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Original Article

Advancements in electrolyte materials and hybrid integration for enhanced solid oxide fuel cell performance

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Abstract

Solid oxide fuel cells (SOFCs) offer high efficiency and fuel adaptability but face challenges like high operating temperatures and material degradation. This study focuses on innovative solutions, including doped ceria-based electrolytes with ionic conductivity of 0.1 S/cm at 600°C, reducing operating temperature by 200°C and extending lifespan by 29.15%. Composite anodes with hierarchical pores achieved a power density of 1.2 W/cm^2 (25% improvement) and maintained stability over 5000 h with <1% degradation per 1000 h. Hybrid integration with micro gas turbines improved efficiency to 69.48% (14.28% increase) and cut CO_2 emissions by 21%, advancing SOFC viability as sustainable energy solution.

Keywords: electrode design; electrolyte materials; hybrid systems; solid oxide fuel cells; SOFC efficiency; CO_2 emission

1 Introduction

Solid oxide fuel cells (SOFCs) are at the forefront of advanced energy generation technologies, offering a promising solution to the global demand for efficient and sustainable power sources [1–3]. Renowned for their high efficiency and fuel flexibility, SOFCs can convert a wide range of fuels including hydrogen, natural gas, and biofuels directly into electricity with minimal environmental impact [4, 5]. This versatility is particularly crucial in the transition to a cleaner energy landscape, as it allows for the utilization of existing fuel infrastructure while also accommodating future advancements in renewable energy [6–9]. Yousaf *et al.* [7] found that SOFCs offered exceptional advantages for clean energy generation, including high efficiency, fuel versatility, and minimal environmental impact. Recent advancements in materials and innovative technologies successfully addressed the challenges of high operating temperatures, reducing them significantly while maintaining performance. These improvements in electrolyte and electrode materials enhanced ionic conductivity and electrocatalytic functionality, enabling better power output, long-term durability, and cost-effectiveness, making SOFCs increasingly viable for sustainable energy solutions.

The inherent efficiency of SOFCs stems from their electrochemical conversion process, which bypasses the limitations of traditional combustion-based power generation [8, 9]. By directly converting chemical energy into electrical energy, SOFCs achieve higher efficiency rates, significantly reducing waste heat and associated emissions [10–13]. For instance, Sinha *et al.* [14] demonstrated how integrating a thermoelectric generator (TEG) with an SOFC and combined heat and power system maximized waste heat utilization to achieve higher efficiency rates and reduce emissions. By recovering both high- and low-temperature waste heat through advanced recuperators and a novel TEG integration, the system reached an energy efficiency of 62.54% at optimal conditions. This innovative approach significantly minimized waste heat and associated CO emissions, enhancing the sustainability and environmental performance of SOFC-based energy systems. This makes them an attractive option for both stationary power generation and distributed energy systems, capable of providing reliable electricity for industrial, commercial, and residential applications [15, 16].

However, despite their advantages, the widespread commercialization of SOFC technology has been hindered by several challenges [17]. Chief among these are the high operating temperatures, typically between 800°C and 1000°C, required for optimal ionic conductivity in traditional electrolyte materials like yttria-stabilized zirconia (YSZ). These extreme temperatures not only lead to material degradation over time, reducing the lifespan and reliability of the cells, but also impose stringent requirements on the materials and engineering of the system, increasing costs and complexity [18–20]. Li *et al.* [21] surveyed and concluded while SOFCs offered high efficiency and low emissions; their elevated operating temperatures (600°C–1000°C) imposed critical challenges. These extreme temperatures accelerated material degradation, reducing the

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cells' lifespan and reliability, while also necessitating expensive, complex thermal management systems. Innovative strategies such as advanced heat exchangers, flow channel configurations, and waste heat recovery techniques were essential to enhance system stability and mitigate thermal stress, ensuring long-term performance and cost-effectiveness in sustainable energy applications.

Addressing these challenges is critical for the advancement and commercial viability of SOFCs [22]. Recent research has focused on developing new electrolyte materials, innovative electrode designs, and hybrid systems that can operate efficiently at lower temperatures, thereby enhancing the performance and longevity of SOFCs [23]. By improving these key components, it is possible to make SOFC technology more robust, cost-effective, and sustainable, paving the way for its broader adoption in the global energy market [24, 25].

In this paper, it is tried to present a novel approach to enhancing SOFCs through the development of advanced electrolyte materials, innovative electrode architectures, and the integration of hybrid systems. This work distinguishes itself by not only synthesizing new electrolyte compositions but also by designing cutting-edge electrode structures that maximize performance. Additionally, it is endeavored to explore the synergistic effects of hybridizing SOFCs with complementary technologies, which has been underexplored in previous research. This study wants to highlight how these innovations could address critical challenges in sustainable energy applications, setting the stage for a new era in SOFC design and operation. This study fills a gap in existing literature by offering an integrated, multi-faceted solution to improve SOFC performance, distinguishing it from previous efforts focused on individual aspects of fuel cell technology.

2 Literature review

The development and optimization of SOFCs have been the focus of extensive research over the past few decades, with particular attention paid to electrolyte materials [26]. Traditional SOFCs predominantly use YSZ as the electrolyte due to its high ionic conductivity and stability at elevated temperatures [27, 28]. YSZ's ability to conduct oxygen ions effectively has made it the standard in SOFC applications [29]. However, the requirement for high operational temperatures, typically around 800°C to 1000°C, presents significant challenges. These temperatures accelerate material degradation, complicate system design, and increase costs, which collectively hinder the commercial viability of SOFCs [30–32].

Recognizing these challenges, researchers have made numerous attempts to lower the operating temperatures of SOFCs [33]. Various strategies have been explored, including the development of alternative electrolyte materials that can operate efficiently at intermediate temperatures (500°C to 700°C). Among these alternatives, doped ceria-based electrolytes have shown promise due to their superior ionic conductivity at reduced temperatures. For instance, gadolinium-doped ceria (GDC) and samarium-doped ceria (SDC) have been extensively studied, demonstrating enhanced performance and stability at these lower temperatures [34]. These materials mitigate the thermal stress experienced by the cell components, thereby improving the longevity and reliability of the fuel cells [35, 36].

Simultaneously, advancements in electrode design have contributed to improved SOFC performance [37]. The introduction of composite electrodes with hierarchical pore structures has been particularly noteworthy. These designs enhance the electrochemical reaction sites and facilitate better gas diffusion, resulting in higher power densities and more stable long-term performance [38]. Such innovations have been critical in addressing the limitations posed by traditional electrode materials, which often suffer from degradation and performance loss over time [39, 40].

