a) Red and pink clusters that focus more on the macroscopic performance at the system level; (b) yellow, green, and purple clusters that focus more on CO_2 electrolysis; (c) dark and light blue clusters that focus more on the durability and relative modeling of SOECs.

The relevance score was then calculated. Terms with a high relevance score tend to represent specific topics covered by the text data, while terms with a low relevance score tend to be of a general nature and tend not to be representative of any specific topic. The pertinent terms amounting to approximately 60% of the most relevant terms, were finally presented.

Moreover, the information on the publication year and citations of the topics are summarized in Table 5. The proton-conducting SOECs can be identified as the most popular topic in the research of SOECs for their closer average publication year and higher annual average citations per article. Further, research enthusiasm on the fuel electrode, the co-electrolysis, and the modeling investigation continues as reflected by an annual average citations per article higher than 11. In contrast, less focus is put on the research of the air electrode and the electrolyte; the average publication year dates back to 2014 and 2015, respectively, with a lower annual average citations per article of around 8 and 9. This may imply that the electrolyte and air electrode materials in the SOECs are relatively mature. Less attention is required to be paid to the electrolyte and the air electrode during the development of the SOEC system and the commercialization of the SOEC technology.

3.2.1 Fuel electrode

Of the 4554 terms analyzed, 149 met the threshold of occurring at least 8 times. Then, 89 terms were chosen as 60% of the most relevant terms. Table 6 shows the terms most frequently recurred in the titles and abstracts of the 1101 articles, as well as the relevance score of the terms.

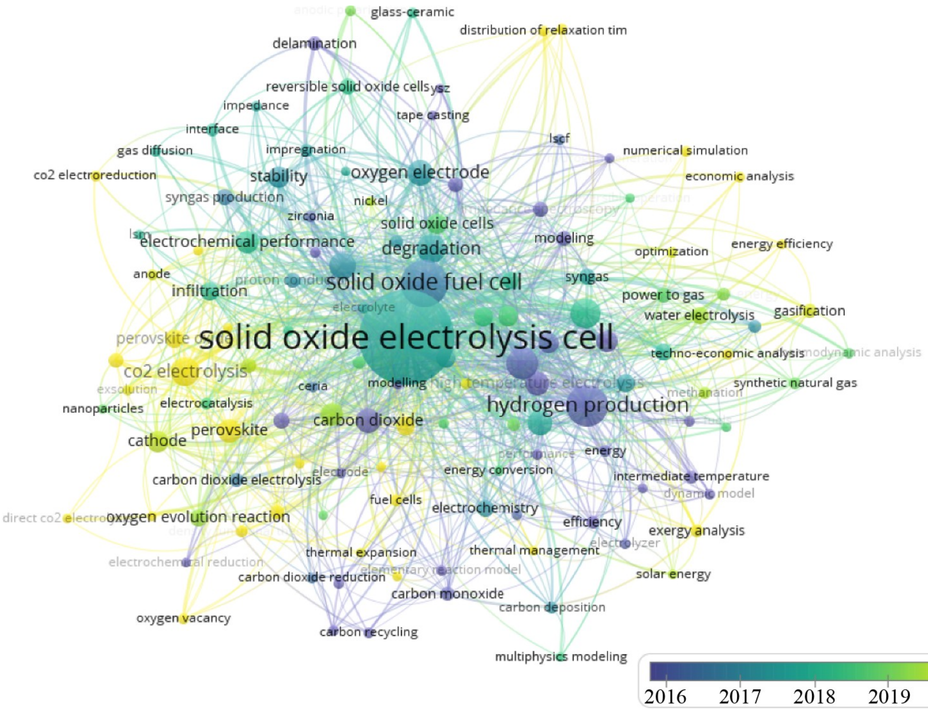


Fig. 7 Average publication years of the keywords in the research of SOECs.

Table 4 Top 20 highly-cited articles in terms of annual average citations per article in the field of SOECs

Title	Authors	Year	Source Journal	Total citations	Average citations per year
Eliminating degradation in solid oxide electrochemical cells by reversible operation	Graves et al. [72]	2015	*Nature Materials*	353	39.22
Electrolysis of carbon dioxide in solid oxide electrolysis cells	Ebbesen & Mogensen [86]	2009	*JPS*	396	26.4
Hybrid-solid oxide electrolysis cell: A new strategy for efficient hydrogen production	Kim et al. [87]	2018	*Nano Energy*	154	25.67
Co-electrolysis of CO_2 and H_2O in solid oxide cells: Performance and durability	Graves et al. [73]	2011	*SSI*	327	25.15
In situ exsolved $FeNi_3$ nanoparticles on nickel doped $Sr_2Fe_{1.5}Mo_{0.5}O_{6-\delta}$ perovskite for efficient electrochemical CO_2 reduction reaction	Lv et al. [79]	2019	*JMCA*	116	23.2
Highly stable and efficient catalyst with in situ exsolved Fe–Ni alloy nanospheres socketed on an oxygen deficient perovskite for direct CO_2 electrolysis	Liu et al. [80]	2016	*ACS Catalysis*	177	22.13
Large-scale electricity storage utilizing reversible solid oxide cells combined with underground storage of CO_2 and CH_4	Jensen et al. [88]	2015	*Energy & Environmental Science (EES)*	197	21.89
Enhancing CO_2 electrolysis performance with vanadium-doped perovskite cathode in solid oxide electrolysis cell	Zhou et al. [81]	2018	*Nano Energy*	129	21.5
Degradation phenomena in a solid oxide electrolysis cell after 9000 h of operation	Tietz et al. [74]	2013	*JPS*	235	21.36
Perovskite oxyfluoride electrode enabling direct electrolyzing carbon dioxide with excellent electrochemical performances	Li et al. [82]	2019	*Advanced Energy Materials*	105	21
Step-change in high temperature steam electrolysis performance of perovskite oxide cathodes with exsolution of B-site dopants	Tsekouras et al. [83]	2013	*EES*	230	20.91
Multi-objective optimization and comparative performance analysis of hybrid biomass-based solid oxide fuel cell/solid oxide electrolyzer cell/gas turbine using different gasification agents	Habibollahzade et al. [89]	2019	*AE*	103	20.6
New optimal design for a hybrid solar chimney, solid oxide electrolysis and fuel cell based on improved deer hunting optimization algorithm	Tian et al. [90]	2020	*Journal of Cleaner Production*	78	19.5
Promoting exsolution of RuFe alloy nanoparticles on $Sr_2Fe_{1.4}Ru_{0.1}Mo_{0.5}O_{6-\delta}$ via repeated redox manipulations for CO_2 electrolysis	Lv et al. [84]	2021	*Nature Communications*	56	18.67
Solid oxide electrolysis cells: Degradation at high current densities	Knibbe et al. [75]	2010	*JES*	258	18.43
Comparison of microstructural evolution of fuel electrodes in solid oxide fuel cells and electrolysis cells	Trini et al. [76]	2020	*JPS*	71	17.75
Thermodynamic assessment of a novel multi-generation solid oxide fuel cell-based system for production of electrical power, cooling, fresh water, and hydrogen	Haghghi [91]	2019	*ECM*	82	16.4
In situ exsolved Co nanoparticles on Ruddlesden-Popper material as highly active catalyst for CO_2 electrolysis to CO	Park et al. [85]	2019	*Applied Catalysis B-Environmental*	81	16.2
Solid oxide electrolysis cells: Microstructure and degradation of the Ni/yttria-stabilized zirconia electrode	Hauch et al. [77]	2008	*JES*	257	16.06
Ni/YSZ electrodes structures optimized for increased electrolysis performance and durability	Hauch et al. [78]	2016	*SSI*	127	15.88

Table 5 Average publication year and (annual) average citations per article of the top 10% of articles ranked by average annual citations from different research topics of SOECs

Topic	Average publication year	Average citations per article	Annual average citations per article
Fuel electrode	2017.05	84.23	11.85
Air electrode	2014.14	78.71	8.14
Electrolyte	2015.20	76.80	8.75
Co-electrolysis	2015.42	96.46	11.01
Proton-conducting SOECs	2019.57	66.14	13.83
Modeling	2017.31	76.66	11.42

Table 6 Most occurring terms in articles related to fuel electrode of SOECs

Term	Occurrences	Relevance score
Stability	63	0.76
Nanoparticle	45	0.71
Cathode material	38	0.81
Catalytic activity	37	0.9
Solid oxide fuel cell	35	1.61
Surface	35	1.07
Mode	30	1.49
Formation	29	0.85
Hydrogen electrode	28	1.51
YSZ	28	0.97
Microstructure	27	0.83
Perovskite	27	0.77
Technology	27	0.43
Development	25	1.50
Ni-YSZ	25	0.85
Oxygen vacancy	25	0.68
Zirconia	24	0.48
Electrocatalytic activity	23	0.89
Electrolysis performance	23	0.38
Oxide	23	1.01
Steam electrolysis	23	0.37

A higher score indicates a greater likelihood that the connected term signifies a specific research topic, whereas a lower score suggests that the term is more general and lacks significant relevance to a particular topic. Figures 8 and 9 demonstrate the co-occurrence network and the average publication years of the terms in articles on fuel electrode of SOECs. The most cited articles, excluding review articles, on fuel electrode of SOECs on average per year are shown in Table S2.

On top of the list, the term "stability" occurs most frequently. During high-temperature operation, the Ni-based electrode may undergo Ni coarsening [93–95], Ni migration [96], and Ni-NiO redox cycles [97–100], severely compromising the long-term stability. Thus, the stability of the electrode remains an intense topic in the field of fuel-electrode research. Further, with the ability to electrolyze CO_2 rather than just H_2O, SOEC possesses a broader application scenario under the background of carbon neutrality. Thus, the research and development of fuel electrode of SOEC is to adapt to the application in CO_2 electrolysis recently. Utilizing the traditional Ni-YSZ (Yttria stabilized zirconia) electrode in electrolytic cells comes with some disadvantages, especially for CO_2 electrolysis. The inherent redox instability of the Ni catalyst in the fuel electrode necessitates the feed of a small quantity of protecting hydrogen to maintain a reducing environment to avoid the formation of NiO, increasing the complexity of a SOEC stack. When being used for CO_2 electrolysis, carbon deposition may take place on the Ni catalyst in the CO_2 atmosphere at high temperatures, potentially resulting in poor stability.

Trini et al. [76] compared the Ni-YSZ electrode microstructure in the mode of SOEC and SOFC. The analysis highlights a more pronounced performance degradation and Ni-YSZ microstructure change in the SOEC mode compared to that in the SOFC mode. The local Ni depletion was considered the major source of performance degradation in the SOEC mode. In place of traditional Ni-YSZ cermet, metal oxide ceramics, such as perovskites bearing a general composition of ABO_3, were sought for as the substitute. Some of the metal oxide ceramics are inherently redox stable, eliminating the need for the supply of protecting hydrogen. Furthermore, these metal oxide ceramics also possess high resistance to carbon deposition. Thus, in order to improve the stability, novel perovskite fuel electrodes are actively sought for as the material of the fuel electrode, as reflected by the frequent occurrence of the keyword "perovskite." As can be seen from Fig. 9, the average publication years of "perovskite", "perovskite cathode", and "perovskite oxide" are more recent than those of Ni-YSZ. Nowadays, scholars are actively studying perovskite materials with not only good stability but also high catalytic and electrochemical performances, which can also be proved by the high occurrence of the term "catalytic activity."

Tsekouras et al. [83] developed doped lanthanum titanates with the formula of $La_{0.4}Sr_{0.4}M_xTi_{1-x}O_{3-\gamma-\delta}$ ($M = Fe^{3+}$ or Ni^{2+}; $x = 0.06$; $\gamma = (4 - n)x/2$) as the fuel

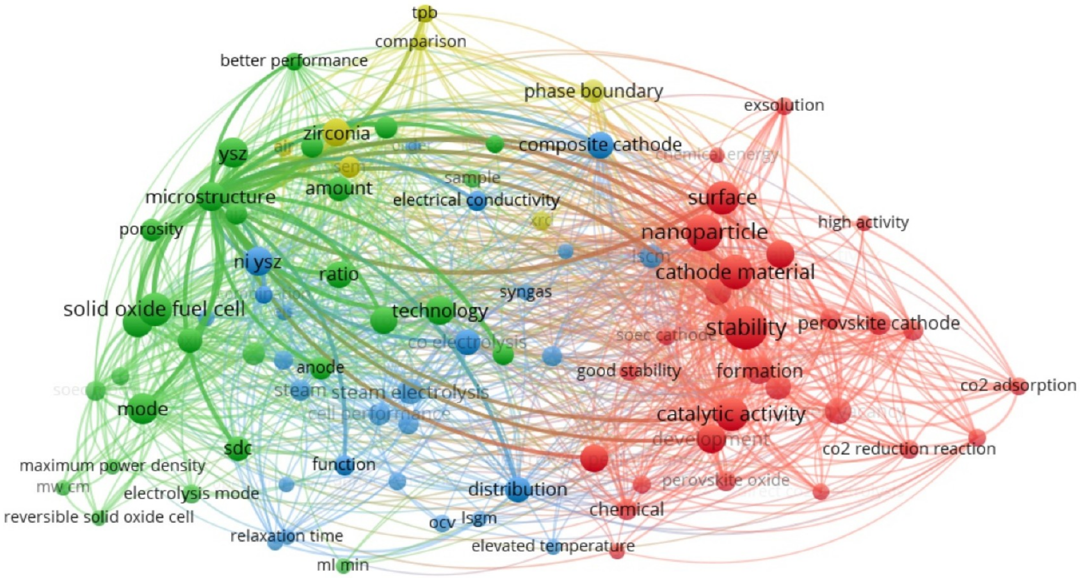


Fig. 8 Co-occurrence network of the terms in the titles, abstracts, and keywords in articles related to fuel electrode of SOECs.

