



Recent Progress in Rare-Earth Element-based Cathode Materials for Solid Oxide Fuel Cells: A Mini Review

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Abstract

The pressing global need for sustainable, and efficient energy sources has fueled the search for innovative approaches to energy production, storage, and delivery. Solid Oxide Fuel Cells (SOFC) offer a promising avenue for efficient energy transformation, with the cathode playing a pivotal role in facilitating electrochemical reactions within the cell. Two types of SOFC cathodes – proton-exchange (H-SOFC) and ion-exchange (O-SOFC) – are explored, highlighting cathode materials such as LaSrCoO_x, LaSrCoFeO_x, LaSrMnO_x, LaSrFeMoO_x, PrSrFeO_x, PrSrCoFeO_x, PrSrCoCuO_x, NdBaSrCoFeO_x, SrFeMoNiO_x, LaSrCuNiO_x, LaSrGeO_x, and LaNiO_x. The review discusses recent advancements in cathode materials, including studies on triple-phase boundaries and the effects of doping. Additionally, studies on tailored rare-earth-based cathode materials highlight their potential to enhance oxygen reduction reaction kinetics and tailor electrochemical properties for specific SOFC requirements.

Keywords: SOFC; Cathode materials; Proton-exchange; Ion-exchange; Rare-earth elements.

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1. Introduction

The large-scale demand for efficient and sustainable energy technologies has driven extensive research into advanced electrochemical energy conversion systems.^[1,2,3] Among these, solid oxide fuel cells (SOFCs) are considered one of the most promising solutions due to their high energy efficiency (up to 60% in standalone systems and over 85% in combined heat and power configurations), fuel flexibility, and low environmental impact.^[4,5,6,7]

Unlike conventional fuel cells that rely on costly noble metal catalysts such as platinum,^[8] SOFCs employ a yttria-stabilized zirconia (YSZ) electrolyte and ceramic electrodes, which are composed of more abundant and cost-effective materials. This not only reduces overall system cost but also enables stable long-term operation at elevated temperatures (500–1000 °C).^[9,10] Moreover, the high operating temperature allows for greater fuel flexibility, accommodating a wide range of fuels including hydrogen, carbon monoxide, and

hydrocarbons.

The cathode is a critical component in SOFCs,^[11,12] playing a crucial role in the oxygen reduction reaction (ORR) and directly influencing the overall electrochemical performance of the cell. Perovskite-structured transition metal oxides (ABO₃-type), shown in Fig.1 as La-containing cathode materials, have attracted considerable attention due to their mixed ionic-electronic conductivity (MIEC), high oxygen exchange kinetics, and structural flexibility. In particular, La_xSr_{1-x}Co_yFe_{1-y}O_{3±δ} (LSCF) has been widely studied for low- and intermediate-temperature SOFCs (LT and IT, 500–800 °C) due to its excellent electrocatalytic activity, high oxygen-ion mobility, and ability to reduce polarization losses.^[13,14]

Rare-earth composite oxides exhibit high ionic, electronic, or mixed conductivity, making them essential for SOFC cathodes. Optimal oxide composition selection enhances ionic conductivity, improves electrode activity, and reduces the activation energy of reactions like oxygen reduction. Recent research increasingly focuses on incorporating rare-earth elements into cathode materials to enhance SOFC efficiency, durability, and long-term performance.^[15,16]

Despite these advantages, several critical challenges remain in optimizing the composition, structure, and fabrication techniques of cathode materials to enhance their electrical conductivity, electrochemical stability, and

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compatibility with other SOFC components. One of the

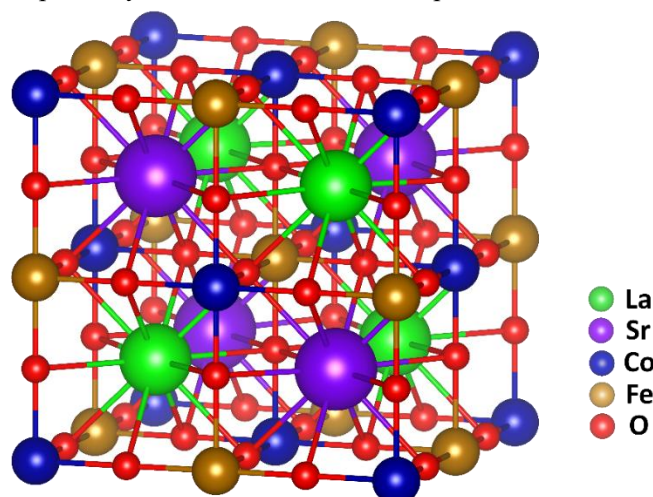


Fig. 1: A view of the perovskite crystal structure of LSCF

fundamental issues is the thermal expansion mismatch between the cathode and electrolyte, which can lead to mechanical degradation during long-term operation.^[17] Additionally, surface degradation phenomena – such as cation segregation, phase decomposition, and strontium (Sr) accumulation – can significantly impair cathode performance over time.^[18]

This review provides a comprehensive analysis of functional cathode materials for modern SOFCs, focusing on their synthesis methods, structural properties, and electrochemical performance. Furthermore, key degradation mechanisms and potential solutions for enhancing the long-term performance of SOFC cathodes are discussed, considering recent advancements in material design.

2. General operation principles of SOFCs

Among the various types of fuel cells, SOFCs have gained prominence due to their versatility, fuel flexibility, and scalability across stationary and distributed power applications.^[19] Ion-exchange SOFCs operate based on the principle of oxygen ion conduction through a solid ceramic electrolyte, typically YSZ.^[20] The cathode plays a significant role in this process, as it catalyzes the ORR,^[21] which is considered the rate-limiting step in SOFC operation. The efficiency of ORR directly impacts the overall electrochemical performance of the cell.

V.A. Sadykov *et al.*^[22] conducted ORR studies, demonstrating that cathodes based on Ruddlesden-Popper phases ($\text{La}_{2-x}\text{Ca}_x\text{NiO}_{4+\delta}$) exhibit high oxygen mobility ($D \sim 10^{-7}$ cm²/s) and a surface exchange coefficient ($k \sim 10^{-5} - 10^{-6}$ cm/s). In comparison, nanocomposite cathodes like $\text{PrNi}_{0.5}\text{Co}_{0.5}\text{O}_{3-\delta} - \text{Ce}_{0.9}\text{Y}_{0.1}\text{O}_{2-\delta}$ (PNC-YDC) show $D^* \sim 10^{-8}$ cm²/s and $k^* \sim 10^{-7}$ cm/s due to their well-developed interfaces. For compositions such as $\text{La}=\text{Pr}_{2-x}\text{Ca}_x\text{NiO}_{4+\delta}$ ($x = 0.1$), the lowest polarization resistance ($R_p \sim 0.17 \Omega \cdot \text{cm}^2$) was achieved. SOFCs with $\text{Pr}_2\text{NiO}_{4+\delta}$ and PNC-YDC cathodes reached a power density of up to 0.5 W/cm² at 700 °C. This suggests that

nanocomposite cathodes with well-developed interfaces significantly enhance the kinetics of ORR, reduce polarization losses, and improve the overall efficiency of SOFCs.