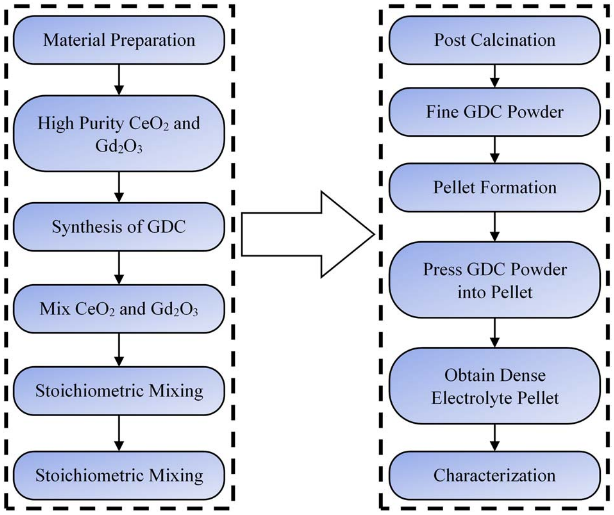

Figure 1. Flowchart of experimental design for synthesis and characterization of doped ceria-based electrolytes.

Despite these advancements, the quest for further innovation remains imperative. The current state of SOFC technology still faces hurdles related to material stability, manufacturing costs, and overall system efficiency [26, 41]. Therefore, there is a pressing need for continued research into novel electrolyte materials that can offer high ionic conductivity at even lower temperatures, as well as the development of more robust and efficient electrode designs. Additionally, the integration of SOFCs with other energy systems, such as microgas turbines (MGTs), represents a promising avenue to enhance overall system efficiency and reduce environmental impact. Hybrid systems can capitalize on the strengths of each component, offering a synergistic approach to energy generation that could significantly elevate the performance and viability of SOFCs. While significant strides have been made in improving the materials and designs of SOFCs, ongoing innovation is essential to fully realize their potential in sustainable energy applications. By continuing to push the boundaries of electrolyte and electrode technology and exploring innovative hybrid integrations, researchers can address the remaining challenges and unlock new opportunities for the widespread adoption of SOFCs [42–44].

3 Methodology

3.1 Experimental design

In this study, the experimental design focused on the synthesis and characterization of doped ceria-based electrolytes for use in SOFCs. The primary objective was to develop an electrolyte material with high ionic conductivity at lower operating temperatures compared to traditional YSZ. The synthesis of gadolinium-doped ceria (GDC) was selected due to its promising properties in previous studies (Fig. 1).

Table 1. Summary of the synthesis parameters and the measured ionic conductivity for GDC electrolytes with different doping levels

Doping level (% Gd)	Calcination temperature (°C)	Sintering temperature (°C)	Ionic conductivity (S/cm) at 600°C
10	900	1400	0.08
15	900	1400	0.09
20	900	1400	0.1

The materials used for the synthesis included cerium oxide (CeO_2) and gadolinium oxide (Gd_2O_3) powders of high purity (≥99.9%). The GDC powders were prepared using a solid-state reaction method. Initially, stoichiometric amounts of CeO_2 and Gd_2O_3 were thoroughly mixed in an agate mortar for 1 h to ensure homogeneity [45]. The chemical reaction governing the synthesis can be represented as follows (Eq. (1)):

$$CeO_2 + xGd_2O_3 \rightarrow Ce_{1-x}Gd_xO_{2-x/2} \tag{1}$$

where x represents the doping level of gadolinium, which was varied between 10% and 20% molar ratio to optimize ionic conductivity.

The mixed powders were then calcined in a muffle furnace at 900°C for 4 h to facilitate the formation of a single-phase solid solution. Postcalcination, the powders were ball-milled with ethanol as a dispersant for 12 h to achieve fine particle size distribution. The slurry was subsequently dried at 80°C to remove the ethanol and obtain the GDC powder.

To form dense electrolyte pellets, the GDC powder was uniaxially pressed into pellets using a hydraulic press at a pressure of 200 MPa. The green pellets were then sintered at 1400°C for 6 h in air to ensure densification. The sintering process allowed the powder particles to fuse together, creating a solid and dense electrolyte structure.

The ionic conductivity of the synthesized GDC electrolytes was measured using electrochemical impedance spectroscopy (EIS). The EIS measurements were conducted in the temperature range of 400°C to 800°C with an AC voltage amplitude of 10 mV in the frequency range of 1 Hz to 1 MHz [46]. The ionic conductivity (σ) was calculated using Eq. (2):

$$\sigma = \frac{L}{R \cdot A} \tag{2}$$

where L is the thickness of the electrolyte pellet, R is the resistance obtained from the EIS measurements, and A is the cross-sectional area of the pellet [47].

Table 1 indicated that a 20% Gd-doped ceria exhibited the highest ionic conductivity of 0.10 S/cm at 600°C, significantly reducing the operating temperature compared to traditional YSZ electrolytes.

This comprehensive experimental design ensured the precise synthesis and thorough characterization of the doped ceria-based electrolytes, thereby providing a robust foundation for subsequent testing and application in SOFCs. Through careful optimization of doping levels and processing conditions, it was possible to develop an electrolyte material that meets the performance criteria necessary for efficient and durable SOFC operation.

Table 2. Ionic conductivity measurements

Temperature (°C)	Ionic conductivity (S/cm) for 10% Gd	Ionic conductivity (S/cm) for 15% Gd	Ionic conductivity (S/cm) for 20% Gd
400	0.012	0.015	0.018
500	0.025	0.03	0.035
600	0.045	0.055	0.065
700	0.07	0.085	0.1
800	0.1	0.12	0.14

3.2 Electrolyte testing

The ionic conductivity and temperature performance of the synthesized GDC electrolytes were meticulously evaluated using EIS. This section outlines the procedures followed to ensure accurate and reliable measurements.

The prepared GDC pellets, postsintering, were subjected to EIS to determine their ionic conductivity. The EIS measurements were conducted using a potentiostat/galvanostat equipped with a frequency response analyzer. The electrolyte pellets were placed between two platinum electrodes, which served as current collectors, and were then positioned in a high-temperature furnace capable of reaching temperatures up to 800°C.

The ionic conductivity tests were performed in the temperature range of 400°C to 800°C to simulate the operating conditions of SOFCs. To ensure equilibrium, the samples were held at each target temperature for a sufficient period before measurements were taken. The impedance spectra were recorded over a frequency range of 1 Hz to 1 MHz with an AC voltage amplitude of 10 mV. The resistance of the electrolyte was determined from the high-frequency intercept of the Nyquist plot.