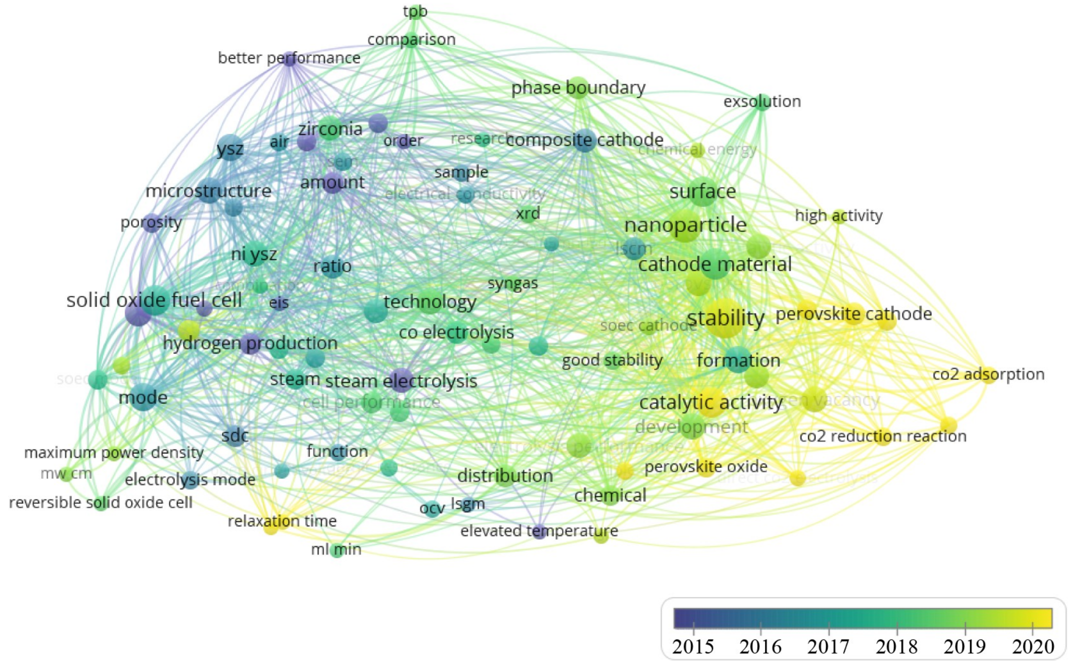


Fig. 9 Average publication years of the terms in articles on fuel electrode of SOECs.

electrodes of SOECs for hydrogen production. It is found that modest B-site Fe^{3+} or Ni^{2+} doping into $La_{0.4}Sr_{0.4}TiO_3$ led to step-changes in steam electrolysis performance, a result of the exsolution of electrocatalytically active metallic nanoparticles. Arrivé et al. [101] discovered that the $La_{0.5}Sr_{0.5}Ti_{0.75}Ni_{0.25}O_3$ (LSTN25) electrode exhibited a metallic behavior in a reducing atmosphere after a high-temperature (1200 °C) reduction. The conductivity increased by up to a factor of 1000 at 800 °C, reaching the specifications for a functional hydrogen electrode which attributed to the increase in Ti^{3+} concentration. Teng et al. [102] reported an A-site deficient $La_{0.4}Sr_{0.55}Co_{0.2}Fe_{0.6}Nb_{0.2}O_{3-\delta}$ (LSCFN55) perovskite as the fuel electrode for SOEC. The cell with the as-developed fuel electrode exhibited a high electrolysis current density of 0.956 A/cm^2 at an applied voltage of 1.3 V at 850 °C. A good stability was also demonstrated in a high humidity and hydrogen partial pressure environment. The high performance and good stability could be due to the combined action of the exsolution of Co_2Fe alloy nanoparticles and the segregation of SrO.

In the research of the fuel electrode suitable for CO_2 electrolysis, Zhou et al. [81] prepared a V-doped $La_{0.2}Sr_{0.8}TiO_{3.1}$ electrode with GDC nanocomposites, and found that due to the synergistic interaction of the elevated positive charge at the B-site with the introduction of extra O^-/O_2^{2-}, the V-doping in the LSF/GDC could greatly enhance the CO_2 dissociative adsorption kinetic. Li et al. [103] reported a perovskite-structured $Sr_{1.9}Fe_{1.5}Mo_{0.4}Ni_{0.1}O_{6-\delta}$ fuel electrode for direct CO_2 electrolysis. They found that nano-sized exsolved NiFe nanoparticles had a significant positive impact on the chemical adsorption and surface reaction kinetics of CO_2 at the cathode. Liu et al. [104] innovated a new cathode design, incorporating *in situ* exsolved Co–Fe alloy nanoparticles into an active double-layered perovskite backbone of $(Pr_{0.4}Sr_{0.6})_3(Fe_{0.85}Mo_{0.15})_2O_7$. A phase change from a cubic perovskite to a double-layered perovskite structure and the exsolution process enhanced the oxygen vacancies in this innovation. Furthermore, the existence of exsolved Co–Fe alloy nanoparticles played a key role in boosting catalytic activity, improving Faraday efficiency, ensuring stability, and exhibiting outstanding resistance to coking in the context of CO_2 electrolysis. Zhang et al. [105] doped the catalytic and redox-active Ce into A-site of $La_{0.7}Sr_{0.3}Cr_{0.5}Fe_{0.5}O_{3-\delta}$, which can *in situ* induce oxygen vacancies within the lattice during reduction under operational conditions. The electrochemical performance and Faraday efficiencies were both improved through Ce doping in the CO_2 electrolysis tests. Li et al. [106] employed the redox-stable ceramic mixed electron and oxygen ion conductor, $Sr_2Fe_{1.5}Mo_{0.5}O_{6-\delta}$ (SFM), as the electrocatalyst for the electrolysis and conversion of CO_2. Without the supply of safe gases such as H_2 or CO, 100% CO_2 was converted into CO. Lv et al. [107] also sought for the addition of GDC into SFM as the composite cathode. The introduction of GDC nanoparticles through infiltration resulted in a substantial increase in the concentration of active sites and the length of three-phase boundaries (TPBs). This increase in active sites and TPBs is advantageous for CO_2 adsorption and the subsequent conversion of CO_2 to other products.

3.2.2 Air electrode

Of the 4400 terms analyzed, 143 met the threshold of occurring at least 8 times. Then, 86 terms were chosen as 60% of the most relevant terms. The top occurring terms are listed in Table 7 with the relevance score of each recurring term. The co-occurrence and the average publication years of the terms are presented in Figs. 10 and 11. The top 20 most cited articles on the air electrode of SOECs on average citations per year excluding reviews are presented in Table S3.

Except for the terms that do not have explicit meanings, the terms “delamination”, “interface”, “polarization”, and “surface” occur frequently and have higher relevance scores. It can be seen that delamination is a key issue when developing the air electrode of SOECs. Further, the $La_{0.6}Sr_{0.4}Co_{0.2}Fe_{0.8}O_{3-\delta}$ (LSCF) perovskite is the most used air-electrode catalyst. It is seen from the co-occurrence network in Fig. 10, the terms in the articles about the air electrode are more complex. It may be concluded that compared with articles about fuel electrodes focusing on the performance of the material itself, air-electrode-related articles focus more on the interaction of the electrodes with other components.

The delamination of the air electrodes during SOEC was a major degradation mechanism shortening the lifespan [108]. Therefore, researchers have done an intense investigation on this issue, and articles on delamination account for a relatively large portion of the highly cited articles in the field of air electrode research. However, it should be mentioned that the majority of reports on the degradation mechanisms of the air electrodes were published between 2011 and 2014. Chen & Jiang [109] found that the delamination of the $La_{0.8}Sr_{0.2}MnO_3$ (LSM) oxygen electrode could be a result of the disintegration of LSM particles at the electrode/

Table 7 Most occurring terms in articles related to the air electrode of SOECs

Term	Occurrence	Relevance score
Fuel cell	73	0.28
Analysis	48	0.99
Delamination	36	1.11
Electrolysis mode	30	0.25
Yttria	30	0.27
Formation	29	0.79
Interface	29	1.28
Mode	29	1.06
Polarization	29	1.42
SOEC mode	29	0.74
Surface	28	1.15
Solid oxide cell	27	0.70
Reversible solid oxide cell	25	0.99
Single cell	25	0.70
Steam electrolysis	24	0.41
Application	23	0.42
Nanoparticle	21	0.69
SOFC mode	21	1.28
Cathode	20	0.63
$La_{0.6}Sr_{0.4}Co_{0.2}Fe_{0.8}O_{3-\delta}$	19	0.28
Porosity	19	0.48

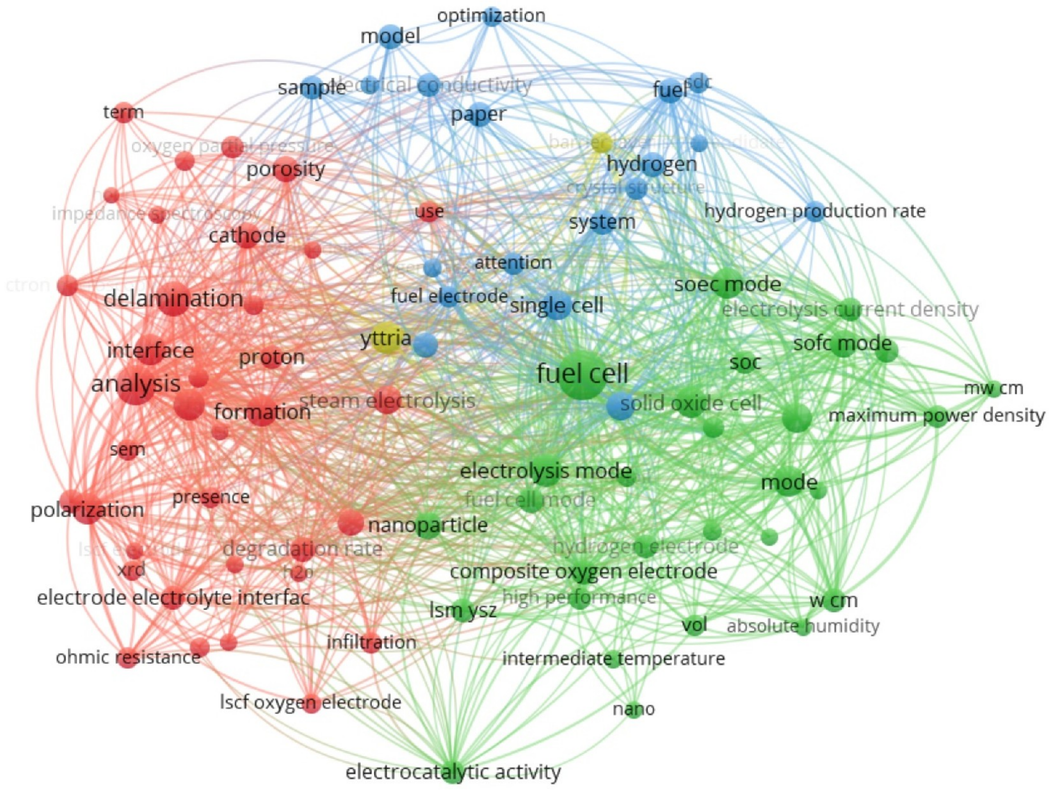


Fig. 10 Co-occurrence network of the terms appearing in articles related to the air electrode of SOECs.