Molecular oxygen from ambient air is reduced at the cathode by accepting electrons, forming oxygen ions:



These ions then migrate through the dense YSZ electrolyte to the anode, where they react with hydrogen:



These electrons flow through an external electrical circuit – from the anode to the cathode – generating electric current and releasing waste heat in the process.^[23] A schematic illustration of the general operating principles of SOFCs is shown in Fig. 2.

There are two main types of SOFCs, distinguished by the type of ionic conductivity in their electrolytes: oxygen-ion conducting SOFCs (O-SOFCs) and proton-conducting SOFCs (H-SOFCs). Cathodes for O-SOFCs are typically perovskite-type compounds (ABX_3) based on rare-earth oxides, such as LaSrCoO_x , LaSrCoFeO_x , LaSrMnO_x , LaSrFeMoO_x , PrSrFeO_x , PrSrCoFeO_x , and PrSrCoCuO_x . These materials exhibit excellent mixed ionic and electronic conductivity, making them well-suited for facilitating the ORR. Meanwhile, for the efficient operation of H-SOFCs, it is necessary to use proton-conducting oxides, such as NdBaSrCoFeO_x , SrFeMoNiO_x , LaSrCuNiO_x , LaSrGeO_x , and LaNiO_x , as electrode materials. These materials provide optimal charge carrier transfer characteristics (H^+ and O^{2-}) to sustain the electrochemical reaction within the cell.^[24,25,26]

3. SOFC progress and challenges

Improving the surface properties of SOFC components and understanding their interactions with atmospheric conditions are crucial for enhancing overall performance.^[27] Key parameters such as the surface exchange rate, electrocatalytic activity, and ORR kinetics strongly influence SOFC efficiency across a range of electrochemical applications, particularly at high (800–1000 °C) and intermediate temperatures (600–800 °C).^[28,29]

SOFCs typically operate at high temperatures (800–1000 °C), enhancing reaction kinetics but also causing material degradation. Prolonged exposure leads to cation segregation, phase instability, and thermal expansion mismatches among cell components, ultimately reducing cell lifespan.^[30] Therefore, selecting thermally stable materials with high structural integrity and consistent electrochemical performance is crucial. To mitigate thermal degradation and reduce operational stress, researchers are actively exploring ways to lower the operating temperature of SOFCs to 600–800 °C without compromising efficiency.^[31] One approach involves using rare-earth elements (REEs) as dopants to enhance oxygen vacancy concentration, increase ionic conductivity, and improve charge transfer by controlling dopant segregation and grain size.^[32] These improvements are

Table 1: Perovskite-type oxide materials: thermal expansion coefficient (TEC), electron (σ_e), and ionic conductivity (σ_i) in air.

	TEC $\times 10^{-6}$, K ⁻¹	T (°C)	σ_e (S cm^{-1})	σ_i (S cm^{-1})	Ref.
La _{0.8} Sr _{0.2} MnO ₃	11.8	900	300	5.93 $\times 10^{-7}$	40
La _{0.7} Sr _{0.3} MnO ₃	11.7	800	240	-	41
La _{0.6} Sr _{0.4} MnO ₃	13	800	130	-	42
Pr _{0.6} Sr _{0.4} MnO ₃	12	950	220	-	43
La _{0.8} Sr _{0.2} CoO ₃	19.1	800	1220	-	44
La _{0.6} Sr _{0.4} CoO ₃	20.5	800	1600	0.22	45
La _{0.8} Sr _{0.2} FeO ₃	12.2	750	155	-	46
La _{0.5} Sr _{0.5} FeO ₃	-	800	369	0.205	47
La _{0.6} Sr _{0.4} FeO ₃	16.3	800	129	5.6 $\times 10^{-3}$	48
Pr _{0.5} Sr _{0.5} FeO ₃	13.2	550	300	-	49
Pr _{0.8} Sr _{0.2} FeO ₃	12.1	800	78	-	50
La _{0.7} Sr _{0.3} Fe _{0.8} Ni _{0.2} O ₃	13.7	750	290	-	51
La _{0.8} Sr _{0.2} Co _{0.8} Fe _{0.2} O ₃	20.1	600	1050	-	52
La _{0.8} Sr _{0.2} Co _{0.2} Fe _{0.8} O ₃	15.4	600	125	-	53
La _{0.6} Sr _{0.4} Co _{0.8} Mn _{0.2} O ₃	18.1	500	1400	-	54
La _{0.6} Sr _{0.4} Co _{0.8} Fe _{0.2} O ₃	21.4	800	269	0.058	55
La _{0.6} Sr _{0.4} Co _{0.2} Fe _{0.8} O ₃	15.3	600	330	8 $\times 10^{-3}$	56
La _{0.8} Sr _{0.2} Co _{0.2} Fe _{0.8} O ₃	14.8	800	87	2.2 $\times 10^{-3}$	57
La _{0.8} Sr _{0.2} Co _{0.8} Fe _{0.2} O ₃	19.3	800	1000	4 $\times 10^{-2}$	58
La _{0.6} Sr _{0.4} Co _{0.9} Cu _{0.1} O ₃	19.2	700	1400	-	59
Pr _{0.8} Sr _{0.2} Co _{0.2} Fe _{0.8} O ₃	12.8	800	76	1.5 $\times 10^{-3}$	60
Pr _{0.7} Sr _{0.3} Co _{0.2} Mn _{0.8} O ₃	11.1	800	200	4.4 $\times 10^{-5}$	61
Pr _{0.6} Sr _{0.4} Co _{0.8} Fe _{0.2} O ₃	19.69	550	950	-	62
Pr _{0.4} Sr _{0.6} Co _{0.8} Fe _{0.2} O ₃	21.33	550	600	-	63
Pr _{0.7} Sr _{0.3} Co _{0.9} Cu _{0.1} O ₃	-	700	1236	-	64
Sr _{0.9} Ce _{0.1} Fe _{0.8} Ni _{0.2} O ₃	18.9	800	87	0.04	65

particularly beneficial for IT-SOFCs, where maintaining high electrochemical activity at reduced temperatures is crucial. However, it is important to note that while REE doping enhances performance in lower-temperature regimes, it does not inherently improve high-temperature durability (800–1000 °C).^[33]

