

Towards the Commercialization of Solid Oxide Fuel Cells

Subjects: [Electrochemistry](#) | [Energy & Fuels](#) | [Green & Sustainable Science & Technology](#)

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The solid oxide fuel cell (SOFC) has become a promising energy conversion technology due to its high efficiency and low environmental impact. Though there are several reviews on SOFCs, comprehensive reports that simultaneously combine the latest developments in materials and integration strategies are very limited. This paper addresses those issues and discusses SOFCs working principles, design types, the fuels used, and the required features for electrodes and electrolytes.

solid oxide fuel cell

solid electrolytes

electrodes

yttria-stabilized zirconia

perovskites

cogeneration

trigeneration

1. Introduction

Research and industry sectors are focusing their attention on fuel cell technologies due to the potential to provide long-term durability clean energy to consumers since they can directly convert the chemical energy of diverse fuels into electricity without combustion. Fuel cells comprise a cathode and an anode separated by an ion-conducting electrolyte, in addition to other components such as interconnects and sealants ^[1]. There are several types of fuel cells, which are generally classified according to the nature of the applied electrolyte. These types include proton exchange membrane fuel cells (PEMFCs), direct methanol fuel cells (DMFCs), alkaline fuel cells (AFCs), molten carbonate fuel cells (MCFCs), phosphoric acid fuel cells (PAFCs), and solid oxide fuel cells (SOFCs) ^[2].

Sir William Grove, in 1839, proposed the concept of the fuel cell. Using his electrolysis background, he designed a reverse process that combined hydrogen and oxygen to produce electricity ^[3]. In 1905, Fritz Haber submitted the first patent on fuel cells with a solid electrolyte, using glass and porcelain as the electrolyte materials and platinum and gold as the electrode materials. Between 1933 and 1959, Francis Thomas Bacon investigated alkaline electrolyte fuel cells, demonstrating the first fully operational fuel cell. Later on, in 1960, NASA used the AFC technology developed by Bacon in its Apollo space program, and in 1990, NASA jet propulsion developed the first direct methanol fuel cell ^{[2][4]}.

SOFCs present several advantages over the other fuel cell types. These include higher flexibility in fuel selection, operating SOFCs directly on practical hydrocarbon fuels, and higher overall efficiency ^[5]. Operating temperatures range between 600–1000 °C, allowing SOFCs to use conventional thermal cycles to yield enhanced thermal efficiency and extract hydrogen from various fuels. This type of fuel cell is tolerant to carbon monoxide (CO), which

is electrochemically oxidized to CO₂ at the anode in opposition to PEM fuel cells, which are highly sensitive to CO poisoning [5][6][7]. SOFCs also have greater tolerance to impurities in the fuel, such as sulfur (as hydrogen sulfide, H₂S, and carbonyl sulfide, COS), and to changes in the fuel composition, meaning that fuel processing conditions are less strict [5][8]. These characteristics allow SOFCs to be supplied with gases obtained from solid and liquid fuels, becoming an advantage for coal-based central power generation and in vehicles powered by diesel or gasoline fuel [7].

This review paper starts by reviewing the general working principle of SOFCs, design types, and the properties of each SOFC component, including electrodes, electrolytes, and interconnects. It also discusses the latest developments and research in each component material to face the challenges stated above. Furthermore, the integration strategies and implementation of this type of fuel cell on a commercial scale are also pointed out.

2. Fundamentals of SOFCs

Fuel cells rely on the transportation processes occurring during electrochemical reactions, where the chemical energy of fuel and oxidant is converted into electric energy, represented by the load through the three main components: anode, electrolyte, and cathode. The most important components of a SOFC are the porous electrodes separated by the dense ceramic electrolyte [2][9].

The configuration can be seal-less and comprise a tubular cell with a cathode-coated core, the anode on the outside of the cell, and the electrolyte in between. The oxidant is introduced throughout the inside of the support tube, while the fuel flows at the outside [2]. Although tubular cells look back on a long history, today, they are relegated to a niche in low-power systems due to the expensive cost of the manufacturing process and the high ohmic losses that reduce the ionic conductivity of the electrolyte [10].

Reforming natural gas or other hydrocarbon fuels to obtain the required hydrogen can be achieved within the fuel cell, excluding the requirement for an external reformer in contrast to the other types of fuel cells [9]. Thus, a huge variety of fuels, such as natural gas, biogas, gasoline, and kerosene, can be applied in SOFCs adopting four different modes: external reforming, internal reforming, partial oxidation, and direct oxidation. The first three are reforming of fuels, wherein hydrocarbon fuels (e.g., C_nH_{2n+2}) are converted into syngas (H₂ and CO) through steam reforming, dry/CO₂ reforming, catalytic partial oxidation, and oxidative steam reforming or auto-thermal reforming and then electrochemically oxidized on the SOFC anode. The last one of these modes corresponds to the direct oxidation of fuels on the anode [11].