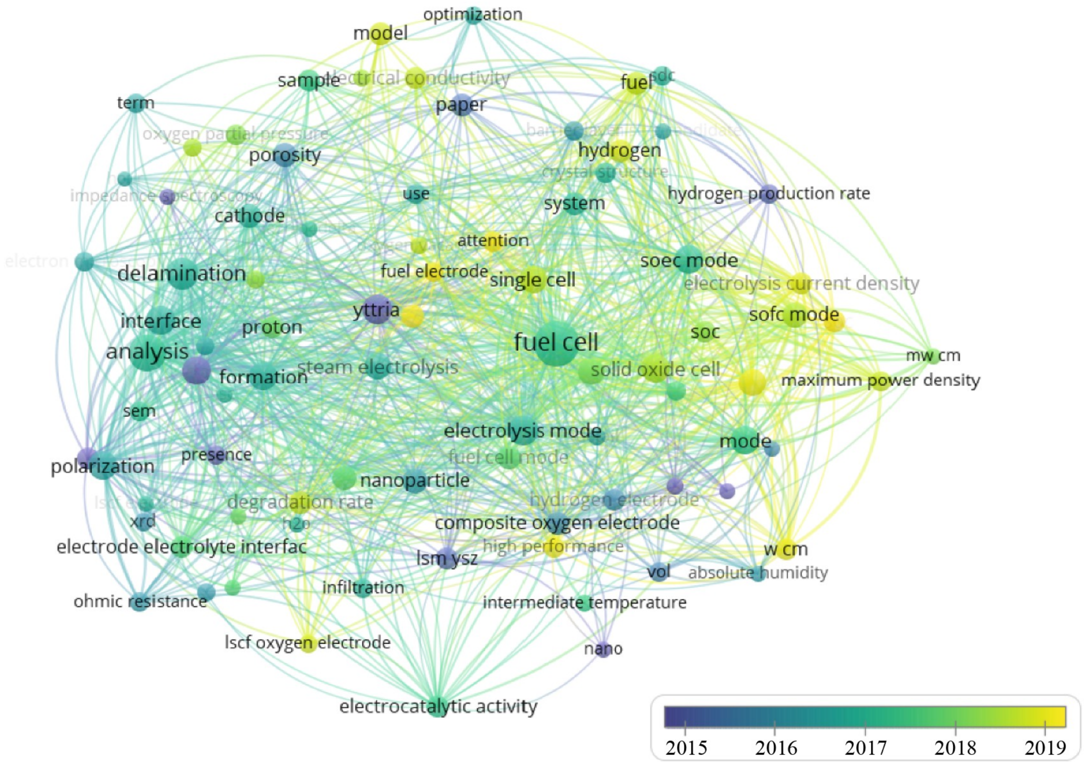


Fig. 11 Average publication years of the terms in articles on the air electrodes of SOECs.

electrolyte interface and the subsequent formation of LSM nanoparticles. Symmetric cells of the configuration air/LSM//YSZ//LSM/air were electrically tested by Keane et al. [110] to comprehend the delamination behavior of the anode. The formation of $La_2Zr_2O_7$ and morphological changes at the air electrode–electrolyte interface became more significant with higher applied bias. Based on the research, they proposed that the delamination was caused by complicated interfacial changes involving interfacial compound formation, YSZ grain boundary porosity development, and other morphological changes. Hjalmarsson et al. [111] compared the degradation of SOEC with two different oxygen electrodes. The first had an LSM-YSZ oxygen electrode and the second had a CGO inter-diffusion barrier positioned between the YSZ electrolyte and an LSCF-CGO oxygen electrode. The LSCF-GDC oxygen electrode showed a lower overall degradation perhaps mainly because of an electrochemically more stable bi-layer electrolyte. Park et al. [112] aimed to develop a quantitative understanding of oxygen electrode delamination. The modeling results showed that SOECs were prone to fail when the electrode overpotentials exceeded approximately 0.2 V, which could happen at higher current densities and lower operating temperatures. The main failure mechanism caused by these conditions is fracture at the electrode/electrolyte interface. Ai et al. [113] reported the successful direct assembly of a barrier-layer-free YSZ electrolyte, working as highly active and stable oxygen electrodes of SOECs.

After that, efforts were made more on developing new materials apart from traditional LSM and LSCF-based air electrodes, and the degradation of the air electrodes is less reported. Laguna-Bercero et al. [114] showcased the remarkable reversible performance and stability of a SOFC/SOEC when equipped with nickelate-based oxygen electrodes, $Pr_2NiO_{4+\delta}$ (PNO), even under the influence of a current load. The decomposition of $PrNiO_3$ and PrO_{2-y} was shown to be able to eliminate the deterioration in the electrochemical performance of the cell and even slightly enhanced the performance. There are also some highly cited articles about the material of the air electrode used in the proton-conducting SOECs. Li et al. [115] also investigated PNO as the air electrode for the proton-conducting SOECs, and found that PNO had a good compatibility with $BaZr_{0.2}Ce_{0.6}Y_{0.2}O_{3-\delta}$ (BZCY) proton-conducting electrolyte and an excellent catalytic activity toward water splitting, making it a promising air electrode. Yang et al. [116] synthesized $Ln_{1.2}Sr_{0.8}NiO_4$ (Ln = La, Pr) as the air electrode in proton-conducting SOECs, and demonstrated the good stability and high current density. Lei et al. [117] evaluated the performance of SFM as the air electrode for proton-conducting SOECs, and found that SFM had a good stability in an H_2O-containing atmosphere under operating conditions.

Table 8 Top recurring terms in articles related to the electrolyte of SOECs

Term	Occurrences	Relevance score
Fuel cell	32	0.14
Conductivity	29	0.51
Electrolysis	28	0.26
Zirconia	21	0.8
Degradation	17	0.79
Electrolysis mode	16	0.33
Addition	15	0.67
Property	15	0.71
Proton	15	1.07
YSZ electrolyte	15	0.79
Application	14	0.51
Atmosphere	14	0.77
Voltage	14	0.74
Microstructure	13	0.71
Technique	13	0.86
CO_2	12	1.13
Electrolyte material	12	1.35
Value	12	0.33
Yttria	12	1.08
Air	11	0.46
CO_2 electrolysis	11	0.9
Delamination	11	0.78
Increase	11	0.4

3.2.3 Electrolyte

Of the 2466 terms analyzed, 118 met the threshold of occurring at least 5 times. Then, the 60% of the most-occurring relevant terms (a total of 71 terms) are chosen to perform the analysis. Table 8 shows the top recurring terms with the relevance score of each recurring term. The co-occurrence and the average publication years of the terms are presented in Figs. 12 and 13. The top 20 articles with the highest average citations per year on electrolytes are exhibited in Table S4.

In the red and green clusters in Fig. 12, the terms such as “zirconia”, “YSZ electrolyte”, “oxygen electrode”, “hydrogen electrode”, “electrode electrolyte interface”, and “degradation”, co-occurred frequently. It can be inferred that the zirconia-based electrolytes are often investigated together with other components of a cell, and the performance and degradation of the electrolyte are highly affected by the electrodes. Laguna-Bercero et al. [118] tested SOFCs with an anode-supported, YSZ-based microtubular design in fuel cell mode and electrolysis mode and found that it produced irreversible degradation of the electrolyte in SOEC mode at high electrolysis voltages (> 1.8 V), caused by the YSZ electroreduction.

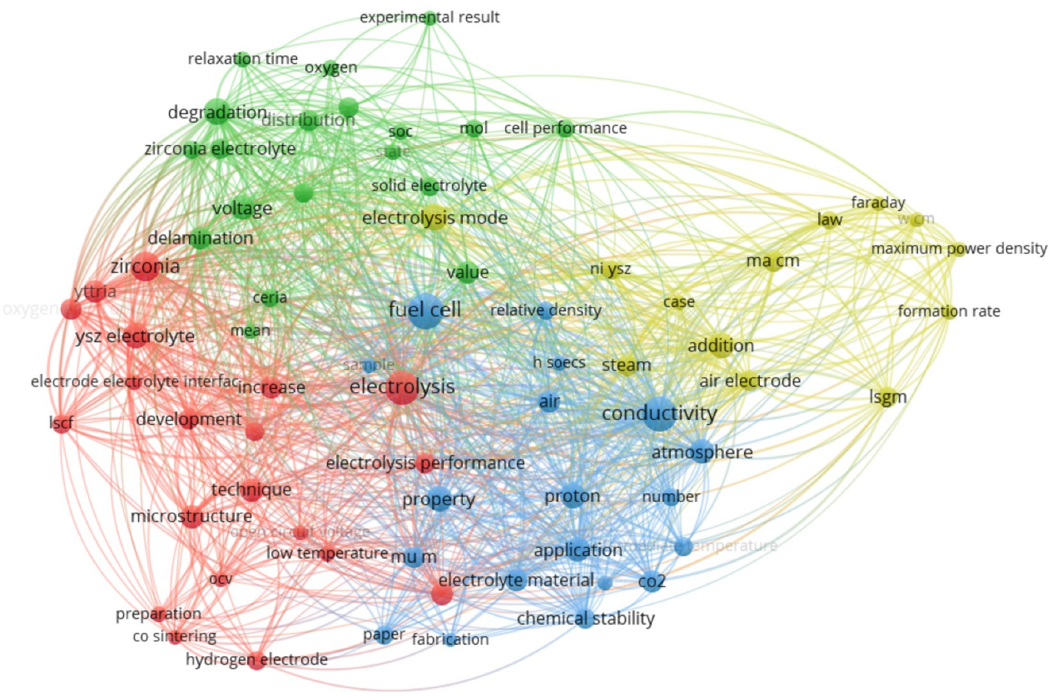


Fig. 12 Co-occurrence of the terms in articles on the electrolyte of SOECs.

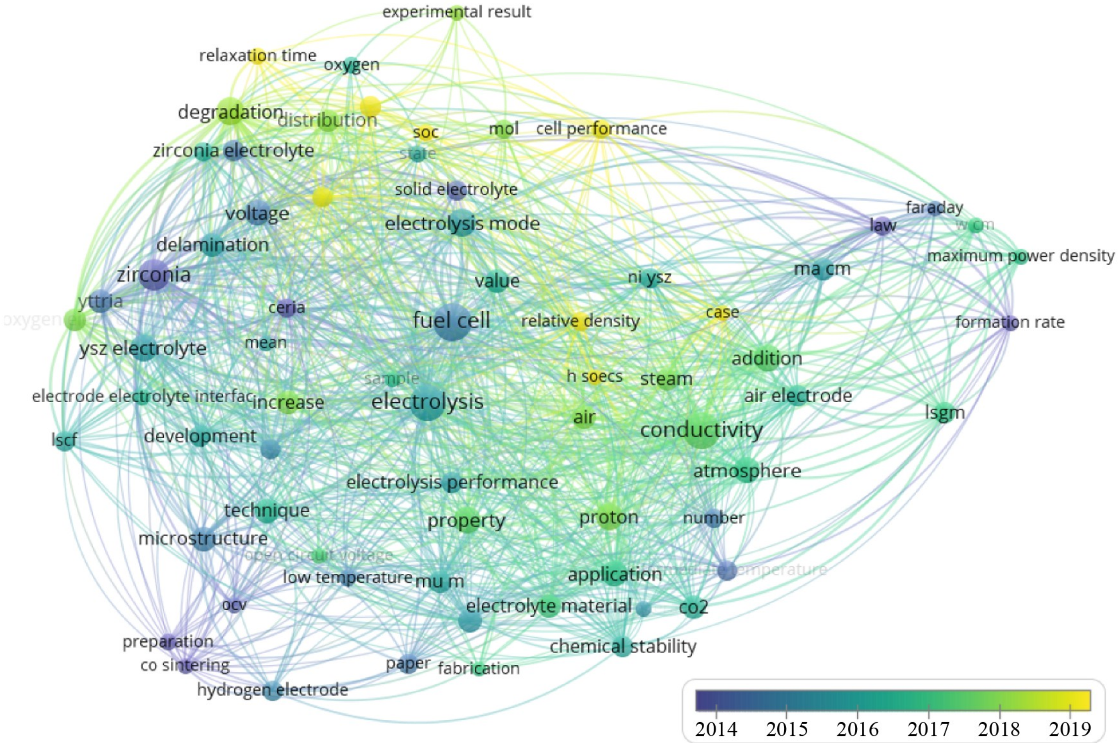


Fig. 13 Average publication years of the terms in articles on the electrolyte of SOECs.

Kim et al. [119] reported the degradation of the YSZ electrolyte in a three-electrode configuration, with LSM-YSZ as the working electrode. The degradation was linked to the deactivation of LSM and the densification of the air electrode, resulting in an undue buildup of pressure and the delamination of the air electrode. Propagation of intergranular fracture was found to occur along the YSZ grain boundaries. Apart from YSZ, novel $LaGaO_3$-based perovskite was also proposed to be used as the electrolyte for higher oxygen ion conductivity

[120]. An applied electrolysis potential of up to 2 V was demonstrated.