Given the growing importance of SOFC technology, significant research efforts have focused extensively on developing and enhancing anode, electrolyte, and cathode materials.^[34] This can be seen in Fig 3, which shows the progress rate of research up to the present day. Flexibility and tolerance to fuel impurities are crucial for achieving consistent high-efficiency power generation in SOFC-based systems.^[35]

SOFCs offer unique advantages over other FC types but also face key challenges related to material stability, compatibility, and electrochemical performance:^[36]

- carbon and sulfur deposition pose hazards such as surface diffusion and charge transfer distortion in the anode, potentially leading to poisoning;
- the limited mobility of O²⁻ ions can affect reaction rates and directionality in solid electrolytes;
- excess polarization potential and non-optimal electrode geometry can limit cathodic reaction rates;
- a mismatch in thermal expansion coefficients among cell components contributes to mechanical failure during thermal cycling;

- chemical instability and incompatibility in both oxidizing and reducing atmospheres may result in material degradation;
- reliable sealing technologies are required to effectively separate fuel and oxidant gases during operation.

To overcome these limitations, it is essential to select cost-effective materials that exhibit low electronic resistance in electrodes, catalysts, interconnects, and sealants, as well as low ionic resistance in electrolytes. Careful material selection and system integration are critical to ensuring high-performance and long-term reliability of SOFC devices.^[37]

4. SOFC cathode materials

Efficient cathode materials are essential for enhancing the overall performance of SOFCs. These materials must demonstrate high oxygen reduction reaction kinetics, good chemical stability at elevated temperatures, and compatibility with other cell components. Researchers have focused on rare earth elements, such as Ce, Ln, Pr, Sc, Gd, and Eu,^[38] due to their unique electronic configurations, redox flexibility, and crystal structure adaptability, which make them attractive candidates for cathode applications.^[39]

Table 2: Cathode polarization resistance (R_p), based on Gd³⁺.

Composition	R_p ($\Omega \text{ cm}^2$)	T (°C)	Ref.
GdBaCo ₂ O _{5+δ}	0.070	750	70
GdBaCo _{1.5} Mn _{0.5} O _{5+δ}	0.040	850/700	70

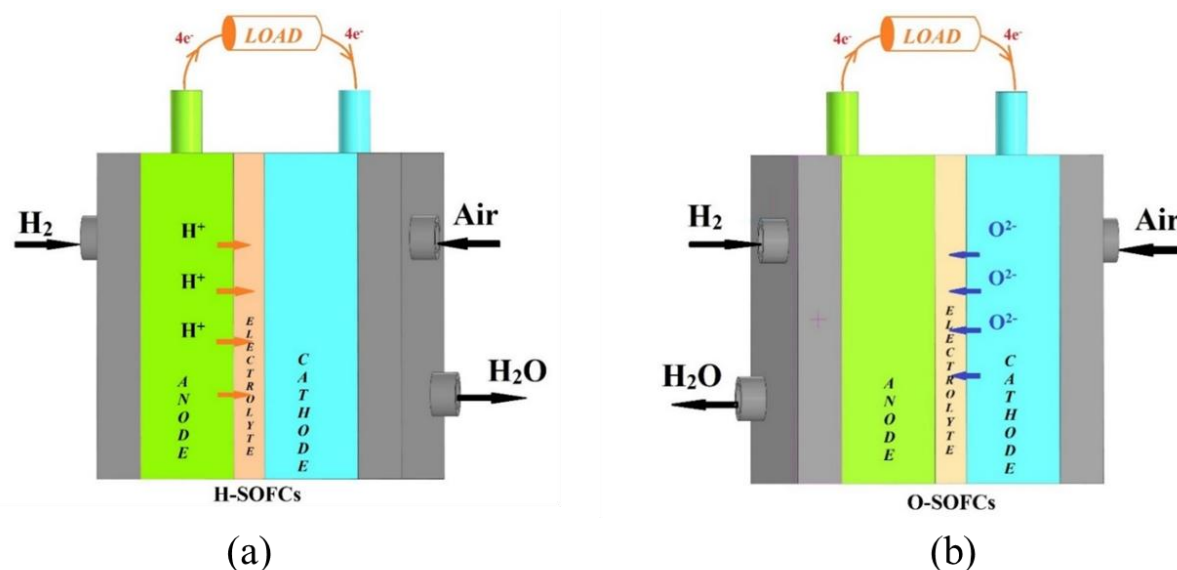


Fig. 2: General principles of SOFCs: (a) H-SOFCs, (b) O-SOFCs.

The selection of appropriate cathode materials requires careful matching with electrolyte materials and ensuring a compatible TEC to prevent mechanical failure. The TEC values of various perovskite-type transition metal oxides are summarized in Table 1.

For specific applications, the choice of cathode material also depends on the desired performance characteristics and suitable fabrication methods. A. M. Abdalla *et al.*^[40] proposed a comprehensive list of commonly used cathode compositions and processing techniques.

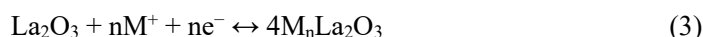
Rare-Earth elements in cathode materials

Enhanced Oxygen Reduction Reaction Kinetics:

R-E elements, including lanthanum (La), gadolinium (Gd), scandium (Sc), praseodymium (Pr), cerium (Ce), and europium (Eu), have demonstrated excellent catalytic activity for ORR. Combining these elements in various compositions can significantly enhance the kinetics of the ORR at the cathode, leading to improved overall cell performance.^[66]

Lanthanum (La)

La_2O_3 is a material for storing energy that has a pseudocapacitive property and can be applied in various ways. The formula for La_2O_3 can store charge through the reaction^[67]:



Shan-Shan Chai *et al.* [60] demonstrated that modifying perovskite materials, such as BaCeO_3 , by partially substituting cerium (Ce) with lanthanum (La) increases oxygen vacancies and reduces the particle size of ruthenium (Ru). These modifications significantly enhance catalytic activity. They developed a $\text{BaCe}_{0.9}\text{La}_{0.1}\text{O}_{3-\delta}$ catalyst with 5% Ru, achieving a high ammonia synthesis rate of up to 34 mmol/g·h at 450 °C and 3 MPa, while maintaining stability even after 100 hours of operation. The addition of La^{3+} increased the electron density of Ru, facilitating the efficient dissociation of N_2 molecules. Furthermore, the uniform distribution of Ru particles prevented agglomeration, ensuring the catalyst's long-term stability.