3. SOFC Applications

As mentioned above, SOFCs are one of the most efficient and environmental-friendly technologies available for power generation. They can be integrated with traditional electrical power plants and provide electricity as on-site power generators [12]. There are three main applications of SOFCs related to this field: combined cycle power plant, cogeneration/trigeneration, and residential applications. SOFC are still not quite suitable for portable

applications and transportation, as mentioned before, due to their high operating temperature, which leads to long start-up and cool-down times [\[13\]](#).

One of the main concerns regarding a conventional GT plant is associated with thermal efficiency since it has considerable losses related to the high irreversibility inside the combustion chamber. This can be improved if direct contact between air and fuel is prevented, as it occurs in fuel cells. A fuel cell–GT hybrid system has a higher energy conversion efficiency, low environmental pollution, and possible use of renewable energy sources as fuel. Although the thermal efficiency depends upon the cycle configuration and layout of the hybrid system, such as a pressurized SOFC–GT combined cycle or a recuperated GT integrated with SOFC, an efficiency until 60% can be reached using the integrated cycle [\[13\]](#).

The prereforming step can be executed using catalytic partial oxidation (CPO) or an adiabatic steam reformer (ASR). The efficiency of this hybrid system depends on the type of prereforming process used, which was found to be higher in a system with ASR type than CPO type. Nevertheless, the ASR reactor needs superheated steam during start-up, which can be a disadvantage [\[14\]](#).

The electrical efficiency is increased if the SOFC fuel-utilization factor is decreased. However, this parameter is limited to certain values; otherwise, the TIT would increase and consequently reduce the efficiency of the plant. Thus, changing the system's configuration has a positive effect on the efficiency of the SOFC–ST combined cycle [\[13\]](#).

4. Commercialization

In summary, the tubular SOFC technology of SWPC was not technically feasible nor commercially viable. One of the major constraints of the SOFC system was related to the demonstrated lifetime of 16,400 h, being less than half the requisite of 40,000 h. Moreover, the manufacturing of the tubular SOFCs and their assembly was complex and labor-intensive, making it extremely expensive and not suited for low-cost mass production processes. Lastly, tubular SOFC systems had intrinsic constraints in attaining high power density. This was due to the long electrical path across the tubes and the large voids within the stack, causing significant ohmic losses, which resulted in a large system with lower power output [\[15\]](#).

In 2017, Kyocera Corporation announced the first 3 kW SOFC for institutional cogeneration using 700-W cell stacks. The system uses Kyocera's ceramic technologies and city gas as fuel to provide 52% generation efficiency and overall efficiency of 90% with exhaust-heat recovery. Besides effectively generating energy, exhaust heat from the power generation process can be used to heat water. Lastly, when compared with conventional cogeneration systems, this system provides significant energy savings and lower CO₂ emissions, and it can adjust the power generation in proportion to demand [\[16\]](#).

Elcogen was founded in 2001 in Estonia and is considered a manufacturer and developer of high-performance anode-supported IT-SOFC and SOFC. Elcogen's stacks operating temperature is 650 °C, allowing longer lifetimes,

primary energy-conversion efficiency to electricity of 74%, and the use of materials of lower cost at the cell, stack, and system levels. Their stacks are used in various applications, such as residential to micro-CHP in a power range of 1–5 kW; standalone or boiler integrated industrial premium power and CHP in a power range of 20 kW to some MW; APU units for transportation in a power range of 1–5 kW; high-temperature electrolysis for wind and solar energy storage; and power to gas/liquids solutions [\[17\]](#).

In 2018, MHPS got its first request for a pressurized hybrid power-generation system to be installed in the Marunouchi Building in Tokyo, held by Mitsubishi Estate Co., Ltd. (Tokyo, Japan). This hybrid system was fueled by city gas, generating electricity with ceramic SOFC stacks, which operated at approximately 900 °C and MGts. Since it is used in a CHP system, exhaust heat can be recovered as steam or hot water, improving the combined efficiency. This hybrid system can decrease CO₂ emissions by nearly 47% compared to conventional power generation systems, supporting the goal of a low-carbon society [\[18\]](#).