To lower the cost of cell fabrication, optimization of the electrolyte preparation process is another key point affecting the commercialization of the SOECs. Gao et al. [121] prepared anode-supported solid oxide cells (SOCs) with thin bi-layer $Y_{0.16}Zr_{0.92}O_{2-\delta}$ (YSZ)/$Gd_{0.1}Ce_{0.9}O_{1.95}$ (GDC) electrolytes by a reduced-temperature (1250 °C) co-firing process enabled by the addition of a Fe_2O_3 sintering aid. The addition of Fe_2O_3 and the reduction of the sintering temperature improved the performance of the solid oxide cells. Mehranjani et al. [122] added Fe_2O_3 in the co-sintering of the GDC/YSZ bilayer electrolyte prepared by tape-casting, increasing the total conductivity of the bilayer electrolyte by an order of magnitude.

In the blue cluster in Fig. 12, the terms such as “conductivity”, “proton”, “CO_2”, “electrolyte material”, and “chemical stability” co-occurred, implying that the articles in this cluster are mainly about the development of electrolyte for proton-conducting SOECs. Compared with the traditional oxygen-ion conducting electrolyte, the proton-conducting ceramic is still in its infancy, as the proton-conducting related terms only emerged in recent years (Fig. 13). Thus, attention is still paid to the characteristics of the electrolyte materials themselves, such as to improve the electrolyte conductivity and the electrolyte stability in a CO_2-contained atmosphere. Further, 6 of the top 20 articles with the highest average citations per year are related to proton-conducting SOECs, verifying the popularity of the research in proton-conducting SOECs.

Bi et al. [123] successfully, for the first time, fabricated a proton-conducting SOEC employing a Y-doped $BaZrO_3$ electrolyte, which was demonstrated to be chemically stable, and showed a promising electrolysis performance. Later, Lei et al. [117] evaluated the performance of a thin (approximately 16 µm in thickness) $BaZr_{0.8}Y_{0.2}O_{3-\delta}$ (BZY) electrolyte in proton-conducting SOECs, showing good stability in a H_2O-containing atmosphere under operating conditions for 100 h. To improve the stability of the Ce-doped $BaZrO_3$ electrolyte, Lyagaeva et al. [124] developed a novel electrolyte composed of $BaCe_{0.5}Zr_{0.3}Dy_{0.2}O_{3-\delta}$ (BCZD) and demonstrated promising output characteristics at 550–750 °C. Li et al. [125] proposed a bilayer electrolyte combining $BaZr_{0.1}Ce_{0.7}Y_{0.1}Yb_{0.1}O_{33-\delta}$ (BZCYYb) and $La_2Ce_2O_7$ (LCO) to create a high-performance and steam-tolerant electrolyte for proton-conducting SOECs. Rajendran et al. [126] proposed a new tri-doped $BaCe_{0.5}Zr_{0.2}Y_{0.1}Yb_{0.1}Gd_{0.1}O_{3-\delta}$ (BCZYYbGd) electrolyte with a very high chemical stability and proton conductivity. Coupled with a $PrNi_{0.5}Co_{0.5}O_{3-\delta}$ steam electrode and a Ni-BCZYYbGd hydrogen electrode, the full cell showed a good stability and was also found to be highly reversible.

3.2.4 Co-electrolysis

Of the 6314 terms analyzed, 156 met the threshold of occurring at least 10 times. Then, 60% of the most relevant terms (94 terms) were selected for further analysis. Table 9 gives the top recurring terms together with the relevance score. The co-occurrence and the average publication years of the terms are presented in Figs. 14 and 15. The top articles with high average citations per year on co-electrolysis using SOECs are shown in Table S5.

In the terms having a practical meaning, “model”, “efficiency”, “electrode”, “system”, “power”, “fuel”, “energy”, “electrolyte”, “electrochemical performance”, “degradation”, etc. occur frequently. It can be concluded that regarding co-electrolysis, the concerns of researchers are roughly divided into two categories: macro-performance focusing on system-level energy efficiency and micro-performance focusing on materials and stability, which are also demonstrated by the co-occurrence network (Fig. 14).

For experimental work, the cell and stack-level performance are focused on. Graves et al. [73] examined the initial performance and durability during co-electrolysis of CO_2 and H_2O using an SOEC, with Ni-YSZ fuel electrode and LSM air electrode. By analyzing the DRT (distribution of relaxation time) of the impedance data measured before and after the stability

Table 9 Most occurring terms in articles related to co-electrolysis using SOECs

Term	Occurrences	Relevance score
Production	101	0.36
°C	100	0.59
Model	96	0.51
Efficiency	82	0.39
Electrode	79	1.11
System	65	0.92
Power	58	1.1
Technology	58	0.49
Fuel	52	0.6
Energy	50	0.48
Paper	50	0.84
Electrolyte	49	0.5
Electrochemical performance	44	0.94
Degradation	43	1.31
Hydrogen	41	0.35
Electricity	40	0.86
Increase	39	0.48
Pressure	39	0.56
Stability	35	0.73
Fuel electrode	34	1.24

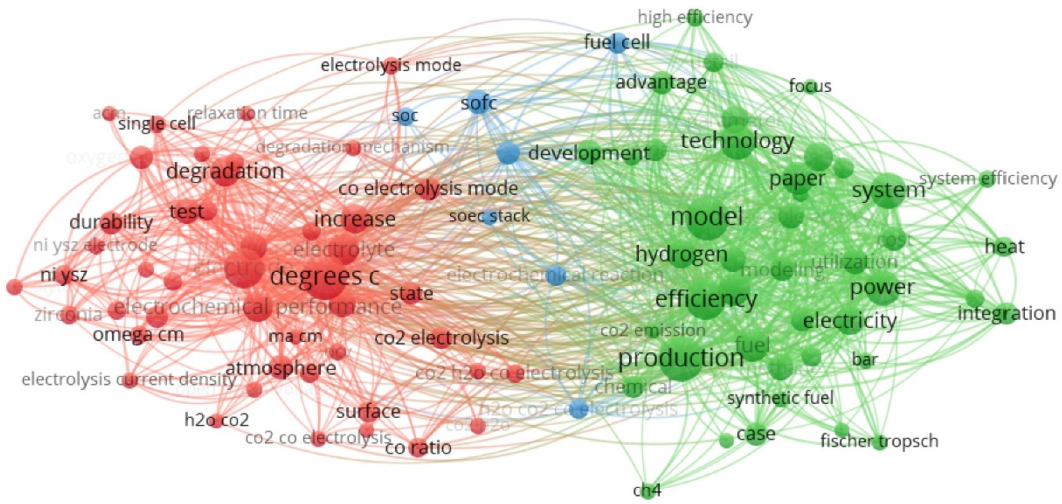


Fig. 14 Co-occurrence of the terms in articles on co-electrolysis using SOECs.

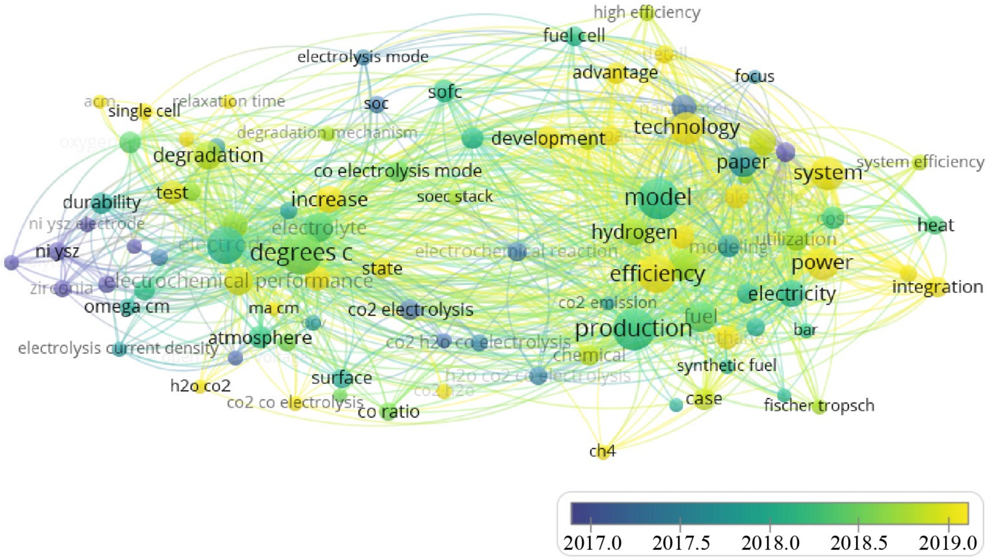


Fig. 15 Average publication years of the terms in articles on co-electrolysis using SOECs.

tests, the degradation mechanism was electrochemically investigated. It was found that degradation at the Ni-YSZ electrode dominated the low-current-density (−0.25 A cm^{-2}) operation, whereas the serial resistance and degradation at the LSM electrode began to play a major role at higher current densities (−0.5 and −1.0 A/cm^2), the Ni-YSZ electrode continued to degrade. Niu et al. [127] reported a novel category of double perovskite, $Sr_2Ti_{1-x}Co_xFeO_6$, as the electrodes for symmetric SOECs. The symmetric cell with a $Sr_2Ti_{0.8}Co_{0.2}FeO_6$ electrode showed a good electrochemical performance and stability for co-electrolysis of CO_2 and H_2O at intermediate temperatures. Apart from producing syngas made of CO and H_2, Chen et al. [128] designed a tubular reactor combining the CO_2–H_2O co-electrolysis and methanation for direct synthesis of CH_4 from CO_2–H_2O feedstock and demonstrated a CH_4 yield of 11.84%. Deka et al. [129] doped Ni and Co into the A-site deficient perovskite, $La_{0.7}Sr_{0.2}FeO_3$, to form $La_{0.7}Sr_{0.2}Ni_xCo_yFe_{1-x-y}O_3$, to be used as cathodes of SOECs in the co-electrolysis of CO_2 and H_2O at 800 °C. With a proton-conducting SOEC, Pan et al. [130] successfully experimentally demonstrated a direct electrochemical co-conversion of CO_2–H_2O to methane, with a CH_4 yield ratio of up to 70%, at 450 °C. On the stack level, Ebbesen et al. [131] investigated the co-electrolysis of CO_2 and H_2O using SOEC stacks having Ni-YSZ fuel electrodes and LSM-YSZ air electrodes. The findings indicated that minute concentrations (at the 10^{-9} level) of impurities in the inlet gases play an important role in the durability of these electrolysis stacks. Purifying the inlet gases supplied to the Ni/YSZ electrode is essential to achieve stable operation without any long-term degradation.

In modeling, the cell and system level are focused on. At the cell level, a 0D model and 2D model were successively developed by Ni [132,133] to study the chemical/electrochemical reactions and the heat/mass transfer in an SOEC for CO_2 and H_2O co-electrolysis. At the system level, Becker et al. [134] presented a system-level model for high-temperature co-electrolysis of CO_2 and H_2O using SOEC for syngas production and subsequent conversion to liquid fuels by a Fischer-Tropsch (F-T) process. Giglio et al. [135] compared the performances of two different plants with high-temperature electrolysis followed by catalytic methanation. One of the plants was involved with pure steam electrolysis while the other plant was involved in co-electrolysis of steam and carbon dioxide. The co-electrolysis plant demonstrated a lower heating value (LHV) efficiency of 81.4%, surpassing the steam electrolysis case by more than five percentage points (76%). Sun et al. [136] presented a thermodynamic analysis of synthetic methane and dimethyl ether (DME) production using pressurized SOECs, in order to determine feasible operating conditions for producing the desired hydrocarbon fuel and avoiding damage to the SOEC stacks.

Table 10 Most frequently occurring terms in articles related to proton-conducting SOECs

Term	Occurrences	Relevance score
Reaction	20	0.60
Fuel cell	20	0.39
Production	17	0.50
Process	15	0.76
Pressure	14	0.78
Atmosphere	13	0.83
Electrolyte material	12	0.77
Air electrode	11	0.86
Air	11	0.78
Rate	11	0.48
CO_2	10	1.65
Conversion	10	1.43
Steam electrolysis	10	0.96
Cathode	9	1.32
H-SOEC	9	0.97
Proton conductivity	9	0.72
Oxygen electrode	8	1.00
Ceramic	8	0.83
mA/cm^2	8	0.69
Electrochemical performance	8	0.68
Advantage	8	0.53

3.2.5 Proton-conducting

As mentioned above, the research on proton-conducting SOEC has been popular in recent years. Therefore, the co-occurrence network and the high-cited articles on proton-conducting SOEC are also analyzed. In total, 97 of the 1928 terms met the threshold of occurring at least 4 times, and 44 terms were selected for further analysis. The top recurring terms are presented in Table 10 together with the relevance score. The co-occurrence and the average publication years of the terms are presented in Figs. 16 and 17 (The 97 terms meeting the threshold are all shown in the co-occurrence network due to the small amounts of the articles and the terms.). The top articles with high average citations per year on proton-conducting SOECs are shown in Table S6.