Gadolinium (Gd)

The oxygen content in cathodes is significantly influenced by the choice of R-E dopant. From an application perspective, polarization resistance (R_p) is a crucial performance metric. For effective cathode operation, R_p values below $0.15 \Omega \cdot \text{cm}^2$ are generally required.^[68] Table 2 shows the polarization resistance values of cathodes composed of $\text{GdBaCo}_{2-x}\text{Mn}_x\text{O}_{5+\delta}$

Table 3: Comparison of electrochemical properties of R-E-based cathode materials for SOFCs.

Cathode materials	Activation energy (eV)	TEC ($\times 10^{-6} \text{ K}^{-1}$)	ASR ($R_p \Omega \cdot \text{cm}^2$)	Electrolyte type	Test temperature (°C)	Ref
$\text{La}_{0.6}\text{Sr}_{0.4}\text{Co}_{0.2}\text{Fe}_{0.8}\text{O}_{3-\delta} + \text{PrO}_{2-\delta}$	1.202	15.8	0.034	YSZ	550-750	58
$\text{La}_{0.6}\text{Sr}_{0.4}\text{Co}_{0.2}\text{Fe}_{0.8}\text{O}_3$	1.190	12.8	0.210	SDC	550-750	67
$\text{Pr}_2\text{NiO}_{4+\delta}$	1.220	13.2	0.075	GDC	600-700	74
$\text{La}_{0.6}\text{Sr}_{0.4}\text{CoO}_{3-\delta} + \text{Gd}^{3+}$	1.500	18.2	0.800	YSZ	700-800	75
$\text{PrBa}_{0.5}\text{Sr}_{0.5}\text{Co}_{1.5}\text{Fe}_{0.5}\text{O}_{5+\delta}$	1.080	17.1	0.050	GDC	550-700	76
$\text{PrBaCo}_2\text{O}_{6-\delta} + \text{Sc}^{3+}$	1.07	15.5	0.086	GDC	600-750	80
$\text{La}_{0.6}\text{Sr}_{0.4}\text{Co}_{0.2}\text{Fe}_{0.8}\text{O}_3$	1.329	16.5	0.730	YSZ	600-700	81

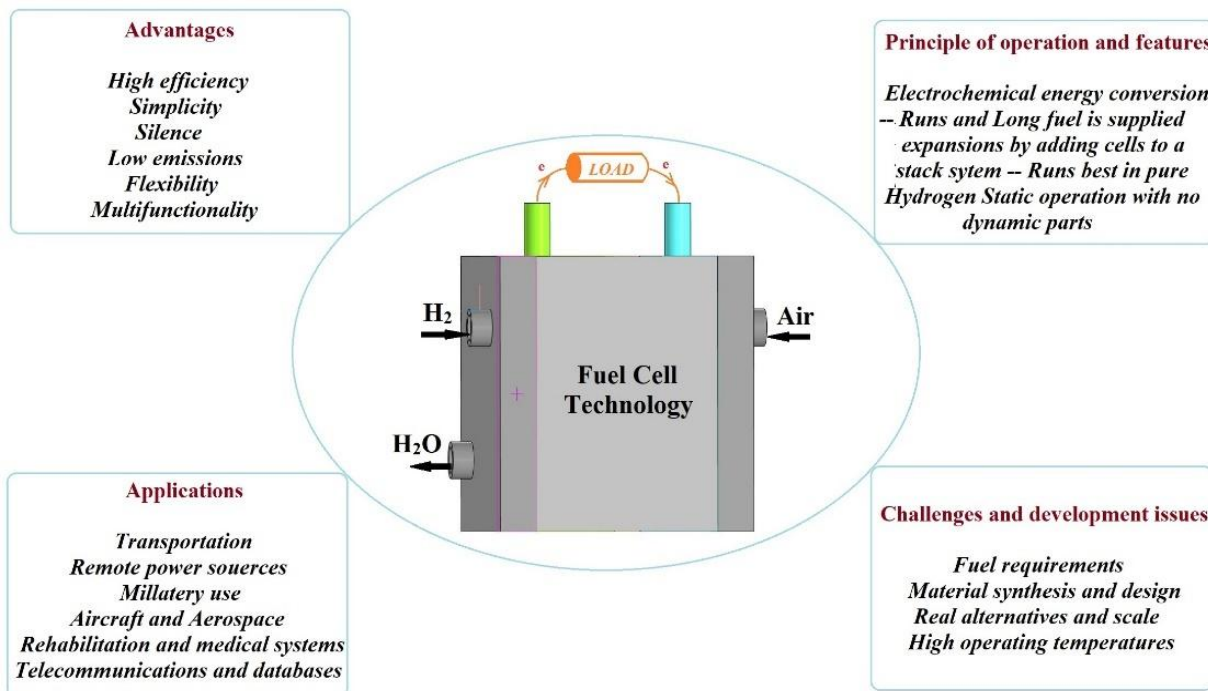


Fig. 3: Introduction to Fuel Cell Technology. Reprinted by A.M. Abdalla *et al.*, [39]. Copyright 2018. Renewable and Sustainable Energy Reviews.

(pure or compound) at different temperatures.

In this instance, a smaller amount of Gd^{3+} causes a significant reduction in R_p . As a result, this cathode can operate efficiently at a temperature of about 800 °C with a moderate Mn content (0.5 mol).^[69] Also, at a temperature of 700 °C, $GdBaCo_{1.4}Mn_{0.6}O_{5+\delta}$ can reach a maximum value of 200 $S \cdot cm^{-1}$ for total electrical conductivity which remains high remaining above 100 $S \cdot cm^{-1}$ down to 650 °C.^[70] These findings suggest that Gd-based cathodes are highly suitable for intermediate-temperature SOFCs (IT-SOFCs).

Cerium (Ce)

Magdalena Zybert *et al.*^[53] reported that cerium (Ce^{4+}) has a dual effect by stabilizing the crystal lattice of the material and protecting its surface. The strong Ce–O bonds minimize cation mixing, improve structural ordering, and prevent irreversible phase transitions.^[71] Moreover, cerium forms a protective CeO_2 layer that shields the surface from harmful chemical interactions, such as side reactions with the environment, thereby reducing the risk of crack formation. Experimental results demonstrate that these modifications greatly enhance the material's stability under high loads and significantly improve its mechanical and chemical resistance.