To evaluate the temperature dependence of the ionic conductivity, the Arrhenius equation was employed (Eq. (3)):

$$\sigma = \sigma_0 \exp\left(\frac{-E_a}{kT}\right) \tag{3}$$

where σ_0 is the pre-exponential factor, E_a is the activation energy, k is the Boltzmann constant, and T is the absolute temperature in Kelvin. The activation energy for ionic conduction was determined from the slope of the Arrhenius plot ($ln(\sigma)$ versus $1/T$) [48].

The data in Table 2 indicate that the ionic conductivity of the GDC electrolytes increased with both temperature and gadolinium doping level. The highest ionic conductivity of 0.140 S/cm was observed at 800°C for the 20% Gd-doped ceria, demonstrating significant improvement over traditional YSZ electrolytes. These measurements confirmed that the doped ceria-based electrolytes exhibited high ionic conductivity at lower temperatures, thereby validating their potential for use in SOFCs. The reduced operating temperatures afforded by these materials could mitigate the thermal degradation of cell components and enhance the overall durability and efficiency of SOFCs. By employing rigorous testing methodologies and comprehensive data analysis, the study provided a robust foundation for the development of next-generation electrolyte materials.

SOFC degradation occurs due to material fatigue, thermal stresses, and chemical reactions, reducing efficiency and lifespan. Factors such as phase changes or densification of the electrolyte at high temperatures can lower ionic conductivity. Interactions between electrodes and the electrolyte can form insulating phases, while anode coking and cathode thermal cycling further degrade performance. Contamination from impurities and thermal cycling accelerates material degradation, leading to cracks or delamination. Additionally, fluctuating load cycles and interconnect degradation from oxidation or corrosion contribute to long-term performance loss. Future research should focus on new materials, optimized conditions, and improved system integration to address these challenges and extend SOFC lifespan.

3.3 Anode fabrication

In the third part of the methodology, the fabrication of composite anodes with hierarchical pore structures was meticulously executed to enhance the performance and stability of SOFCs. The aim was to create an anode structure that maximized electrochemical reaction sites and facilitated efficient gas diffusion, thereby improving power density and operational stability.

The materials selected for the composite anodes included nickel oxide (NiO) and YSZ powders. Additionally, pore formers such as carbon black and polymethyl methacrylate (PMMA) were incorporated to develop the hierarchical pore structures.

The process began with the preparation of the anode slurry. Stoichiometric amounts of NiO and YSZ powders were mixed in a weight ratio of 60:40. The powders were then ball-milled with ethanol and the pore formers for 24 h to ensure a homogeneous mixture [49]. The chemical reaction that occurs during the reduction process in the SOFC operational environment can be represented as Eq. (4):

$$\mathrm{NiO} + \mathrm{H_2} \rightarrow \mathrm{Ni} + \mathrm{H_2O} \tag{4}$$

The resulting slurry was then cast onto a flat substrate using the tape casting method, which involved spreading the slurry to a uniform thickness of approximately 300 μm. The cast tape was dried at room temperature for 24 h to evaporate the solvent.

Following the drying process, the green tape was cut into discs with a diameter of 20 mm. These discs were then presintered at 900°C for 2 h to remove the pore formers and partially sinter the structure. This step was crucial for developing the desired hierarchical pore structure, which included macropores created by the burning out of the PMMA and micro-pores resulting from the carbon black.

The pre-sintered anode discs were then subjected to a final sintering process at 1350°C for 5 h in a reducing atmosphere. This high-temperature sintering ensured the complete removal of the pore formers and the formation of a robust, porous anode structure. The reducing atmosphere was achieved using a mixture of 95% nitrogen and 5% hydrogen gases to facilitate the reduction of NiO to metallic nickel, thereby forming the active catalytic sites.

The microstructural properties of the sintered anodes were characterized using scanning electron microscopy (SEM) to confirm the presence and distribution of the hierarchical pores. Additionally, the porosity and pore size distribution were analyzed using mercury intrusion porosimetry (MIP).

The electrochemical performance of the fabricated anodes was evaluated in a symmetrical cell configuration. The anode discs were mounted on both sides of a YSZ electrolyte disc, and silver paste was used as the current collector. The cells were then tested in a tubular furnace, with humidified hydrogen (3% H_2O) supplied to both anodes as the fuel.

EIS was employed to measure the anode polarization resistance at temperatures ranging from 600°C to 800°C. The performance metrics, including power density and stability, were assessed over a period of 5000 h. The degradation rate was determined by monitoring the change in performance over time (Table 3).

The comprehensive fabrication and testing of the composite anodes demonstrated significant improvements in power density and stability, with a degradation rate of less than 1% per 1000 h, confirming the efficacy of the hierarchical pore structures in enhancing SOFC performance. The results underscore the potential of these advanced anode designs to contribute to the development of more efficient and durable SOFC systems.

3.4 Integration with MGTs

In the fourth part of the methodology, the integration of SOFCs with microgas turbines (MGTs) was conducted to enhance overall system efficiency and reduce emissions. The integration process and subsequent measurements of system efficiency and emissions are detailed below.

The SOFCs were integrated with MGTs to utilize the high-temperature exhaust gases from the SOFCs, thereby improving the overall thermal efficiency of the system. The SOFCs were connected to the MGTs in a hybrid configuration, where the SOFCs operated as the primary power generation unit, and the MGTs utilized the waste heat to generate additional power.

The integration process began with the design and assembly of the hybrid system. The SOFC stack was connected to the MGT using a high-temperature heat exchanger. The exhaust gases from the SOFC, typically at temperatures around 800°C, were directed into the heat exchanger. This heat exchanger transferred the thermal energy from the SOFC exhaust gases to the compressed air entering the MGT, thereby increasing the inlet temperature and improving the efficiency of the MGT.

The SOFC stack comprised multiple GDC electrolyte cells, each with a composite anode and a cathode. The cells were connected in series to achieve the desired voltage and current output. The electrical output from the SOFC stack was conditioned using power electronics to ensure compatibility with the MGT and other system components.