Except for the terms having no specific meaning, the terms “reaction”, “pressure”, “atmosphere”, “electrolyte material”, “air electrode”, “CO_2”, and “proton conductivity” occur frequently. This agrees with the discussions made in Section 3.2.3. The studies on proton-conducing SOEC are still at an early stage and the most concerns are on the material development, the electrochemical performance, and the stability at the cell level.

Apart from the work that has been mentioned before, He et al. [137] improved the performance of a proton-conducting SOEC by successfully fabricating cells with reduced thickness of the $BaCe_{0.5}Zr_{0.3}Y_{0.2}O_{3-\delta}$ electrolyte. The performance and the operating mode reversibility of the cell were characterized by various reacting atmospheres. Wu et al. [138] developed a self-architectured ultra porous 3D fuel electrode for efficient proton-conducting SOECs working below 600 °C. A high current density and good stability were demonstrated. From a modeling perspective, Munoz-Garcia & Pavone [139] employed the first-principle methods (DFT + U) to design a new single-phase triple-conducting oxide based on the well-tested mixed ion-electron conductive electrocatalyst $Sr_2Fe_{1.5}Mo_{0.5}O_{6-\delta}$ (SFM) double perovskite, aiming at promoting the proton transport. Key processes including the formation of oxygen vacancies, the water dissociative incorporation, and the proton transfer along the oxide sublattice were considered. At the cell level, Lei et al. [140] proposed a heterogeneous design for proton-conducting SOECs, with different proton conducting materials for the electrolyte and in the fuel electrode. In the heterogeneous design, a better stability and a higher efficiency of electrolysis cells could be achieved synchronously. Kim et al. [87] reported a SOEC based on a mixed-ion conductor capable of simultaneously transporting both oxygen ions and protons. This innovative design, referred to as “hybrid-SOEC,” demonstrated a remarkable feature by maintaining consistent performance for over 60 h of continuous operation without any noticeable degradation.

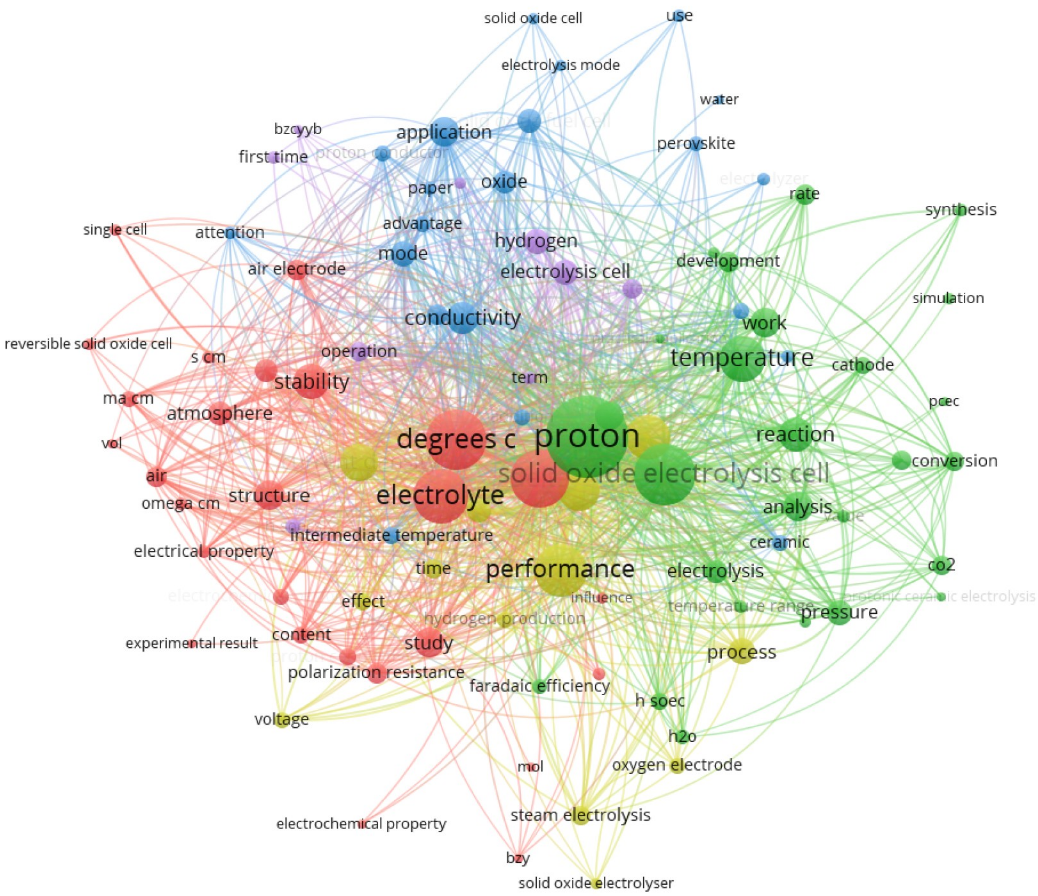


Fig. 16 Co-occurrence of the terms in articles on proton-conducting SOECs.

This suggests that the Hybrid-SOEC is a robust system for hydrogen production.

3.2.6 Modeling

To understand what has been studied in SOEC through modeling, the co-occurrence network and the high-cited articles of SOEC modeling are also analyzed. Of the 8169 terms, 171 terms met the threshold of occurring at least 10 times, and 60% of the most relevant terms were chosen. The top recurring terms are presented in Table 11 together with the relevance score. The co-occurrence and the average publication years of the terms are presented in Figs. 18 and 19. The top articles with high average citations per year on the modeling of SOECs are shown in Table S7.

Similar to co-electrolysis studies, the terms of articles about modeling can also be roughly divided into two categories, one category being more macro and the other more micro. Overall, so far as the study on the model of SOECs is concerned, the study on the system is more recent than that on the microstructure. In the terms having specific meanings, “efficiency”, “system”, “electrode”, “energy”, “power”, etc. occurred more frequently. The more occurrence of the terms “efficiency” and “system” than other terms may also signify that the modeling of SOECs focuses more on the macro system-level performance. It is worth mentioning that economic analysis of SOECs seems to have become popular in recent years, as reflected by the terms, “economic analysis” and “cost”.

At the system level, apart from the modeling studied by Graves et al. [73] mentioned before, Jensen et al. [88] introduced an innovative storage approach that combines recent advancements in SOECs with subsurface storage of CO_2 and CH_4. This integrated method enhanced the round-trip efficiency of large-scale electricity storage, which was over 10%, and the storage cost was estimated to be comparable to that of pumped hydro storage. Habibollahzade et al. [89] proposed a novel configuration consisting of a biomass-based anode/cathode recycling SOFC integrated with a gas turbine and SOEC. The system proposed was subject to analysis and comparison from energy, exergy, and exergoeconomic perspectives through a parametric study involving various gasification agents. Tian et al. [90] integrated a solar chimney with SOFC and SOEC to store surplus energy as hydrogen for nighttime use. They also introduced an enhanced iteration

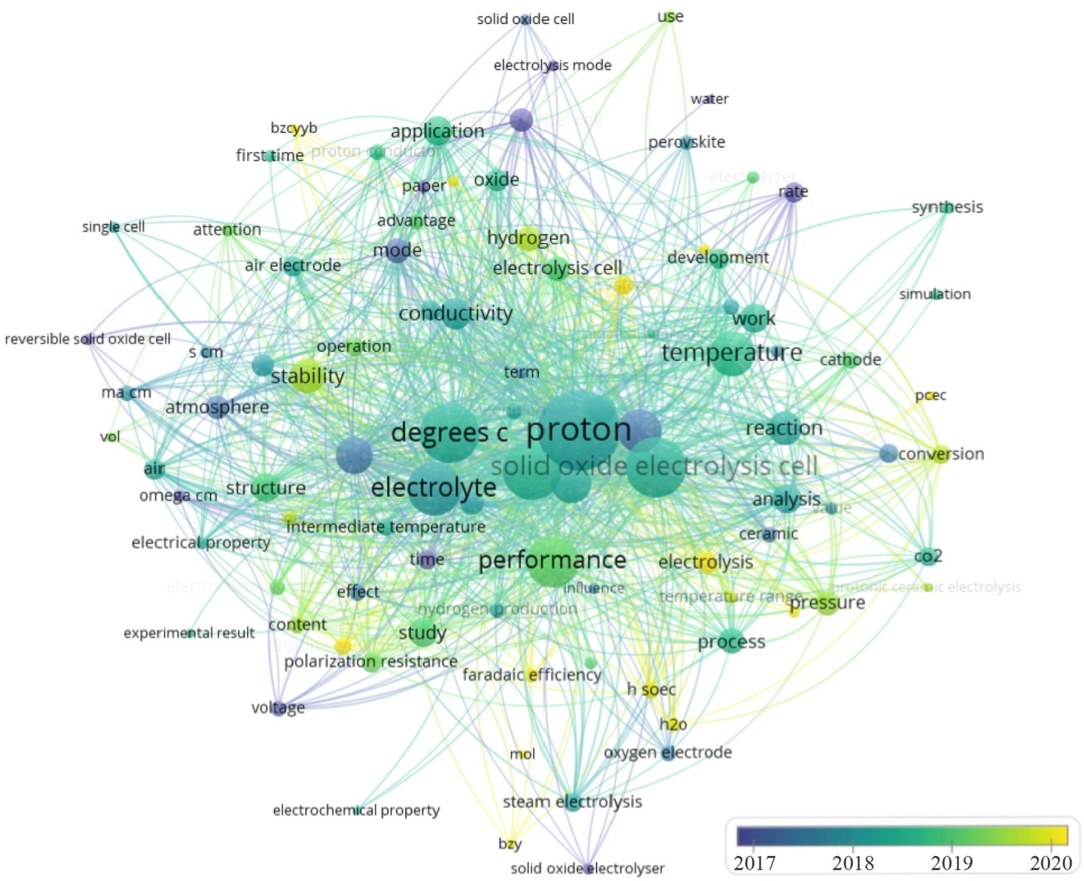


Fig. 17 Average publication years of the terms in articles on proton-conducting SOECs.

of the deer hunting optimization algorithm. The optimal selection of the system parameters based on economic analysis was performed with the MATLAB platform and the results were compared with that of the genetic algorithm and particle swarm optimization algorithm. Salomone et al. [141] investigated the coupling between a completely renewable-energy-source-based electric profile in a future scenario and a power-to-gas plant and performed a comprehensive technical, managemental, and economic assessment of the system. Mastropasqua et al. [142] also made a techno-economic analysis of SOEC water electrolysis coupled with a parabolic dish solar field. The system presented a designed SOEC efficiency greater than 80% and thus a solar-to-hydrogen efficiency greater than 30%. The LCOH was expected to be between 5.9 and 9.1 €/kg(H_2), not competitive with other H_2 production routes but in line with other solar-to-hydrogen solutions.

At the cell level, Udagawa et al. [143] reported the development of a one-dimensional dynamic model of an SOEC stack with cathode-supported planar cells. The model, which consisted of an electrochemical model, a mass balance, and four energy balances, was employed to study the steady-state behavior of the stack at different operating conditions. Stoots et al. [144] conducted a comparison between the exponential results and the predictions derived from a chemical equilibrium model on high-temperature electrolysis of H_2O and co-electrolysis of CO_2 and H_2O. The results indicated an excellent agreement between the predicted and the measured outlet compositions. Cinti et al. [145] developed the concept of integrating an SOEC and a Fischer-Tropsch process in a small plant size, which was compatible with the power output of renewable energy. Based on the experimental results of an SOC stack operated in a co-electrolysis mode, three system-level models were developed to evaluate the most promising option. Aiming at producing hydrogen from solar energy, AlZahrani et al. [146] integrated the solar tower technology, thermal energy storage with a power plant and a high-temperature SOEC. The hydrogen production was evaluated based on different cell and solar field operating conditions.