Europium (Eu)

Shao-Lun Cui *et al.*^[72] observed that europium (Eu^{3+}), though less commonly used, exhibits a strong stabilizing effect. Its large ionic radius increases the interplanar distance within the material's structure, positively influencing its mechanical resistance and stability. Like cerium,^[73] europium forms a thin protective surface layer that reduces cation mixing and prevents structural damage. Experimental results have shown that even small amounts of europium (0.5%) can significantly

enhance the durability of materials, improving their resistance to both mechanical and chemical stress.

Praseodymium (Pr)

Clément Nicollet *et al.*^[74] studied SOFC cathodes based on $Pr_2NiO_{4+\delta}$, a Ruddlesden-Popper compound known for its high oxygen surface exchange coefficient (k) and oxygen diffusion coefficient (DO^2).^[75]

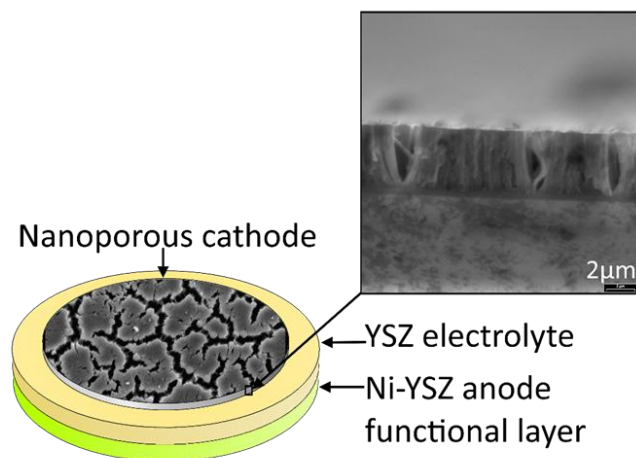


Fig. 4: Thin-film heterostructural SOFC.

The applied method involves infiltrating a solution of praseodymium and nickel nitrates (in a 2:1 ratio) into a porous Gd-doped ceria (GDC) substrate. Heat treatment at 900 °C in a nitrogen atmosphere was found to promote the formation of the $Pr_2NiO_{4+\delta}$ phase due to the reduction of Pr valence to 3+, which is characteristic of the $Pr_2NiO_{4+\delta}$ phase. However,

Table 4: Classification of key SOFC technical challenges and corresponding solution strategies.

Category	Challenge	Solution strategy	Ref.
	- Cr poisoning surface coating;	Chromium evaporation from steel interconnects causes surface degradation, which can be mitigated by Mn–Co spinel coatings applied via slurry or plasma spraying.	120
Short-term optimizable items	- Difficulty controlling layer quality;	Dense, adherent coatings with low porosity are produced by adjusting electrodeposition (pH 3.0–3.5, –1.1 to –1.5 V) or plasma spray.	121
	- Thermal expansion mismatch (TEC incompatibility).	Mismatch between TEC of components causes stress and cracking, mitigated by material selection and buffer layer addition.	122
Long-term basic research items	- Poor performance at intermediate temperatures;	TEC mismatch and low conductivity (with excess Fe) require careful A/B-site co-doping in double perovskites like PGBCO.	123
	- Lack of multifunctional, compatible material systems.	Novel material systems are needed that combine high ionic/electronic conductivity, thermal stability, and chemical compatibility; development involves computational screening and doping strategies.	124

residual phases of Pr₆O₁₁ and NiO were also detected. SEM analysis revealed that infiltration at 900 °C produces nanoparticles (40–80 nm) uniformly distributed on the GDC surface, whereas higher temperatures (1000 °C) lead to their disappearance because of sintering.^[76]

Electrochemical studies on symmetric cells revealed that the polarization resistance (R_p) reached its minimum value (0.075 Ω·cm² at 600 °C) for cathodes treated at 900 °C under a nitrogen atmosphere. This improvement is attributed to the increased specific surface area of the cathode and the catalytic effect of the residual Pr₆O₁₁ phase.^[77] Furthermore, cathodes fabricated using the infiltration method exhibited a greater reduction in R_p compared to those prepared by traditional techniques such as screen printing. This also highlights the potential of Pr₂NiO_{4+δ} for application in solid oxide fuel cells (SOFCs) and underscores the significance of optimizing heat treatment and infiltration processes to enhance the electrochemical performance of cathodes.^[78]

Scandium (Sc)

The effect of scandium (Sc³⁺) doping on the properties of the PrBaCo₂O_{5+δ} (PBCO) material was investigated. The study demonstrated that Sc³⁺ doping enhances the electrochemical performance of the cathodes by increasing oxygen vacancy concentration and optimizing the lattice structure.^[79]

Xiangnan Li *et al.*^[80] reported a minimum polarization resistance (ASR) of 0.123 Ω·cm² at 600 °C for cathodes with x=0.5. Meanwhile, Donghwi Jeong *et al.*^[80] observed a reduction in ASR to 0.44 Ω·cm² at 500 °C for PrBaCo_{1.9}Sc_{0.1}O_{5+δ}. Furthermore, Jeong's study showed that the maximum power density of the cathodes reached 0.73 W·cm⁻² at 500 °C, which is 1.3 times higher than that of the undoped materials reported in Li's work.

Both studies underscore the potential of Sc³⁺ doping to enhance the performance of cathodes for low-temperature (LT-SOFC) and intermediate-temperature (IT-SOFC) solid oxide fuel cell applications, highlighting their promise for further development.

For a more precise visual comparison of the characteristics of various rare earth cathode materials, we have compiled Table 3, which includes key parameters – activation energy (Ae), thermal expansion coefficient (TEC), and area-specific resistance (ASR) at different temperatures – as well as the testing conditions.

Based on the analysis, the composition containing La_{0.6}Sr_{0.4}Co_{0.2}Fe_{0.8}O_{3-δ}+ PrO_{2-δ} was identified as optimal, demonstrating the lowest area-specific resistance (ASR) while maintaining an acceptable thermal expansion coefficient (TEC), making it a promising cathode material for intermediate-temperature solid oxide fuel cells (IT-SOFCs).