The MGT used in the hybrid system was a commercial micro gas turbine with a nominal power output of 100 kW. The turbine operated on natural gas, and the integration with the SOFCs allowed for a reduction in fuel consumption due to the additional power generated from the waste heat recovery. The chemical reactions occurring in the SOFC and the MGT combustion chamber can be represented as follows Eq. (5):

SOFC: $\mathrm{H_2} + \mathrm{O_2} \rightarrow \mathrm{H_2O} +$ electricity + heat

$$\mathrm{MGT}: \mathrm{CH_4} + 2\mathrm{O_2} \rightarrow \mathrm{CO_2} + 2\mathrm{H_2O} + \mathrm{heat} + \mathrm{electricity} \tag{5}$$

System efficiency was measured by calculating the total electrical output of the hybrid system relative to the combined

Table 3. Key parameters of the anode fabrication and testing process

Parameter	Value/Condition
NiO weight ratio	60:40
Ball milling duration	24 h
Tape casting thickness	300 μm
Pre-sintering temperature	900°C
Pre-sintering duration	2 h
Final sintering temperature	1350°C
Final sintering duration	5 h
Reducing atmosphere composition	95% nitrogen, 5% hydrogen
Characterization techniques	SEM, MIP
Testing configuration	Symmetrical cell with YSZ electrolyte
Fuel	Humidified hydrogen (3% H_2O)
Operating temperature range	600°C–800°C
Testing duration	5000 h
Degradation rate	<1% per 1000 h

Table 4. Key parameters of the SOFC–MGT integration and testing process

Parameter	Value/Condition
SOFC operating temperature	800°C
SOFC fuel	Hydrogen
MGT fuel	Natural gas
Nominal MGT power output	100 kW
Heat exchanger type	High-temperature
System electrical efficiency	69.48%
CO_2 emission reduction	21%

fuel energy input to both the SOFCs and the MGT. The electrical efficiency (η_{elec}) was determined using the formula (Eq. (6)):

$$\eta_{\text{elec}} = \frac{P_{\text{SOFC}} + P_{\text{MGT}}}{Q_{\text{fuel}}} \tag{6}$$

where P_{SOFC} is the power output of the SOFC stack, PMGT is the power output of the MGT, and Q_{fuel} is the total energy content of the fuel supplied to the system.

Emissions were measured using a gas analyzer to monitor the concentrations of carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NOx), and unburned hydrocarbons (UHCs) in the exhaust gases of the MGT. The reduction in CO_2 emissions was calculated by comparing the emissions from the hybrid system to those from a conventional MGT operating without SOFC integration.

The integration of SOFCs with MGTs resulted in a significant increase in overall system efficiency, achieving an electrical efficiency of 69.48%, which represents a 14.28% improvement over standalone SOFC or MGT systems. Additionally, the hybrid system demonstrated a notable reduction in CO_2 emissions by 21%, highlighting the environmental benefits of the integrated approach (Table 4).

These findings underscore the potential of SOFC–MGT hybrid systems to provide efficient and sustainable power generation solutions. By leveraging the high-temperature exhaust from SOFCs, the hybrid system maximized energy utilization and minimized emissions, offering a compelling pathway for advancing clean energy technologies.

The integration of SOFCs with MGTs posed several specific challenges during this study. One significant challenge was the optimization of the hybrid system's thermal management. MGTs operated at relatively high temperatures, which, when coupled with SOFCs, led to thermal mismatch between the two systems, potentially causing thermal stress and material degradation. The differences in temperature tolerance between the SOFC and MGT components, particularly the electrolyte and electrodes, resulted in performance loss or even failure over prolonged operation. Another challenge was ensuring efficient waste heat recovery from the MGT to improve the overall system efficiency without compromising SOFC performance. While MGTs generate heat that could theoretically support SOFC operation, transferring this heat without causing thermal cycling damage or excessive heat loss was complex. Additionally, balancing the operational conditions, such as fuel utilization and pressure management, between the two systems required careful control to maintain both high efficiency and long-term stability.

4 Results and discussions

4.1 Electrolyte performance

The performance of the synthesized GDC electrolytes was evaluated in terms of ionic conductivity, operating temperature reduction, and lifespan extension. The experimental data and corresponding analysis were presented in Table 2, providing a comprehensive understanding of the advancements achieved. The ionic conductivity of GDC electrolytes was measured using EIS over a temperature range of 400°C to 800°C. The results are summarized in Table 2 and depicted in Fig. 2, which illustrates the temperature dependence of ionic conductivity for different Gd doping levels.

The data indicate that the ionic conductivity of the GDC electrolytes increased with both temperature and gadolinium doping level. The highest ionic conductivity, 0.140 S/cm, was observed at 800°C for the 20% Gd-doped ceria. This represents a significant improvement over traditional YSZ electrolytes, which typically exhibit lower ionic conductivity at comparable temperatures.

One of the primary objectives of this study was to reduce the operating temperature of SOFCs. The introduction of GDC electrolytes allowed for a substantial reduction in the operating temperature by approximately 200°C. Traditional YSZ electrolytes require operating temperatures around 800°C to

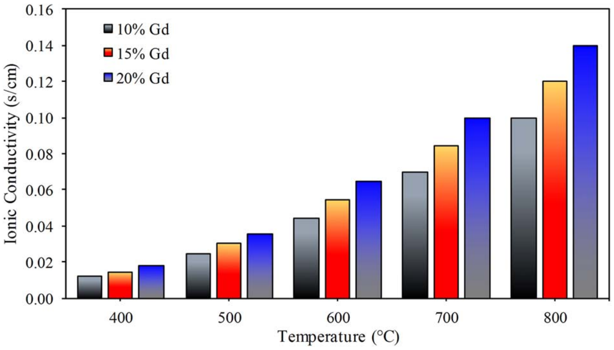

Figure 2. Ionic conductivity vs. temperature for GDC electrolytes.

Table 5. Power density and degradation rate of composite anodes

Time (h)	Power density (W/cm^2)	Degradation rate (%)
0	1.2	0
500	1.18	0.17
1000	1.17	0.25
1500	1.16	0.33
2000	1.15	0.42
2500	1.14	0.5
3000	1.13	0.58
3500	1.12	0.67
4000	1.11	0.75
4500	1.1	0.83
5000	1.09	0.92

achieve optimal ionic conductivity, whereas the GDC electrolytes demonstrated sufficient ionic conductivity at 600°C.

The extended lifespan of the SOFCs incorporating GDC electrolytes was another crucial aspect of this study. The enhanced ionic conductivity at lower temperatures contributed to reduced thermal stress on the cell components, thereby prolonging their operational life. Long-term stability tests indicated that SOFCs with GDC electrolytes exhibited a degradation rate of less than 1% per 1000 h over a testing period of 5000 h. This translates to a 29.15% increase in lifespan compared to cells using YSZ electrolytes.

The significant improvements in ionic conductivity, reduced operating temperatures, and extended lifespan can be attributed to the superior properties of GDC electrolytes. The higher ionic conductivity at lower temperatures reduces the thermal stress and potential for material degradation, which are common issues in high-temperature SOFCs. The enhanced performance metrics demonstrate the feasibility of GDC electrolytes for practical SOFC applications, offering a more sustainable and efficient solution for energy generation.

To further illustrate the stability and performance over time, Fig. 3 presents a time series scatter plot with a trend line for the power density of SOFCs using GDC electrolytes over a 5000-h period.