4 Conclusions

The technology of SOECs is an encouraging and promising alternative that converts electrical energy into chemical energy with a high efficiency and no

Table 11 Most occurring terms in articles related to modeling of SOECs

Term	Occurrences	Relevance score
Efficiency	125	0.34
System	118	0.58
Production	111	0.18
Electrode	90	1.70
Hydrogen	81	0.45
Energy	74	0.36
Technology	72	0.36
Solid oxide fuel cell	71	0.54
°C	68	0.48
Power	67	0.74
Voltage	56	0.41
Mechanism	55	1.30
Cathode	52	0.50
Electricity	50	0.60
Distribution	49	0.69
Cost	45	1.32
Concentration	42	0.77
Solid oxide cell	41	0.75
Heat	40	0.84
Increase	40	0.76
Storage	40	0.52

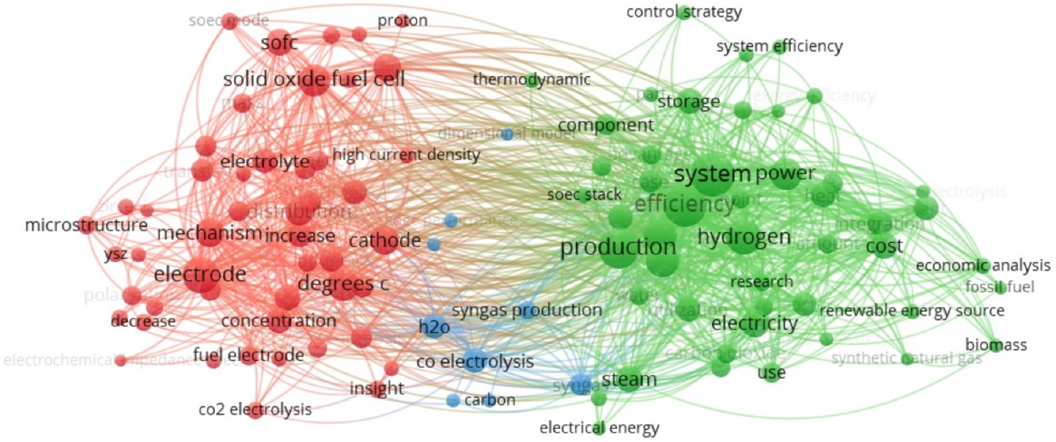


Fig. 18 Co-occurrence of the terms in articles on modeling of SOECs.

environmental damage. An initial step involves conducting a scientometric analysis of all published articles in the field of SOECs to identify research trends. A total of 1279 high-quality articles published between 1983 and 2023 were retrieved and analyzed. Notably, the number of articles published per year in this field continues to grow.

The findings from the scientometric analysis have contributed to the identification and generation of various research themes that are commonly explored in the context of SOECs. In the research of fuel electrodes, the stability of the materials is the most concerned, while in the research of air electrodes, articles related to delamination account for a high proportion. Moreover, CO_2 electrolysis and H-SOECs are two popular research topics of SOECs recently.

This paper offers a thorough overview of the research and development of SOECs, serving as a valuable resource for students, SOEC research enthusiasts, funding sponsors, and government policymakers to stay

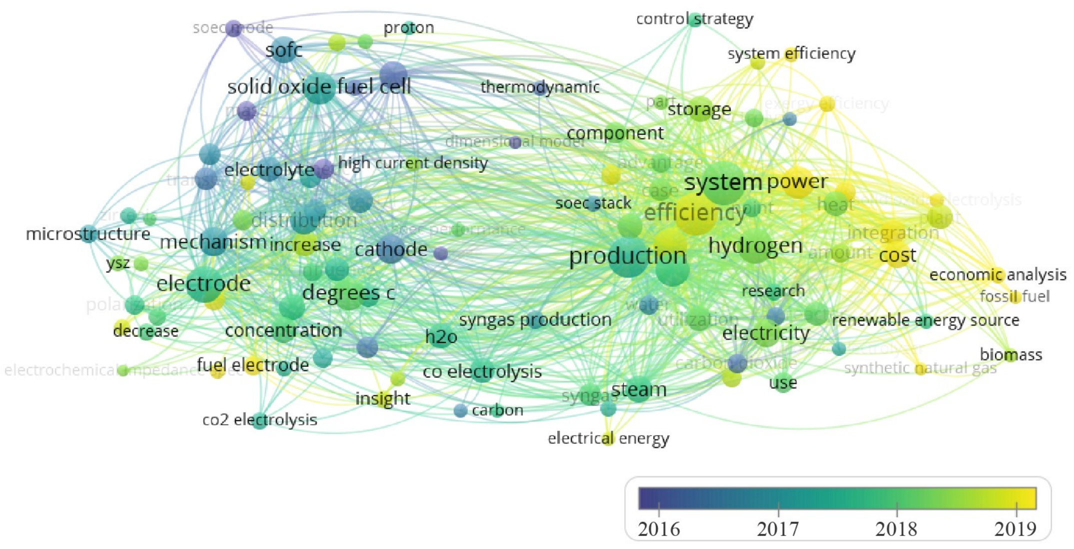


Fig. 19 Average publication years of the terms in articles on modeling of SOECs.

informed about the trends, advancements, and future of SOECs and their various research areas. Nonetheless, it is important to note that this paper only provides a high-level summary and general introduction of the research topics involved in the different aspects of SOEC development, without delving into the specific details of the articles.

Acknowledgements This work was supported by the National Natural Science Foundation of China (Grant Nos. 52102226 and 11932005), the Department of Education of Guangdong Province, China (Grant Nos. 2021KCXTD006 and 2021KQNCX272), the Science, Technology and Innovation Commission of Shenzhen Municipality, China (Grant Nos. GJHZ20220913143009017, JCYJ20210324120404013, and GXWD20220811165757005), and the Development and Reform Commission of Shenzhen Municipality, China (Grant No. XMHT20220103004).

Electronic Supplementary Material Supplementary material is available in the online version of this article at https://doi.org/10.1007/s11708-024-0945-5 and is accessible for authorized users.

Competing Interests The authors declare that they have no competing interests.

References

1. Trattner A, Klell M, Radner F. Sustainable hydrogen society—Vision, findings and development of a hydrogen economy using the example of Austria. International Journal of Hydrogen Energy, 2022, 47(4): 2059–2079
2. Liu X, Yan Z, Wu J, et al. Prediction of impedance responses of protonic ceramic cells using artificial neural network tuned with the distribution of relaxation times. Journal of Energy Chemistry, 2023, 78: 582–588
3. Kim C, Cho S H, Cho S M, et al. Review of hydrogen infrastructure: The current status and roll-out strategy. International Journal of Hydrogen Energy, 2023, 48(5): 1701–1716
4. Guo Q, Geng J, Pan J, et al. Brief review of hydrocarbon-reforming catalysts map for hydrogen production. Energy Reviews, 2023, 2(3): 100037
5. Calandra D, Wang T, Cane M, et al. Management of hydrogen mobility challenges: A systematic literature review. Journal of Cleaner Production, 2023, 410: 137305
6. Zheng Y, Wang S, Pan Z, et al. Electrochemical CO_2 reduction to CO using solid oxide electrolysis cells with high-performance Ta-doped bismuth strontium ferrite air electrode. Energy, 2021, 228: 120579
7. Pan Z, Shi H, Wang S, et al. Highly active and stable A-site Pr-doped LaSrCrMnO-based fuel electrode for direct CO_2 solid oxide electrolyzer cells. International Journal of Hydrogen Energy, 2020, 45(29): 14648–14659
8. Hu S, Li H, Dong X, et al. Rational design of CO_2 electroreduction cathode via *in situ* electrochemical phase transition. Journal of Energy Chemistry, 2022, 66: 603–611
9. Liu R. The world’s first offshore wind power non-desalination of seawater in situ electrolysis for hydrogen production successfully tested in Fujian, China. Frontiers in Energy, 2023, 17(3): 317–319
10. Akdağ O. The operation and applicability to hydrogen fuel technology of green hydrogen production by water electrolysis using offshore wind power. Journal of Cleaner Production, 2023, 425: 138863
11. Zheng Y, Wang J, Yu B, et al. A review of high temperature co-electrolysis of H_2O and CO_2 to produce sustainable fuels using solid oxide electrolysis cells (SOECs): Advanced materials and technology. Chemical Society Reviews, 2017, 46(5): 1427–1463
12. Zhuang Z, Li Y, Yu R, et al. Reversely trapping atoms from a perovskite surface for high-performance and durable fuel cell cathodes. Nature Catalysis, 2022, 5: 300–310
13. Pan Z, Shen J, Wang J, et al. Thermodynamic analyses of a standalone diesel-fueled distributed power generation system based on solid oxide fuel cells. Applied Energy, 2022, 308:

118396

14. Yang X, Yin Y, Yu S, et al. Gluing $Ba_{0.5}Sr_{0.5}Co_{0.8}Fe_{0.2}O_{3-\delta}$ with Co_3O_4 as a cathode for proton-conducting solid oxide fuel cells. Science China Materials, 2023, 66(3): 955–963
15. Teng Z, Han M. Significant potential of Solid Oxide Fuel Cell systems for distributed power generation and carbon neutrality. Frontiers in Energy, 2022, 16(6): 879–882
16. Liang F, Pan Z, Wang H, et al. Scalable and facile fabrication of tri-layer electrolytes by reactive sputtering for efficient and durable solid oxide fuel cells. Chemical Engineering Journal, 2024, 484: 149523
17. Sai W, Pan Z, Liu S, et al. Event-driven forecasting of wholesale electricity price and frequency regulation price using machine learning algorithms. Applied Energy, 2023, 352: 121989
18. Min G, Choi S, Hong J. A review of solid oxide steam-electrolysis cell systems: Thermodynamics and thermal integration. Applied Energy, 2022, 328: 120145
19. Jolaoso L A, Bello I T, Ojelade O A, et al. Operational and scaling-up barriers of SOEC and mitigation strategies to boost H2 production- a comprehensive review. International Journal of Hydrogen Energy, 2023, 48(85): 33017–33041
20. Wang W, Tian Y, Liu Y, et al. Tailored Sr–Co-free perovskite oxide as an air electrode for high-performance reversible solid oxide cells. Science China Materials, 2021, 64(7): 1621–1631
21. Biswas S, Kaur G, Paul G, et al. A critical review on cathode materials for steam electrolysis in solid oxide electrolysis. International Journal of Hydrogen Energy, 2023, 48(34): 12541–12570
22. Li H Y, Kamlungsua K, Shin J, et al. Boosting the performance in steam electrolysis of solid oxide electrolysis cell by potassium-doping in $Sr_2Fe_{1.5}Mo_{0.5}O_{6-\delta}$ cathode. Journal of Cleaner Production, 2023, 424: 138747
23. Zheng Y, Li Y, Wu T, et al. Controlling crystal orientation in multilayered heterostructures toward high electro-catalytic activity for oxygen reduction reaction. Nano Energy, 2019, 62: 521–529
24. Li F, Li Y, Chen H, et al. Impact of strain-induced changes in defect chemistry on catalytic activity of $Nd_2NiO_{4+\delta}$ electrodes. ACS Applied Materials & Interfaces, 2018, 10(43): 36926–36932
25. Zheng Y, Zhao C, Li Y, et al. Directly visualizing and exploring local heterointerface with high electro-catalytic activity. Nano Energy, 2020, 78: 105236
26. Li Y, Zhang W, Wu T, et al. Segregation induced self-assembly of highly active perovskite for rapid oxygen reduction reaction. Advanced Energy Materials, 2018, 8(29): 1801893
27. Song Y, Kim H, Jang J H, et al. Pt3Ni alloy nanoparticle electro-catalysts with unique core-shell structure on oxygen-deficient layered perovskite for solid oxide cells. Advanced Energy Materials, 2023, 13(42): 2302384
28. Yu C, Pan Z, Zhang H, et al. Numerical multi-physical optimization of operating condition and current collecting setup for large-area solid oxide fuel cells. Frontiers in Energy, 2024, early access, https://doi.org/doi:10.1007/s11708-023-0919-z
29. Liu H, Clausen L R, Wang L, et al. Pathway toward cost-effective green hydrogen production by solid oxide electrolyzer. Energy & Environmental Science, 2023, 16(5): 2090–2111
30. Prosser J H, James B D, Murphy B M, et al. Cost analysis of hydrogen production by high-temperature solid oxide electrolysis. International Journal of Hydrogen Energy, 2024, 49: 207–227
31. Harman J, Hjalmarsson P, Mermelstein J, et al. 1 MW-class solid oxide electrolyser system prototype for low-cost green hydrogen. ECS Transactions, 2021, 103(1): 383–392
32. Liu G, Kupecki J, Deng Z, et al. Efficiency analysis of a novel reversible solid oxide cell system with the secondary utilization of the stack off-gas: A model-based study. Journal of Cleaner Production, 2023, 397: 136570
33. Li Y, Li Y, Zhang S, et al. Mutual conversion of $CO-CO_2$ on a perovskite fuel electrode with endogenous alloy nanoparticles for reversible solid oxide cells. ACS Applied Materials & Interfaces, 2022, 14(7): 9138–9150
34. Li Y, Singh M, Zhuang Z, et al. Efficient reversible CO/CO_2 conversion in solid oxide cells with a phase-transformed fuel electrode. Science China Materials, 2021, 64(5): 1114–1126
35. Lin W, Su W, Li Y, et al. Enhancing electrochemical CO_2 reduction on perovskite oxide for solid oxide electrolysis cells through *in situ* A-site deficiencies and surface carbonate deposition induced by lithium cation doping and exsolution. Small, 2023, 19(41): 2303305
36. Monaco F, Lanzini A, Santarelli M. Making synthetic fuels for the road transportation sector via solid oxide electrolysis and catalytic upgrade using recovered carbon dioxide and residual biomass. Journal of Cleaner Production, 2018, 170: 160–173
37. Hauch A, Küngas R, Blennow P, et al. Recent advances in solid oxide cell technology for electrolysis. Science, 2020, 370(6513): eaba6118
38. Cao J, Li Y, Zheng Y, et al. A novel solid oxide electrolysis cell with micro-/nano channel anode for electrolysis at ultra-high current density over 5 A cm^{-2}. Advanced Energy Materials, 2022, 12(28): 2200899
39. Wang Y, Ge X, Lu Q, et al. Accelerated deprotonation with a hydroxy-silicon alkali solid for rechargeable zinc-air batteries. Nature Communications, 2023, 14(1): 6968
40. Wang Y, Lu Q, Li F, et al. Atomic-scale configuration enables fast hydrogen migration for electrocatalysis of acidic hydrogen evolution. Advanced Functional Materials, 2023, 33(43): 2213523
41. Zhang W, Liu M, Gu X, et al. Water electrolysis toward elevated temperature: Advances, challenges and frontiers. Chemical Reviews, 2023, 123(11): 7119–7192
42. Subotić V, Hochenauer C. Analysis of solid oxide fuel and electrolysis cells operated in a real-system environment: State-of-the-health diagnostic, failure modes, degradation mitigation and performance regeneration. Progress in Energy and Combustion Science, 2022, 93: 101011
43. Nechache A, Hody S. Alternative and innovative solid oxide electrolysis cell materials: A short review. Renewable & Sustainable Energy Reviews, 2021, 149: 111322
44. Jiang Y, Chen F, Xia C. A review on cathode processes and materials for electro-reduction of carbon dioxide in solid oxide electrolysis cells. Journal of Power Sources, 2021, 493: 229713