5. Tailoring electrochemical properties

Researchers can manipulate the composition and structure of rare-earth based cathode materials to tailor their electrochemical properties.^[81] This flexibility allows for fine-tuning the performance of the cathode to meet specific requirements, such as optimizing electrical conductivity or increasing catalytic activity. Such control also contributes to enhanced material stability, ensuring long-term durability and reliability of cathode materials.^[82]

The electrochemical properties of several materials, including La₂O₃, MnO₂, LMO, and LMO-Pt, were examined using cyclic voltammetry (CV) and linear sweep voltammetry (LSV).^[83,84,85] The experiment was conducted in a 0.10 M KOH aqueous electrolyte. The results showed that La₂O₃, LMO, and LMO-Pt had similar CV responses. In contrast, MnO₂ had slightly higher cathode currents in the potential range from 1.0 to -0.3V. ORR activity was assessed through LSV, revealing onset potentials of approximately 0.7V for MnO₂, LMO, and LMO-Pt, and 0.8V for La₂O₃. According to the Tafel slope analysis, there were variations in the ORR mechanisms, and La₂O₃ displayed a unique electrochemical behavior. Impedance spectroscopy measurements using Potentiostatic Electrochemical Impedance Spectroscopy (PEIS) and Galvanostatic Electrochemical Impedance Spectroscopy

(GEIS)^[86] revealed differences in capacitive features and charge transfer resistances among the materials. According to the GEIS results, the ORR activity ranking was as follows: $\text{MnO}_2 > \text{LMO-Pt} > \text{LMO} > \text{La}_2\text{O}_3$, with variations attributed to chemical characteristics and mass transport limitations. Impedance plots showed significant elongations in La_2O_3 , indicating its role in ORR mechanism adsorption and spill-over effects.^[87] These findings aid in understanding the electrochemical properties of these materials for potential catalytic applications in energy conversion systems.

6. Enhancing of SOFC cathode performance

Doping

Doping of SOFC cathodes is a critical strategy for enhancing their electro-catalytic properties, electrical conductivity, and mechanical stability, as well as reducing device production costs.^[88] Below are selected studies on commonly used materials, their dopants, and the resulting impacts on performance.

L. Wang *et al.*^[42] prepared $\text{Sr}_2\text{FeMo}_{0.5}\text{X}_{0.5}\text{O}_6$ ($\text{X} = \text{Ni}, \text{Co}, \text{Mn}, \text{Zn}$) materials and tested their properties. Co and Ni dopants resulted a pure phase, while the dopants Mn and Zn caused an apparent secondary phase. Using a Co-dopant provides clear advantages when oxygen vacancy concentration and diffusion kinetics. The Co-doped SFM cathode exhibited a significantly lower activation energy of 0.76 eV compared to the values of 5.52 eV and 2.28 eV observed for the Ni-doped SFM cathode under different conditions. Co-doped SFM's cathodic reaction accelerates, resulting in 1306 mW cm^{-2} fuel cell performance at 700°C . This discovery demonstrates that using a suitable dopant can solve the low-performance issue of a standard SFM cathode, making it a favourable candidate for H-SOFCs.^[89,90]

J. Ma *et al.*^[61] discuss the creation and assessment of La_2CuO_4 (LSCN), a perovskite oxide that has been doped with Sr and Ni for use as a cathode material in protonic ceramic fuel cells (PCFCs). Sr and Ni were successfully integrated into the lattice, transforming the crystal structure from orthorhombic to tetragonal, which improved ORR activity of the LSCN cathode. At 750°C , the cathode showed a peak power density of $1020 \text{ mW}\cdot\text{cm}^{-2}$ and demonstrated excellent stability over 100 hours of testing at 650°C . The study also provides insight into the material's thermal expansion behavior, defect chemistry, and electrochemical performance, indicating that it has significant potential for use in PCFC applications.^[91]

J. Zhou *et al.*^[73] has explored the use of triple-conducting layered perovskites, specifically $\text{NdBa}_{0.5}\text{Sr}_{0.5}\text{Co}_{1.5}\text{Fe}_{0.5}\text{O}_{5+\delta}$ (NBSCF), as a cathode material for H-SOFCs. They investigated the impregnation of NBSCF onto the surface of LSCF cathodes to enhance electro-catalysis and stability. The

findings show that the impregnation of triple conducting NBSCF can significantly improve the migration of protons, leading to a notable enhancement in cell performance. Overall, the impregnation of triple-conducting NBSCF onto LSCF cathodes has shown great promise in enhancing the performance of H-SOFCs by addressing the challenges associated with cathode reactions.^[92]

L. Bian *et al.*^[48] found that when $\text{Mo}^{5+/6+}$ is introduced into $\text{La}_{0.8}\text{Sr}_{0.2}\text{FeO}_3$, it increases the lattice parameters and unit volume. This is due to the instantaneous ionic radius of Mo and lower valence Fe. The valence of Fe is equal to 0.78/0.645/0.585 Å for $\text{Fe}^{2+}/\text{Fe}^{3+}/\text{Fe}^{4+}$. After exposure to H_2 (3% H_2O) at 800°C for 10 hours, LSFMo oxides retain their perovskite structure without any secondary phases, unlike LSF oxides, which decompose into the Ruddlesden-Popper phase and metallic iron.^[93] These studies indicate that $\text{Mo}^{5+/6+}$ substitution significantly increases the structural stability of LSF in reducing media.^[94] Therefore, LSFMo oxide exhibits high catalytic activity and can potentially be used as a symmetrical cathode material for SOFC.^[95]

M.Z. Khan *et al.*^[11] discussed using LSBCFN as a cathode material and presented a promising strategy for effectively suppressing surface segregation of Sr. This was achieved by doping Nb B-sites in CBP, which prevented Sr migration through the GDC intermediate layer via vapor phase transport.^[96] Developing reliable Sr-free cathodes can solve performance issues associated with cation migration effectively.

L. Gan *et al.*^[63] experimentally manufactured cathodic half-cells with the matched Coefficient of Thermal Expansions, allowing for Co and Co-W alloy coatings on LSM and LSCF cathodes via screen printing. The Co-W coating effectively suppresses Cr diffusion, preventing SrCrO_4 formation. The absence of Cr oxides indicated that Cr cations failed to penetrate the CoWO_4 barrier, inhibiting Cr diffusion. EDS analysis showed Cr diffusion and oxide formation in uncoated LSM and LSCF, resulting in voids and accelerated oxidation.^[97] Co-coating shows protective effects, yet structural failures occur with LSM showing Mn-enriched intrusion and cracks. Co-cracking leads to decreased electrical conductivity. CoCr_2O_4 spinel forms in Co-coated LSCF, lowering conductivity. Co-W coating presented a multilayer structure, inhibiting Cr diffusion and avoiding internal Ferritic Stainless-Steel oxidation.^[98] Co-W-coated LSM exhibited better performance and durability than Co-coated LSM, while Co-W-coated LSCF faced potential spallation.