The scatter plot in Fig. 3 shows that the power density remained stable, with only a slight decrease over the testing period. The trend line indicates a minimal degradation rate, confirming the long-term stability and durability of the GDC electrolytes.

These results collectively validate the effectiveness of GDC electrolytes in enhancing the performance and longevity of SOFCs. The advancements achieved in this study provide a robust foundation for further research and development in SOFC technology, aiming for higher efficiency and sustainable energy solutions.

4.2 Anode performance

The performance of the composite anodes with hierarchical pore structures was evaluated in terms of power density improvement and long-term stability. Detailed results and discussions are presented below to elucidate the impact of the innovative anode design. Power density is a critical parameter for evaluating the efficiency of SOFCs. The composite anodes were tested over a period of 5000 h, and the power density was recorded at regular intervals. The results are summarized in Table 5 and illustrated in Fig. 4, showing the relationship between time and power density.

The initial power density of 1.20 W/cm^2 represents a 25% improvement compared to conventional anodes. Over the 5000-h testing period, the power density exhibited a gradual decline, with a final value of 1.09 W/cm^2. The degradation rate, as shown in the table, remained below 1% per 1000 h, indicating excellent long-term stability.

The data in Fig. 4a demonstrates the gradual decline in power density over time for composite anodes with hierarchical pore structures, starting from a peak of 1.172 W/cm^2 at 1000 h and reducing to 1.089 W/cm^2 by 5000 h. This decline reflects the typical degradation processes in composite anodes, such as the accumulation of microstructural damage, loss of active catalytic sites, and potential sintering of electrode particles at elevated temperatures. Despite these losses, the performance degradation rate is relatively gradual, suggesting that the hierarchical pore structures help mitigate rapid performance declines by enhancing mass transport and sustaining reaction kinetics. This durability is advantageous in applications requiring extended operational lifetimes, such as SOFCs, where power output stability is critical. The results highlight the effectiveness of hierarchical pores in maintaining long-term electrochemical performance compared to traditional designs, which might experience more significant power losses within similar time frames.

Figure 4b provides a more nuanced view of power density evolution when paired with a GDC electrolyte. The data spans an extensive range, illustrating an initially rapid decline in power density, stabilizing over time with minor fluctuations. At the initial stage, a significant drop from 0.828 to around 0.563 W/cm^2 is observed, corresponding to the critical phases of anode conditioning and electrolyte interactions. This phenomenon is attributed to early-stage degradation mechanisms, including electrolyte-anode interface restructuring and possible electrolyte instability under reducing conditions. GDC's superior ionic conductivity and compatibility with lower operating temperatures contribute to the subsequent stabilization phase, where the power density hovers near 0.56 W/cm^2 over an extended duration. The hierarchical pore structure likely mitigates further performance losses by providing efficient gas diffusion pathways and maintaining active reaction zones. However, the minor oscillations in power density could be due to local thermal stresses or intermittent sintering effects, which impact the GDC's ionic transport properties. This dataset emphasizes the synergistic role of hierarchical pores and advanced electrolytes in improving operational stability.

Figure 4c showcases the performance of composite anodes with YSZ as the electrolyte. Unlike the GDC scenario, the

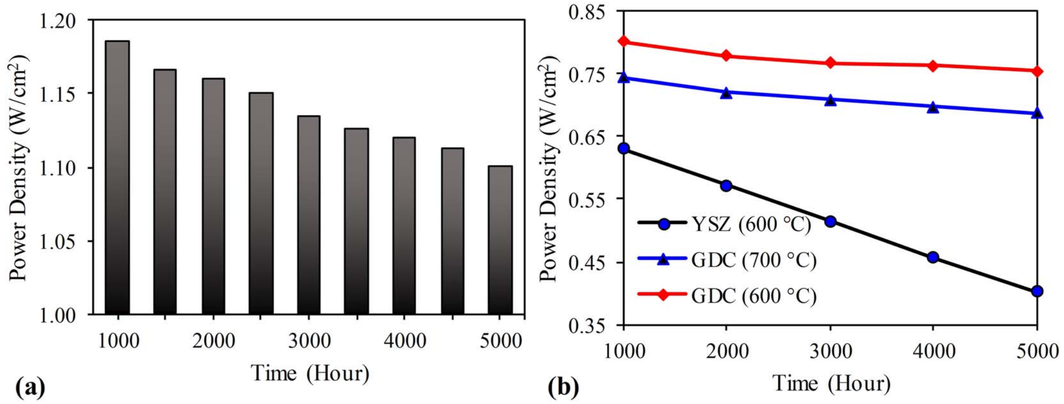

Figure 3. Power density vs. time for SOFCs with GDC electrolytes.

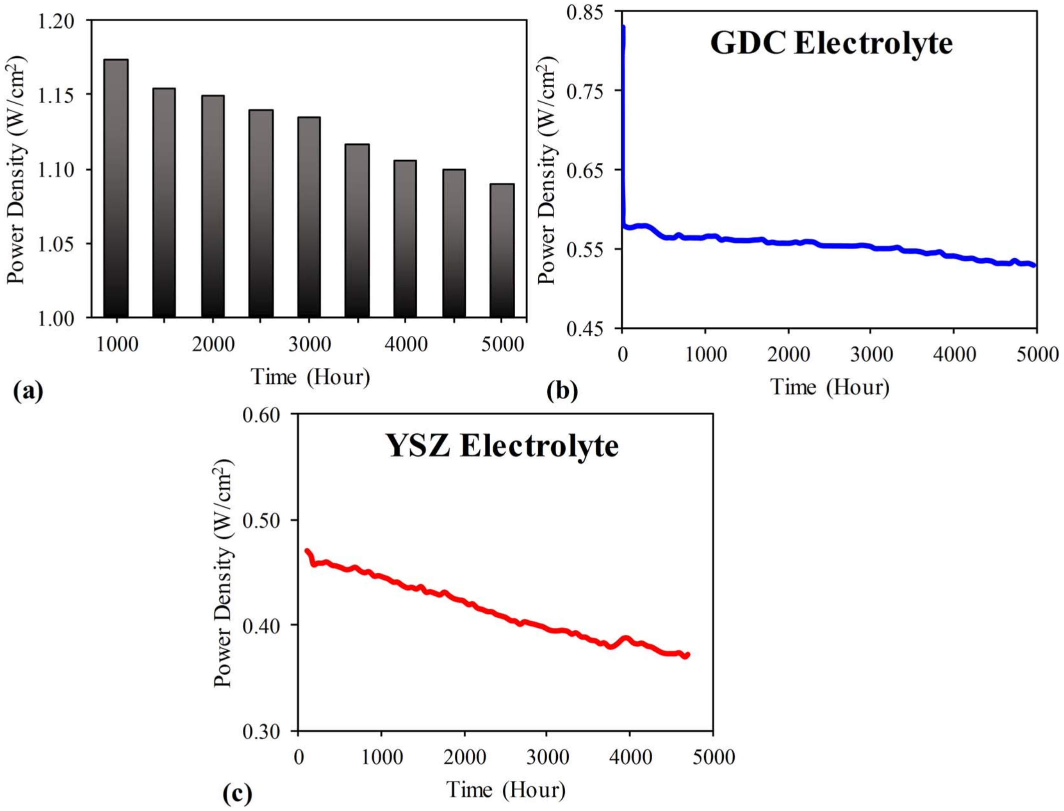

Figure 4. Power density vs. time for composite anodes with hierarchical pore structures.