45. Cao J, Su C, Ji Y, et al. Recent advances and perspectives of fluorite and perovskite-based dual-ion conducting solid oxide fuel cells. Journal of Energy Chemistry, 2021, 57: 406–427
46. Ye L, Xie K. High-temperature electrocatalysis and key materials in solid oxide electrolysis cells. Journal of Energy Chemistry, 2021, 54: 736–745
47. Gao Y, Zhang M, Fu M, et al. A comprehensive review of recent progresses in cathode materials for proton-conducting SOFCs. Energy Reviews, 2023, 2(3): 100038
48. Khan M S, Xu X, Knibbe R, et al. Air electrodes and related degradation mechanisms in solid oxide electrolysis and reversible solid oxide cells. Renewable & Sustainable Energy Reviews, 2021, 143: 110918
49. Wang Y, Li W, Ma L, et al. Degradation of solid oxide electrolysis cells: Phenomena, mechanisms, and emerging mitigation strategies—A review. Journal of Materials Science and Technology, 2020, 55: 35–55
50. Chen K, Jiang S P. Surface segregation in solid oxide cell oxygen electrodes: Phenomena, mitigation strategies and electrochemical properties. Electrochemical Energy Reviews, 2020, 3(4): 730–765
51. Li Z, Zhang H, Xu H, et al. Advancing the multiscale understanding on solid oxide electrolysis cells via modelling approaches: A review. Renewable & Sustainable Energy Reviews, 2021, 141: 110863
52. Küngas R. Review—Electrochemical CO_2 reduction for CO production: Comparison of low- and high-temperature electrolysis technologies. Journal of the Electrochemical Society, 2020, 167(4): 044508
53. Lv X, Chen M, Xie Z, et al. Electrochemical conversion of C1 molecules to sustainable fuels in solid oxide electrolysis cells. Chinese Journal of Catalysis, 2022, 43(1): 92–103
54. Song Y, Zhang X, Xie K, et al. High-temperature CO_2 electrolysis in solid oxide electrolysis cells: Developments, challenges, and prospects. Advanced Materials, 2019, 31(50): 1902033
55. Gu J, Zhang X, Zhao Y, et al. Advances and challenges in symmetrical solid oxide electrolysis cells: Materials development and resource utilization. Materials Chemistry Frontiers, 2023, 7(18): 3904–3921
56. Tian Y, Abhishek N, Yang C, et al. Progress and potential for symmetrical solid oxide electrolysis cells. Matter, 2022, 5(2): 482–514
57. Tucker M C. Progress in metal-supported solid oxide electrolysis cells: A review. International Journal of Hydrogen Energy, 2020, 45(46): 24203–24218
58. Lei L, Zhang J, Yuan Z, et al. Progress report on proton conducting solid oxide electrolysis cells. Advanced Functional Materials, 2019, 29(37): 1903805
59. Medvedev D. Trends in research and development of protonic ceramic electrolysis cells. International Journal of Hydrogen Energy, 2019, 44(49): 26711–26740
60. Liu F, Ding D, Duan C. Protonic ceramic electrochemical cells for synthesizing sustainable chemicals and fuels. Advanced Science, 2023, 10(8): 2206478
61. Cobo M J, López-Herrera A G, Herrera-Viedma E, et al. Science mapping software tools: Review, analysis, and cooperative study among tools. Journal of the American Society for Information Science and Technology, 2011, 62(7): 1382–1402
62. Zhang L, Han K, Wang Y, et al. A bibliometric analysis of Stirling engine and in-depth review of its application for energy supply systems. Energy Reviews, 2023, 2(4): 100048
63. Khatun R, Xiang H, Yang Y, et al. Bibliometric analysis of research trends on the thermochemical conversion of plastics during 1990–2020. Journal of Cleaner Production, 2021, 317: 128373
64. Bello I T, Zhai S, He Q, et al. Scientometric review of advancements in the development of high-performance cathode for low and intermediate temperature solid oxide fuel cells: Three decades in retrospect. International Journal of Hydrogen Energy, 2021, 46(52): 26518–26536
65. Pilkington A. Bibexcel-Quick Start Guide to Bibliometrics and Citation Analysis. London: World Scientific Publishing, 2018
66. Liu X, Zhang J, Guo C. Full-text citation analysis: A new method to enhance scholarly networks. Journal of the American Society for Information Science and Technology, 2013, 64(9): 1852–1863
67. Van Eck, N, Waltman L. Software survey: VOSviewer, a computer program for bibliometric mapping. Scientometrics, 2010, 84(2): 523–538
68. Ozsari I. Trend analysis and evaluation of hydrogen energy and hydrogen storage research. Energy Storage, 2023, 5(6): e471
69. Raman R, Nair V K, Prakash V, et al. Green-hydrogen research: What have we achieved, and where are we going? Bibliometrics analysis Energy Reports, 2022, 8: 9242–9260
70. Wu S, Xu X, Li X, et al. High-performance proton-conducting solid oxide fuel cells using the first-generation Sr-doped $LaMnO_3$ cathode tailored with Zn ions. Science China Materials, 2022, 65(3): 675–682
71. Li Z, Zhang H, Xu H, et al. Advancing the multiscale understanding on solid oxide electrolysis cells via modelling approaches: A review. Renewable & Sustainable Energy Reviews, 2021, 141: 110863
72. Graves C, Ebbesen S D, Jensen S H, et al. Eliminating degradation in solid oxide electrochemical cells by reversible operation. Nature Materials, 2015, 14(2): 239–244
73. Graves C, Ebbesen S D, Mogensen M. Co-electrolysis of CO_2 and H_2O in solid oxide cells: Performance and durability. Solid State Ionics, 2011, 192(1): 398–403
74. Tietz F, Sebold D, Brisse A, et al. Degradation phenomena in a solid oxide electrolysis cell after 9000 h of operation. Journal of Power Sources, 2013, 223: 129–135
75. Knibbe R, Traulsen M L, Hauch A, et al. Solid oxide electrolysis cells: Degradation at high current densities. Journal of the Electrochemical Society, 2010, 157(8): B1209–B1217
76. Trini M, Hauch A, De Angelis S, et al. Comparison of microstructural evolution of fuel electrodes in solid oxide fuel cells and electrolysis cells. Journal of Power Sources, 2020, 450: 227599
77. Hauch A, Ebbesen S D, Jensen S H, et al. Solid oxide electrolysis cells: Microstructure and degradation of the Ni/yttria-stabilized zirconia electrode. Journal of the

Electrochemical Society, 2008, 155(11): B1184–B1193

78. Hauch A, Brodersen K, Chen M, et al. Ni/YSZ electrodes structures optimized for increased electrolysis performance and durability. Solid State Ionics, 2016, 293: 27–36
79. Lv H, Lin L, Zhang X, et al. *In situ* exsolved $FeNi_3$ nanoparticles on nickel doped $Sr_2Fe_{1.5}Mo_{0.5}O_{6-\delta}$ perovskite for efficient electrochemical CO_2 reduction reaction. Journal of Materials Chemistry. A, Materials for Energy and Sustainability, 2019, 7(19): 11967–11975
80. Liu S, Liu Q, Luo J L. Highly stable and efficient catalyst with in situ exsolved Fe−Ni alloy nanospheres socketed on an oxygen deficient perovskite for direct CO_2 electrolysis. ACS Catalysis, 2016, 6(9): 6219–6228
81. Zhou Y, Zhou Z, Song Y, et al. Enhancing CO_2 electrolysis performance with vanadium-doped perovskite cathode in solid oxide electrolysis cell. Nano Energy, 2018, 50: 43–51
82. Li Y, Li Y, Wan Y, et al. Perovskite oxyfluoride electrode enabling direct electrolyzing carbon dioxide with excellent electrochemical performances. Advanced Energy Materials, 2019, 9(3): 1803156
83. Tsekouras G, Neagu D, Irvine J T S. Step-change in high temperature steam electrolysis performance of perovskite oxide cathodes with exsolution of B-site dopants. Energy & Environmental Science, 2013, 6(1): 256–266
84. Lv H, Lin L, Zhang X, et al. Promoting exsolution of RuFe alloy nanoparticles on $Sr_2Fe_{1.4}Ru_{0.1}Mo_{0.5}O_{6-\delta}$ via repeated redox manipulations for CO_2 electrolysis. Nature Communications, 2021, 12(1): 5665
85. Park S, Kim Y, Han H, et al. *In situ* exsolved Co nanoparticles on Ruddlesden-Popper material as highly active catalyst for CO_2 electrolysis to CO. Applied Catalysis B: Environmental, 2019, 248: 147–156
86. Ebbesen S D, Mogensen M. Electrolysis of carbon dioxide in solid oxide electrolysis cells. Journal of Power Sources, 2009, 193(1): 349–358
87. Kim J, Jun A, Gwon O, et al. Hybrid-solid oxide electrolysis cell: A new strategy for efficient hydrogen production. Nano Energy, 2018, 44: 121–126
88. Jensen S H, Graves C, Mogensen M, et al. Large-scale electricity storage utilizing reversible solid oxide cells combined with underground storage of CO_2 and CH_4. Energy & Environmental Science, 2015, 8(8): 2471–2479
89. Habibollahzade A, Gholamian E, Behzadi A. Multi-objective optimization and comparative performance analysis of hybrid biomass-based solid oxide fuel cell/solid oxide electrolyzer cell/gas turbine using different gasification agents. Applied Energy, 2019, 233–234: 985–1002
90. Tian M W, Yan S R, Han S Z, et al. New optimal design for a hybrid solar chimney, solid oxide electrolysis and fuel cell based on improved deer hunting optimization algorithm. Journal of Cleaner Production, 2020, 249: 119414
91. Haghghi M A, Holagh S G, Chitsaz A, et al. Thermodynamic assessment of a novel multi-generation solid oxide fuel cell-based system for production of electrical power, cooling, fresh water, and hydrogen. Energy Conversion and Management, 2019, 197: 111895
92. Su H N, Lee P C. Mapping knowledge structure by keyword co-occurrence: A first look at journal papers in Technology Foresight. Scientometrics, 2010, 85(1): 65–79
93. De Angelis S, Jørgensen P S, Tsai E H R, et al. Three dimensional characterization of nickel coarsening in solid oxide cells via *ex-situ* ptychographic nano-tomography. Journal of Power Sources, 2018, 383: 72–79
94. Tanasini P, Cannarozzo M, Costamagna P, et al. Experimental and theoretical investigation of degradation mechanisms by particle coarsening in SOFC electrodes. Fuel Cells, 2009, 9(5): 740–752
95. Simwonis D. Nickel coarsening in annealed Ni/8YSZ anode substrates for solid oxide fuel cells. Solid State Ionics, 2000, 132(3–4): 241–251
96. Mogensen M B, Chen M, Frandsen H L, et al. Ni migration in solid oxide cell electrodes: Review and revised hypothesis. Fuel Cells, 2021, 21(5): 415–429
97. Chen G, Guan G, Abliz S, et al. Rapid degradation mechanism of Ni-CGO anode in low concentrations of H_2 at a high current density. International Journal of Hydrogen Energy, 2011, 36(14): 8461–8467
98. Saadabadi S A, Illathukandy B, Aravind P V. Direct internal methane reforming in biogas fuelled solid oxide fuel cell: The influence of operating parameters. Energy Science & Engineering, 2021, 9(8): 1232–1248
99. Hanasaki M, Uryu C, Daio T, et al. SOFC durability against standby and shutdown cycling. Journal of the Electrochemical Society, 2014, 161(9): F850–F860
100. Faes A, Nakajo A, Hessler-Wyser A, et al. $RedO_x$ study of anode-supported solid oxide fuel cell. Journal of Power Sources, 2009, 193(1): 55–64
101. Arrivé C, Delahaye T, Joubert O, et al. Exsolution of nickel nanoparticles at the surface of a conducting titanate as potential hydrogen electrode material for solid oxide electrochemical cells. Journal of Power Sources, 2013, 223: 341–348
102. Teng Z Y, Xiao Z, Yang G, et al. Efficient water splitting through solid oxide electrolysis cells with a new hydrogen electrode derived from A-site cation-deficient $La_{0.4}Sr_{0.55}Co_{0.2}Fe_{0.6}Nb_{0.2}O_{3-\delta}$ perovskite. Materials Today. Energy, 2020, 17: 100458
103. Li Y, Hu B, Xia C, et al. A novel fuel electrode enabling direct CO_2 electrolysis with excellent and stable cell performance. Journal of Materials Chemistry. A, Materials for Energy and Sustainability, 2017, 5(39): 20833–20842
104. Liu S, Liu Q, Luo J L. CO_2-to-CO conversion on layered perovskite with in situ exsolved Co−Fe alloy nanoparticles: an active and stable cathode for solid oxide electrolysis cells. Journal of Materials Chemistry. A, Materials for Energy and Sustainability, 2016, 4(44): 17521–17528
105. Zhang Y Q, Li J H, Sun Y F, et al. Highly active and redox-stable Ce-doped LaSrCrFeO-based cathode catalyst for CO_2 SOECs. ACS Applied Materials & Interfaces, 2016, 8(10): 6457–6463
106. Li Y H, Chen X, Yang Y, et al. Mixed-conductor $Sr_2Fe_{1.5}Mo_{0.5}O_{6-\delta}$ as robust fuel electrode for pure CO_2 reduction in solid oxide electrolysis cell. ACS Sustainable