Surface modification (thin-film cathode)

One of the main challenges in developing thin-film cathodes is to enhance the material's performance by using a thin-film heterostructure, approximately 50 to 100 μm thick, in contact with the YSZ functional layer (see Fig. 3). The functional layer aims to improve electrochemical reactions by balancing conductivity and porosity to minimize potential drops across its thickness. However, from a practical standpoint, the most

important issue to address soon in the fabrication of μ -SOFCs is their thermal-mechanical stability.^[99] For example, R. Wang *et al.*^[100] reported achieving a maximum power density of $140 \text{ mW}\cdot\text{cm}^{-2}$ at 580°C for solid oxide fuel cells based on YSZ using hydrogen as fuel. They deposited a porous cathode thin-film onto the YSZ side using a pulsed laser, while a porous NiO-YSZ layer was deposited onto the porous Ni side to enhance the triple-phase boundary (TPB). Moreover, there have been reports on the approach that employs a Ni substrate for the production of μ -SOFCs.

Experimental studies^[101] have identified $\text{NdBaFeCo}_{0.5}\text{Cu}_{0.5}\text{O}_{5+\delta}$ as a promising double perovskite material, demonstrating that the partial substitution of barium (Ba) with strontium (Sr) in its structure significantly enhances its thermal and electrical transport properties. Notably, the highest specific electrical conductivity of 299 S/cm was recorded at 750°C for the composition $\text{NdSrFeCo}_{0.5}\text{Cu}_{0.5}\text{O}_{5+\delta}$.

Advancements in cathode technology also play a crucial role in improving the performance of SOFCs. C. Gumeci *et al.*^[102] discovered that a three-dimensional nanofiber network cathode offers high porosity and large interfacial contact areas, which leads to improved ORR kinetics. The nanofiber cathode demonstrated a lower polarization resistance of approximately 0.025 mm^2 at around 700°C compared to the commercial BSCF cathode, which has a polarization resistance of about $0.040 \Omega \text{ cm}^2$ under similar conditions. Additionally, PBSCF fibers demonstrated peak power densities of $\sim 2539 \text{ mW/cm}^2$ at 750°C and $\sim 1580 \text{ mW/cm}^2$ at 700°C , while the BSCF cathode exhibited power densities of $\sim 1974 \text{ mW/cm}^2$ at 750°C and $\sim 1304 \text{ mW/cm}^2$ at 700°C . In addition to structural modifications, material composition also plays a key role in optimizing SOFC cathodes. When integrated into electrode structures, such as cathodes, nanofiber networks significantly increase the available surface area for electrochemical reactions.^[103] This enhancement facilitates faster oxygen ion transport across YSZ, reducing polarization losses and ultimately improving SOFC efficiency. Moreover, Fe-based perovskites, such as $\text{SrFe}_{0.9}\text{Ti}_{0.1}\text{O}_{3-\delta}$ exhibit high catalytic activity at 700°C , characterized by a surface oxygen exchange coefficient of $1.5 \times 10^{-3} \text{ cm/s}$, making them competitive alternatives to traditional R-E-based cathode materials.^[104]

In general, Fe-containing cathode materials represent a promising approach for developing efficient and cost-effective SOFCs, offering both high performance and long-term operational stability.

Nanostructured cathode

Sudhanshu Dwivedi *et al.*,^[6] reviewing various cathode materials, point out the thermal expansion mismatch between cathode and electrolyte materials, which may lead to delamination, and cite nano structuring and doping as methods to improve performance and stability. Shah *et al.*^[105] highlight that the delamination mechanism and temperature gradients between the cathode and electrolyte need to be considered for the long-term performance of SOFCs, pointing out the high thermal expansion coefficient (TEC) of some promising

cathode materials such as BSCF ($\text{Ba}_{0.5}\text{Sr}_{0.5}\text{Co}_{0.8}\text{Fe}_{0.2}\text{O}_{3-\delta}$) and suggest strategies to use negative thermal expansion (NTE) materials and cation substitution. In turn, Omeiza *et al.*^[106] note that the long-term availability of heteroatoms (such as cobalt, lanthanum, and strontium) used for doping may face supply chain constraints and suggest focusing on sustainable materials and raw material availability as key factors for future research.

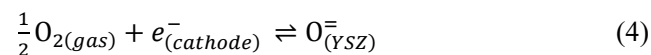
The high cost of fuel cells and their durability and long-life problems have made using nanomaterials desirable in their devices and related applications. In addition, environmental protection and sustainable development have made the choice of nanostructured materials extremely important. Recent studies have shown that improving the cathode in the SOFS is limited and needs further development (Fig. 4).^[107,108]

The use of nanotechnology in the energy sector has significantly expanded, increasing power and efficiency.^[109] R-E elements have excellent electrical and electrochemical properties and high mechanical, thermal, and chemical stability, making them the most promising to use.^[110]

Triple phase boundary

In solid oxide fuel cells, electrochemical reactions occur at the triple phase boundary (TPB) point, where the gas phase, the solid electrode phase, and the electrolyte phase meet. A longer TPB is important for improving the performance of lower or intermediate-temperature SOFCs, with the TPB length being a critical geometric parameter that dominates electrode and SOFC efficiency. The length of this TPB is closely connected to the micromorphology of the electrode itself.^[111]

SOFC cathodes are engineered to have a high reaction rate for the multistep ORR:



This multi-stage reaction includes diffusion, adsorption, electronic conductivity, charge transfer reactions, and ionic conductivity. In electrically conductive perovskite-type materials such as doped LaMnO_3 , LaCoO_3 , PrCuO_3 , or LaFeO_3 , three potential reaction paths are considered for the most common cathode materials^[112,113] electrode surface, electrode volume, and electrolyte surface pathways.

- the surface path of the electrode refers to the process of oxygen particles adsorbing and moving along the electrode surface in the direction of TPB, followed by the complete transfer of ions into the electrolyte;

- in this process, the locally dissociated, ionized oxygen forms get embedded into the solid electrode. These oxide ions then transferred through the electrode's volume and subsequently transfer to the electrolyte by ion transfer;

- the surface path of the electrolyte takes into account the adsorption of oxygen particles on the electrolyte's surface and their migration along the electrolyte's surface to the TPB.