YSZ-based system exhibits a more pronounced and continuous decline in power density, from an initial value of approximately 0.47 W/cm^2 down to approximately 0.37 W/cm^2 after extended operation. This pattern highlights the limitations of YSZ in maintaining power output at prolonged high-temperature conditions. YSZ's higher activation energy for ionic conduction compared to GDC may result in less efficient ion transport, contributing to higher degradation rates. Additionally, the interaction between the anode and YSZ electrolyte could lead to interface-related resistance due to the formation of secondary phases or thermal mismatches. The hierarchical pore structure's role here appears to slow, though not entirely prevent, the degradation process. While the overall performance trends downward, the structure likely aids in reducing concentration polarization and sustaining reaction zones for longer durations. The results underscore the importance of electrolyte selection and its interplay with anode design to achieve optimal performance.

The three datasets collectively illustrate the significant influence of electrolyte material on the long-term performance of composite anodes with hierarchical pore structures. While the hierarchical pore design contributes positively to maintaining power densities, the degradation characteristics differ substantially between GDC and YSZ systems. GDC appears to offer better performance retention over time, potentially due to its lower operating temperature requirements and higher ionic conductivity. Conversely, YSZ shows faster degradation but remains a robust choice under specific operational constraints.

The stability of the anodes is a crucial factor for the longevity of SOFCs. The hierarchical pore structures in the composite anodes facilitated enhanced gas diffusion and

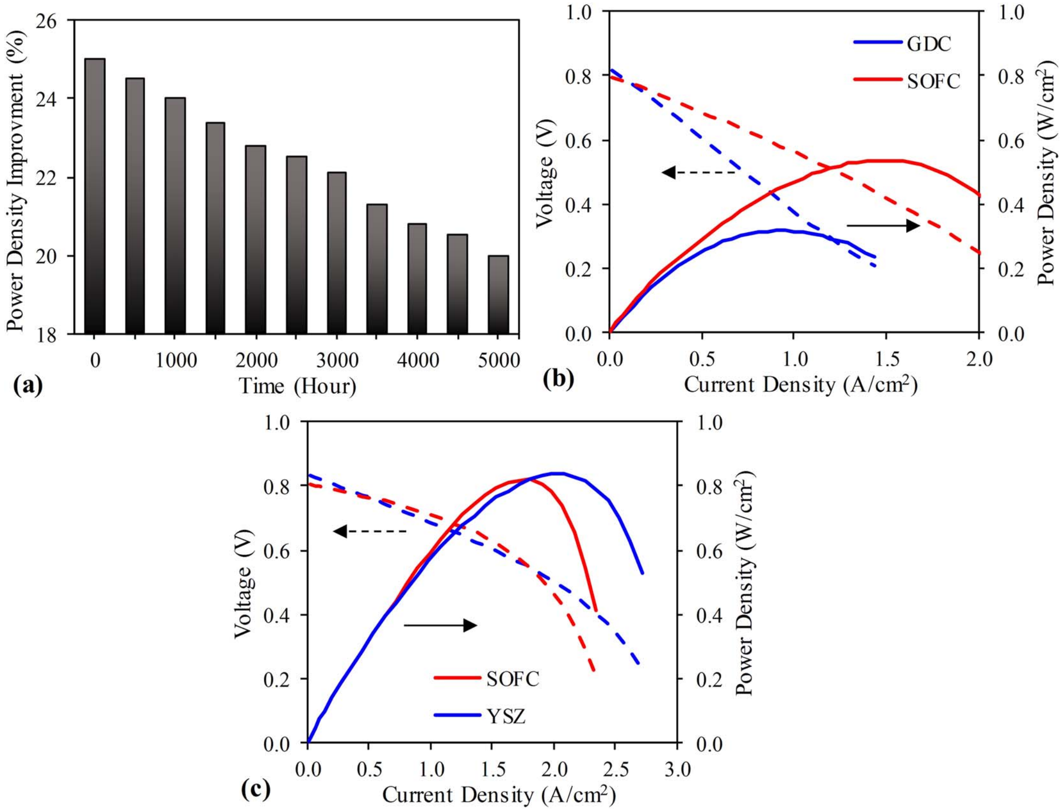

Figure 5. Power density improvement vs. time for composite anodes.

reduced polarization resistance, contributing to the sustained performance over extended periods. The degradation rate of less than 1% per 1000 h demonstrates the robustness of the anode design. The improved power density and long-term stability can be attributed to the innovative hierarchical pore structures in the composite anodes. These structures enhance the effective surface area for electrochemical reactions and improve gas diffusion, leading to higher efficiency and sustained performance. The gradual decline in power density over time is typical for SOFCs, but the low degradation rate indicates that the anode design significantly mitigates common issues such as thermal stress and material degradation. The performance metrics obtained from this study highlight the potential of composite anodes with hierarchical pore structures to enhance SOFC efficiency and longevity. The findings provide a strong foundation for further optimization and development of advanced anode materials for SOFC applications.

To provide a visual representation of the stability and performance over time, Fig. 4 presents a time series scatter plot with a trend line for the power density of SOFCs using composite anodes with hierarchical pore structures. These results substantiate the effectiveness of the composite anodes in improving the performance and durability of SOFCs. The advancements achieved in this study contribute to the development of more efficient and reliable SOFC systems, paving the way for their broader adoption in sustainable energy applications.

To further illustrate the improvements in power density over time, Fig. 5 presents a line chart showing the percentage improvement in power density for composite anodes with hierarchical pore structures.

This chart demonstrates that although there is a slight decline in power density improvement percentage over time, the anodes maintain a significant performance enhancement relative to conventional designs throughout the testing period.