Chemistry & Engineering, 2017, 5(12): 11403–11412

107. Lv H F, Zhou Y, Zhang X, et al. Infiltration of $Ce_{0.8}Gd_{0.2}O_{1.9}$ nanoparticles on $Sr_2Fe_{1.5}Mo_{0.5}O_{6-\delta}$ cathode for CO_2 electroreduction in solid oxide electrolysis cell. Journal of Energy Chemistry, 2019, 35: 71–78
108. Pan Z, Liu Q, Yan Z, et al. On the delamination of air electrodes of solid oxide electrolysis cells: A mini-review. Electrochemistry Communications, 2022, 137: 107267
109. Chen K, Jiang S P. Failure mechanism of $(La,Sr)MnO_3$ oxygen electrodes of solid oxide electrolysis cells. International Journal of Hydrogen Energy, 2011, 36(17): 10541–10549
110. Keane M, Mahapatra M K, Verma A, et al. LSM-YSZ interactions and anode delamination in solid oxide electrolysis cells. International Journal of Hydrogen Energy, 2012, 37(22): 16776–16785
111. Hjalmarsson P, Sun X, Liu Y L, et al. Influence of the oxygen electrode and inter-diffusion barrier on the degradation of solid oxide electrolysis cells. Journal of Power Sources, 2013, 223: 349–357
112. Park B K, Zhang Q, Voorhees P W, et al. Conditions for stable operation of solid oxide electrolysis cells: oxygen electrode effects. Energy & Environmental Science, 2019, 12(10): 3053–3062
113. Ai N, He S, Li N, et al. Suppressed Sr segregation and performance of directly assembled $La_{0.6}Sr_{0.4}Co_{0.2}Fe_{0.8}O_{3-\delta}$ oxygen electrode on Y_2O_3-ZrO_2 electrolyte of solid oxide electrolysis cells. Journal of Power Sources, 2018, 384: 125–135
114. Laguna-Bercero M A, Monzón H, Larrea A, et al. Improved stability of reversible solid oxide cells with a nickelate-based oxygen electrode. Journal of Materials Chemistry. A, Materials for Energy and Sustainability, 2016, 4(4): 1446–1453
115. Li W, Guan B, Ma L, et al. High performing triple-conductive $Pr_2NiO_{4+\delta}$ anode for proton-conducting steam solid oxide electrolysis cell. Journal of Materials Chemistry. A, Materials for Energy and Sustainability, 2018, 6(37): 18057–18066
116. Yang S, Wen Y, Zhang J, et al. Electrochemical performance and stability of cobalt-free $Ln_{12}Sr_{0.8}NiO_4$ (Ln = La and Pr) air electrodes for proton-conducting reversible solid oxide cells. Electrochimica Acta, 2018, 267: 269–277
117. Lei L, Tao Z, Wang X, et al. Intermediate-temperature solid oxide electrolysis cells with thin proton-conducting electrolyte and a robust air electrode. Journal of Materials Chemistry. A, Materials for Energy and Sustainability, 2017, 5(44): 22945–22951
118. Laguna-Bercero M A, Campana R, Larrea A, et al. Electrolyte degradation in anode supported microtubular yttria stabilized zirconia-based solid oxide steam electrolysis cells at high voltages of operation. Journal of Power Sources, 2011, 196(21): 8942–8947
119. Kim J, Ji H I, Dasari H P, et al. Degradation mechanism of electrolyte and air electrode in solid oxide electrolysis cells operating at high polarization. International Journal of Hydrogen Energy, 2013, 38(3): 1225–1235
120. Ishihara T, Jirathiwathanakul N, Zhong H. Intermediate temperature solid oxide electrolysis cell using $LaGaO_3$ based perovskite electrolyte. Energy & Environmental Science, 2010, 3(5): 665–672
121. Gao Z, Zenou V Y, Kennouche D, et al. Solid oxide cells with zirconia/ceria bi-layer electrolytes fabricated by reduced temperature firing. Journal of Materials Chemistry. A, Materials for Energy and Sustainability, 2015, 3(18): 9955–9964
122. Mehranjani A S, Cumming D J, Sinclair D C, et al. Low-temperature co-sintering for fabrication of zirconia/ceria bi-layer electrolyte via tape casting using a Fe_2O_3 sintering aid. Journal of the European Ceramic Society, 2017, 37(13): 3981–3993
123. Bi L, Shafi S P, Traversa E. Y-doped $BaZrO_3$ as a chemically stable electrolyte for proton-conducting solid oxide electrolysis cells (SOECs). Journal of Materials Chemistry. A, Materials for Energy and Sustainability, 2015, 3(11): 5815–5819
124. Lyagaeva J, Danilov N, Vdovin G, et al. A new dy-doped $BaCeO_3$-$BaZrO_3$ proton-conducting material as a promising electrolyte for reversible solid oxide fuel cells. Journal of Materials Chemistry. A, Materials for Energy and Sustainability, 2016, 4(40): 15390–15399
125. Li W, Guan B, Ma L, et al. Synergistic coupling of proton conductors $BaZr_{0.1}Ce_{0.7}Y_{0.1}Yb_{0.1}O_{3-\delta}$ and $La_2Ce_2O_7$ to create chemical stable, interface active electrolyte for steam electrolysis cells. ACS Applied Materials & Interfaces, 2019, 11(20): 18323–18330
126. Rajendran S, Thangavel N K, Ding H, et al. Tri-doped $BaCeO_3$-$BaZrO_3$ as a chemically stable electrolyte with high proton-conductivity for intermediate temperature solid oxide electrolysis cells (SOECs). ACS Applied Materials & Interfaces, 2020, 12(34): 38275–38284
127. Niu B B, Lu C, Yi W, et al. *In-situ* growth of nanoparticles-decorated double perovskite electrode materials for symmetrical solid oxide cells. Applied Catalysis B: Environmental, 2020, 270: 118842
128. Chen L, Chen F L, Xia C R. Direct synthesis of methane from CO_2−H_2O co-electrolysis in tubular solid oxide electrolysis cells. Energy & Environmental Science, 2014, 7(12): 4018–4022
129. Deka D J, Gunduz S, Fitzgerald T, et al. Production of syngas with controllable H_2/CO ratio by high temperature co-electrolysis of CO_2 and H_2O over Ni and Co-doped lanthanum strontium ferrite perovskite cathodes. Applied Catalysis B: Environmental, 2019, 248: 487–503
130. Pan Z, Duan C, Pritchard T, et al. High-yield electrochemical upgrading of CO_2 into CH_4 using large-area protonic ceramic electrolysis cells. Applied Catalysis B: Environmental, 2022, 307: 121196
131. Ebbesen S D, Høgh J, Nielsen K A, et al. Durable SOC stacks for production of hydrogen and synthesis gas by high temperature electrolysis. International Journal of Hydrogen Energy, 2011, 36(13): 7363–7373
132. Ni M. 2D thermal modeling of a solid oxide electrolyzer cell (SOEC) for syngas production by H_2O/CO_2 co-electrolysis. International Journal of Hydrogen Energy, 2012, 37(8): 6389–6399
133. Ni M. An electrochemical model for syngas production by co-electrolysis of H_2O and CO_2. Journal of Power Sources, 2012, 202: 209–216
134. Becker W L, Braun R J, Penev M, et al. Production of Fischer-

Tropsch liquid fuels from high temperature solid oxide co-electrolysis units. Energy, 2012, 47(1): 99–115

135. Giglio E, Lanzini A, Santarelli M, et al. Synthetic natural gas via integrated high-temperature electrolysis and methanation: Part I-Energy performance. Journal of Energy Storage, 2015, 1: 22–37
136. Sun X F, Chen M, Jensen S H, et al. Thermodynamic analysis of synthetic hydrocarbon fuel production in pressurized solid oxide electrolysis cells. International Journal of Hydrogen Energy, 2012, 37(22): 17101–17110
137. He F, Song D, Peng R, et al. Electrode performance and analysis of reversible solid oxide fuel cells with proton conducting electrolyte of $BaCe_{0.5}Zr_{0.3}Y_{0.2}O_{3-\delta}$. Journal of Power Sources, 2010, 195(11): 3359–3364
138. Wu W, Ding H, Zhang Y, et al. 3D self-architectured steam electrode enabled efficient and durable hydrogen production in a proton-conducting solid oxide electrolysis cell at temperatures lower than 600 °C. Advanced Science, 2018, 5(11): 1800360
139. Muñoz-García A B, Pavone M. First-principles design of new electrodes for proton-conducting solid-oxide electrochemical cells: A-site doped $Sr_2Fe_{1.5}Mo_{0.5}O_{6-\delta}$ perovskite. Chemistry of Materials, 2016, 28(2): 490–500
140. Lei L, Zhang J, Guan R, et al. Energy storage and hydrogen production by proton conducting solid oxide electrolysis cells with a novel heterogeneous design. Energy Conversion and Management, 2020, 218: 113044
141. Salomone F, Giglio E, Ferrero D, et al. Techno-economic modelling of a power-to-gas system based on SOEC electrolysis and CO_2 methanation in a RES-based electric grid. Chemical Engineering Journal, 2019, 377: 120233
142. Mastropasqua L, Pecenati I, Giostri A, et al. Solar hydrogen production: Techno-economic analysis of a parabolic dish-supported high-temperature electrolysis system. Applied Energy, 2020, 261: 114392
143. Udagawa J, Aguiar P, Brandon N P. Hydrogen production through steam electrolysis: Model-based steady state performance of a cathode-supported intermediate temperature solid oxide electrolysis cell. Journal of Power Sources, 2007, 166(1): 127–136
144. Stoots C M, O'Brien J E, Herring J S, et al. Syngas production via high-temperature coelectrolysis of steam and carbon dioxide. Journal of Fuel Cell Science and Technology, 2009, 6(1): 011014
145. Cinti G, Baldinelli A, Di Michele A, et al. Integration of solid oxide electrolyzer and Fischer-Tropsch: A sustainable pathway for synthetic fuel. Applied Energy, 2016, 162: 308–320
146. AlZahrani A A, Dincer I. Design and analysis of a solar tower based integrated system using high temperature electrolyzer for hydrogen production. International Journal of Hydrogen Energy, 2016, 41(19): 8042–8056
147. Sunfire. Successful test operation of the world's largest high-temperature electrolysis module. 2024, available at the website of Sunfire
148. Shanghai Institute of Applied Physics, Chinese Academy of Engineering. A successful start of 200-kW SOEC system developed by SINAP. 2024, available at the website of CAS