Composite cathodes

The performance of the SOFC system at lower temperatures also depends on the sample's geometric ratio (L/M). The

cross-sectional area should be maximized, while the thickness should be minimized to shorten the electrical path and enhance the durability of the SOFC. Reducing the electrolyte thickness can enhance SOFC performance at lower temperatures, with an optimal cathode area of 0.15–0.20 cm².^[114]

It is important to consider the pressure applied when forming the samples. When manufacturing a dense composite cathode, uniaxial pressing with a pressure of 7-12 Mpa should be used.^[115] This pressure range ensures optimal densification while preserving sufficient porosity for gas diffusion. Higher pressures enhance grain boundary contact, reducing interfacial resistance and improving overall electrochemical performance. However, excessive pressure may decrease porosity, hindering oxygen diffusion and negatively affecting the kinetics of the ORR.

Furthermore, the addition of 10% ammonium acid increases the porosity of the cathode fired at a temperature of 1300 °C, demonstrating the good compatibility of the materials used in composite cathodes.^[116] This process promotes the formation of interconnected pores, enhancing gas permeability and catalytic activity. Maintaining a balance between densification and porosity is crucial for achieving high SOFC performance.

Additionally, alternative processing techniques, such as tape casting and screen printing, can modify the cathode microstructure, affecting grain size and mechanical integrity.^[117] Understanding the correlation between processing parameters and material properties enables the optimization of cathode performance in terms of ORR activity, conductivity, and long-term stability. By carefully selecting manufacturing conditions, the cathode microstructure can be tailored to achieve the desired electrochemical properties.

7. Challenges in high-efficient SOFC cathodes

Recent advancements in rare-earth based cathode materials for SOFCs have shown promising results.^[118] Researchers have explored innovative compositions, including double perovskites and layered structures, to enhance performance further.^[119] However, challenges such as material cost, resource availability, and the potential for rare-earth scarcity remain significant considerations in developing and commercializing these materials. Among these, ensuring long-term stability remains one of the most pressing issues. As numerous studies have demonstrated, scandium-stabilized zirconia (ScSZ)-based electrolytes are susceptible to degradation due to phase transformations and impurity diffusion, which result in increased resistance and reduced ionic conductivity, even after prolonged exposure to high temperatures for 100-1000 hours.^[120] Similarly, nickel-based anode cermet's, particularly Ni/GDC, suffer from metallic phase agglomeration during prolonged operation, carbon deposition when utilizing hydrocarbon fuels, and high sensitivity to sulfur-containing impurities, resulting in partially irreversible degradation.^[120,121] In industrial applications, SOFCs are expected to operate for at least 5.000-

40.000 hours, highlighting the critical importance of long-term stability.

Another critical challenge is the mismatch in thermomechanical and chemical properties among the functional layers in the multilayer SOFC structure. The formation of non-conductive phases, such as SrZrO₃, at the cathode-electrolyte interface due to chemical interactions between the materials significantly degrades interfacial conductivity.^[122] Differences in the thermal expansion coefficients of individual components can induce internal stresses, leading to delamination and cracking of layers during thermal cycling.^[123]

Several materials, such as Pr_{0.5}Gd_{0.5}BaCo_{2-y}Fe_yO_{5+δ}, PBCO, and GBCO powders, are synthesized by solid-state reactions used as SOFC cathodes. These^[124] materials were analyzed for their electrical conductivity and thermal expansion properties. Symmetrical cells were then prepared for cathodic polarization resistance analysis. The findings indicate that co-doping on the A/B sites of the materials enhances their electrical conductivity while reducing their thermal expansion. However, increased Fe doping in PGBCO compositions lowers electrical conductivity despite reducing thermal expansion.

These examples highlight the need for a systematic analysis of technological limitations. This study classifies key SOFC challenges by solvability, distinguishing short-term (engineering) and long-term (fundamental) approaches with corresponding solutions (Table 4).

Further research is needed to optimize double perovskite materials for IT-SOFC cathodes, with a long-term focus on enhancing their electrochemical and thermomechanical properties.

8. Conclusion and perspective

The quest for efficient and sustainable energy solutions has driven intensive research into improving the performance of SOFCs, with a particular focus on cathode materials. Rare-earth elements have emerged as valuable contributors to the development of advanced cathodes, offering enhanced catalytic activity, chemical stability, and tunable electrochemical properties.

The influence of doping on cathode materials has also been extensively studied, with findings indicating that suitable dopants can significantly improve the performance of traditional cathode materials. For example, the introduction of Co-dopants in SFM cathodes resulted in lower activation energy, leading to improved fuel cell performance.

Recent advancements in rare-earth-based cathode materials-including novel compositions such as double perovskites-demonstrate considerable potential for further enhancing SOFC efficiency and durability. However, challenges such as material cost, long-term stability, and resource availability remain critical concerns.

To overcome these challenges, several strategies are under investigation:

- development of composite and infiltrated cathodes that combine high oxygen ion and electron conductivity;
- application of protective buffer layers (e.g., doped ceria) between cathode and electrolyte to suppress unwanted reactions;
- optimization of thin-film epitaxial architectures to reduce ohmic losses and operating temperatures;
- introduction of non-precious metal-based alternatives, such as Fe/Mn-based perovskites, to enhance cost-effectiveness.

In summary, rare-earth-doped cathodes continue to offer high promise for SOFC development, but future research must increasingly focus on balancing performance with cost, durability, and manufacturability to enable reliable and economically viable commercial SOFC systems.

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Conflict of Interest

There are no conflicts to declare.

Supporting Information

Not applicable.

Nomenclatures

ASR – Area-Specific Resistance
 FC – Fuel Cell
 GEIS – Galvanostatic Electrochemical Impedance Spectroscopy
 H-SOFC – Proton-Exchange Solid Oxide Fuel Cell
 IT-SOFC – Intermediate-Temperature Solid Oxide Fuel Cell
 LT-SOFC – Low-Temperature Solid Oxide Fuel Cell
 O-SOFC – Ion-Exchange Solid Oxide Fuel Cell
 ORR – Oxygen Reduction Reaction
 PEIS – Potentiostatic Electrochemical Impedance Spectroscopy
 R-E – Rare-Earth elements
 R_p – Polarization Resistance
 SOFC – Solid Oxide Fuel Cell
 TEC – Thermal Expansion Coefficient
 TPB – Triple-Phase Boundary

CRedit Statement

Renat Beissenov: Conceptualization, Supervision, Project administration, Funding acquisition. **Bolat Bazarbayev:** Investigation, Methodology, Formal analysis, Writing – Original Draft, Visualization. **Mukhtar Yeleuov:** Data curation, Validation, Writing – Review & Editing. **Azamat Kudaibergen:**

Resources, Software, Visualization.

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