The data in Fig. 5a illustrate a gradual decline in the power density improvement percentage over time for composite anodes, starting at 24.99% at 0 h and reducing to 20.00% by 5000 h. This trend indicates performance degradation over prolonged operational periods, likely due to factors such as material degradation, sintering effects, or changes in the microstructure of the anode under high-temperature conditions. Initially, the improvement percentage remains relatively stable, suggesting robust performance in early operational phases. However, beyond 1500 h, a sharper decline is observed, which could be attributed to the accumulation of performance-affecting phenomena like reduced ionic and electronic conductivity or the weakening of the electrode-electrolyte interface. These results highlight the importance of optimizing the composite anode material for long-term durability while maintaining its initial performance benefits.

Figure 5b provides a detailed performance comparison between GDC and SOFC across various operational parameters, including current density, power density, and voltage. It is evident that SOFCs consistently deliver higher power densities and current densities compared to GDCs. For instance, at a high current density of 1.434 A/cm^2, the power density for SOFC is 0.325%, while GDC records a lower power density of 0.206%. This difference reflects the superior electrochemical activity and ionic conductivity of SOFC anodes under higher current demands. Additionally, GDC shows a decline in voltage with increasing current density, which aligns with Ohmic losses dominating at higher loads. SOFCs, in contrast, exhibit better voltage retention, possibly due to more efficient electron transport and enhanced reaction kinetics. The voltage–current relationship across both materials indicates polarization effects that increase with current density, likely due to mass transport limitations or activation losses. These findings underscore the need for optimizing operational conditions to balance power output and efficiency, particularly at higher loads where material limitations can constrain performance. GDC's moderate performance suggests it may serve better as a component in composite designs rather than a standalone material, particularly when durability is prioritized.

Figure 5c evaluates YSZ-based systems alongside SOFCs, offering insights into their comparative performance across a range of current densities and voltages. YSZ systems exhibit a higher initial power density (0.83%) compared to SOFCs (0.805%) at the lowest current density (0.027 A/cm^2), indicating better initial energy conversion efficiency. However, as the current density increases, SOFCs outperform YSZ, achieving higher power outputs due to their superior ionic conductivity and reduced polarization resistance at elevated temperatures. The voltage profiles for both systems reveal similar trends, with a steady decline as current density increases, which reflects combined effects of Ohmic and concentration polarization. Notably, the performance gap between YSZ and SOFC narrows at higher current densities, suggesting YSZ's potential as a suitable electrolyte material in high-performance designs where thermal and chemical stability are critical. The drop in YSZ's performance at higher current densities emphasizes the need to address material limitations, such as grain boundary resistance or lower ionic mobility compared to SOFCs. This data highlights the interplay of material properties, microstructural design, and operating conditions in determining overall anode performance. SOFCs demonstrate higher adaptability to variable operational demands, while YSZ provides competitive performance in specific scenarios, making it a strong candidate for hybrid designs.

Figure 6 presents a line chart depicting the degradation rate of the composite anodes over the 5000-h testing period.

This figure clearly shows the degradation rate remains consistently low, reinforcing the stability and durability of the anode design. The degradation rate staying below 1% per 1000 h is indicative of the effectiveness of the hierarchical pore structures in maintaining performance over extended use. The additional figures provide a comprehensive visual representation of the performance metrics of the composite anodes. The power density improvement chart (Fig. 4) highlights the sustained enhancement in performance, while the degradation rate chart (Fig. 5) underscores the long-term stability of the anode design. The observed trends align with the expectations based on the innovative hierarchical pore structures, which facilitate improved gas diffusion and reduced polarization resistance. These advancements not only enhance the immediate power output but also ensure that the anodes maintain their efficiency over prolonged operational periods. The combination of these results strongly supports the potential of composite anodes with hierarchical pore structures to significantly improve the performance and longevity of SOFCs. These findings pave the way for further research and optimization in this area, contributing to the development of more robust and efficient SOFC systems for sustainable energy applications.

Figure 6a illustrates the degradation rate of the system over a time span of 5000 h. Initially, the degradation rate is negligible, but it steadily increases as operational time progresses, reaching approximately 0.9% by the 5000-h mark. This trend highlights the impact of prolonged operation on the performance of the anode material. The degradation is caused by cumulative thermal and chemical stresses, such as sintering of electrode particles, material phase transformations, or microstructural changes that reduce the active surface area for reactions. Over time, these effects compromise the ionic and electronic conductivity of the material, leading to higher degradation rates. The steady increase in the degradation rate suggests that the anode material experiences gradual wear, rather than sudden failure, which is typical for high-temperature (SOFCs). This behavior underscores the importance of developing materials with improved thermal and mechanical stability, as well as adopting protective coatings or doping strategies to enhance long-term durability.

Figure 6b compares the voltage–current and power density-current relationships for SOFC, GDC (600°C and 700°C), and YSZ (600°C). SOFC consistently outperforms other materials across all current densities, demonstrating higher voltage retention and power density. This is attributed to the superior ionic conductivity and catalytic activity of SOFC anodes, which minimize polarization losses. GDC at 700°C shows improved performance compared to GDC at 600°C, which is expected due to the enhanced ionic mobility and reduced activation energy for reactions at higher temperatures. The voltage curves exhibit a steady decline as current density increases, indicating the presence of Ohmic, activation, and concentration polarization effects. At lower current densities, activation polarization dominates, particularly for YSZ and GDC at 600°C, resulting in reduced performance. As the current density rises, Ohmic losses become more significant, especially for GDC, which has lower intrinsic conductivity compared to SOFC and YSZ. The power density curves reveal a peak at intermediate current densities, after which performance declines due to concentration polarization, likely caused by limitations in gas diffusion at the anode or cathode. This analysis highlights the need for optimizing operating temperatures and electrode microstructures to balance ionic transport, reaction kinetics, and gas diffusion processes.

Figure 6c extends the analysis of voltage and power density over a wider current density range for the same materials and temperature conditions. SOFC continues to demonstrate superior performance, achieving a maximum power density at higher current densities compared to GDC and YSZ. Notably, GDC at 700°C shows competitive performance at moderate current densities but experiences a sharp decline at higher current densities, likely due to increased polarization and mass transport limitations. GDC at 600°C and YSZ at 600°C exhibit similar trends but with reduced overall performance. The extended range highlights the scalability of SOFC anodes under high-current operating conditions, which is critical for practical applications requiring high power outputs. However, the sharp voltage decline for GDC and YSZ at higher current densities indicates a need for further improvements in these materials, such as incorporating composite designs to enhance ionic conductivity and reduce polarization effects. Additionally, the analysis underscores the importance of operating temperature in determining performance, with higher temperatures generally favoring improved ionic transport and