In Europe, the Fuel Cells and Hydrogen Joint Undertaking (FCH-JU) is a public-private partnership established to support research, technological development, and demonstration activities in the field of fuel cells and hydrogen energy technologies. It intends to rapidly introduce these technologies to the market, realizing their potential as an instrument in reaching a carbon-free energy system [\[19\]](#).

References

1. Sreedhar, I.; Agarwal, B.; Goyal, P.; Singh, S.A. Recent advances in material and performance aspects of solid oxide fuel cells. *J. Electroanal. Chem.* 2019, 848, 113315.
2. Abdalla, A.M.; Hossain, S.; Petra, P.M.I.; Ghasemi, M.; Azad, A.K. Achievements and trends of solid oxide fuel cells in clean energy field: A perspective review. *Front. Energy* 2020, 14, 359–382.
3. Ormerod, R.M. Solid oxide fuel cells. *Chem. Soc. Rev.* 2003, 32, 17–28.
4. Sharaf, O.Z.; Orhan, M.F. An overview of fuel cell technology: Fundamentals and applications. *Renew. Sustain. Energy Rev.* 2014, 32, 810–853.
5. Lyu, Y.; Xie, J.; Wang, D.; Wang, J. Review of cell performance in solid oxide fuel cells. *J. Mater. Sci.* 2020, 55, 7184–7207.
6. Zakaria, Z.; Kamarudin, S.K.; Timmiati, S.N. Membranes for direct ethanol fuel cells: An overview. *Appl. Energy* 2016, 163, 334–342.
7. Zakaria, Z.; Awang Mat, Z.; Abu Hassan, S.H.; Boon Kar, Y. A review of solid oxide fuel cell component fabrication methods toward lowering temperature. *Int. J. Energy Res.* 2020, 44, 594–611.
8. Dodds, P.E.; Staffell, I.; Hawkes, A.D.; Li, F.; Grünewald, P.; McDowall, W.; Ekins, P. Hydrogen and fuel cell technologies for heating: A review. *Int. J. Hydrog. Energy* 2015, 40, 2065–2083.

9. Stambouli, A.B.; Traversa, E. Solid oxide fuel cells (SOFCs): A review of an environmentally clean and efficient source of energy. *Renew. Sustain. Energy Rev.* 2002, 6, 433–455.
10. Months, E.P.; Date, A.S.; Gandiglio, M.; Hakala, T.; Fontell, E. ComSos “Commercial-scale SOFC systems”. 2019, pp. 1–11. Available online: <https://www.comsos.eu/com18/com18-cont/uploads/2020/02/Market-analysis-of-CHP-solutions-applied-in-commercial-applications.pdf> (accessed on 17 September 2021).
11. Hussain, A.M.; Wachsman, E.D. Liquids-to-Power Using Low-Temperature Solid Oxide Fuel Cells. *Energy Technol.* 2019, 7, 20–32.
12. Larminie, J.; Dicks, A.; McDonald, M.S. *Fuel Cell Systems Explained*; J. Wiley: Chichester, UK, 2003.
13. Choudhury, A.; Chandra, H.; Arora, A. Application of solid oxide fuel cell technology for power generation—A review. *Renew. Sustain. Energy Rev.* 2013, 20, 430–442.
14. Rokni, M. Thermodynamic analysis of an integrated solid oxide fuel cell cycle with a rankine cycle. *Energy Convers. Manag.* 2010, 51, 2724–2732.
15. Behling, N.H. Chapter 6—History of Solid Oxide Fuel Cells. In *Fuel Cells: Current Technology Challenges and Future Research Needs*; Behling, N.H., Ed.; Elsevier: Amsterdam, The Netherlands, 2013; pp. 223–421.
16. KYOCERA Develops Industry’s First 3-Kilowatt Solid-Oxide Fuel Cell for Institutional Cogeneration; Most Efficient SOFC on the Market Using Proprietary Ceramic Technology|News Releases|KYOCERA, (n.d.). Available online: https://global.kyocera.com/news-archive/2017/0702_bnfo.html (accessed on 19 April 2021).
17. Elcogen—Solid Oxide Cells and Stacks. 2021. Available online: <https://elcogen.com/> (accessed on 3 May 2021).
18. Mitsubishi Power, Ltd. MHPS Receives First Order for Integrated Fuel Cell and Gas Turbine Hybrid Power Generation System. 2021. Available online: <https://power.mhi.com/news/20180131.html> (accessed on 19 April 2021).
19. Who We Are|www.fch.europa.eu. 2021. Available online: <https://www.fch.europa.eu/page/who-we-are> (accessed on 19 April 2021).

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