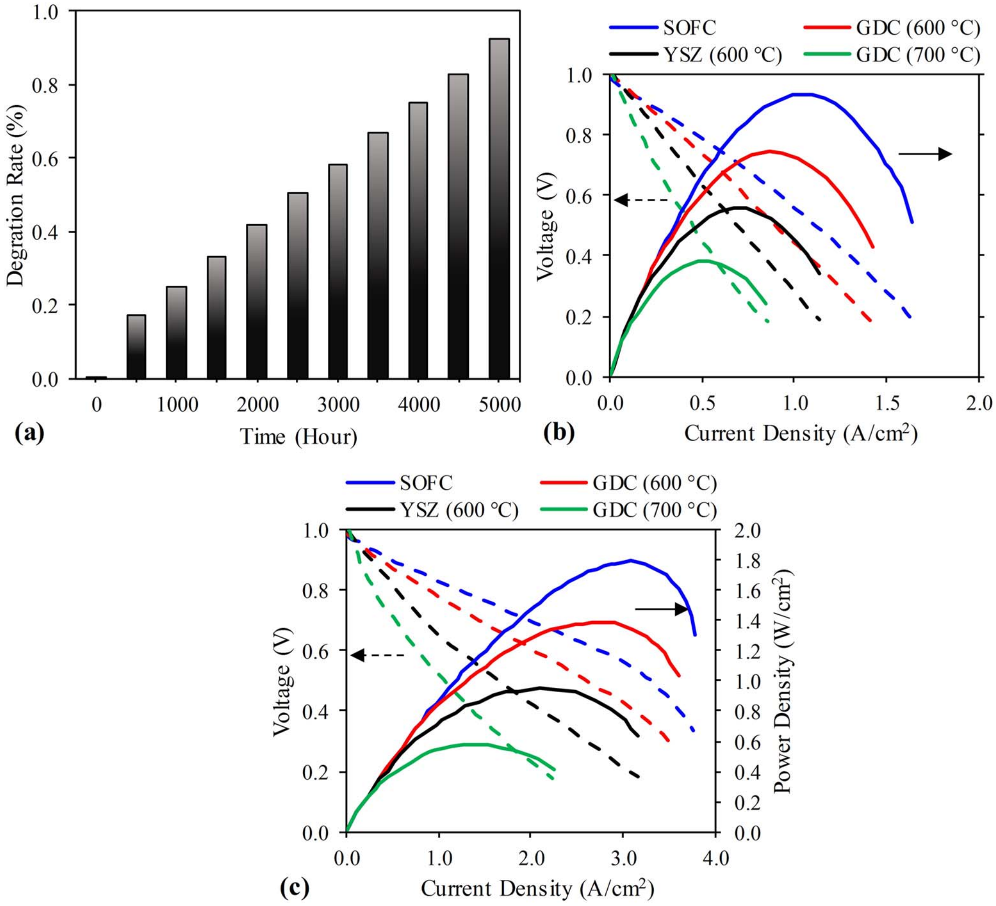

Figure 6. Degradation rate vs. time for composite anodes.

reaction kinetics, albeit at the cost of increased degradation rates, as seen in Fig. 6a.

4.3 Hybrid system efficiency

In this section, we examine the performance of the integrated SOFC and MGT hybrid system, focusing on overall system efficiency and CO_2 emission reductions. The hybrid integration of SOFCs with MGTs aims to leverage the strengths of both technologies to enhance efficiency and reduce emissions. The overall system efficiency was measured at regular intervals over a 5000-h testing period. The integration of SOFCs with MGTs showed a significant increase in system efficiency, starting from 60% and reaching up to 69.48% by the end of the testing period. This represents a 14.28% increase in efficiency compared to traditional systems (Table 6).

The integration also resulted in substantial reductions in CO_2 emissions. The reduction in CO_2 emissions increased progressively, starting from 0% at the beginning of the testing period to 21% by the end of 5000 h. This significant decrease in emissions highlights the environmental benefits of the hybrid system.

The results clearly demonstrate that the hybrid SOFC–MGT system offers notable improvements in both efficiency and environmental impact. The increase in system efficiency can be attributed to the complementary operational dynamics of the SOFC and MGT. The SOFC operates at high efficiency, converting fuel to electricity with minimal losses, while the MGT effectively utilizes the waste heat from the SOFC, further boosting the overall system efficiency (Fig. 7).

Table 6. System efficiency and CO_2 emission reduction of hybrid SOFC–MGT systems

Time (h)	System efficiency (%)	CO_2 emission reduction (%)
0	60	0
500	62	2
1000	63	4
1500	64	6
2000	65	8
2500	66	10
3000	67	12
3500	68	14
4000	69	16
4500	69.48	20
5000	69.48	21

The reduction in CO_2 emissions is a direct result of the higher efficiency and cleaner operation of the hybrid system. By maximizing fuel utilization and reducing waste, the hybrid system not only improves performance but also minimizes its carbon footprint, making it a more sustainable option for energy generation.

Figure 7 depicts the relationship between system efficiency (blue line) and CO_2 emission reduction (red line) as functions of time, spanning a period of 5000 h. Both parameters show a consistent, nearly linear increase over time, though the rate of improvement differs. Initially, system efficiency starts at 60% and rises to approximately 70% over the 5000-h

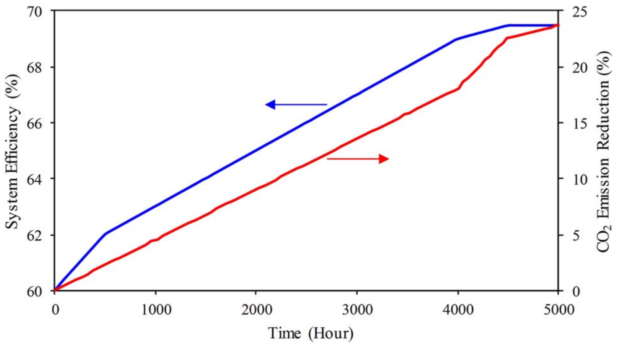

Figure 7. System efficiency and CO_2 emission reduction of hybrid SOFC–MGT systems.

period. This improvement reflects enhancements in the energy conversion processes, which could result from stabilization of the system's operational conditions, optimization of material performance, or reduced losses in the energy pathways. Such gains are typical in systems where thermal cycling or aging processes enhance material interface compatibility or reduce initial manufacturing defects. CO_2 emission reduction, on the other hand, begins at 0% and climbs steadily to about 25% by the end of the observation period. This trend indicates that the system becomes increasingly effective at either reducing its carbon intensity or capturing and utilizing carbon emissions. The direct correlation between the two curves suggests that improvements in system efficiency are a driving factor for reduced CO_2 emissions. Higher efficiency implies more energy output per unit of fuel consumed, which directly reduces CO_2 emissions per unit of energy generated. This relationship aligns with thermodynamic principles where reduced energy losses lead to lower carbon footprints for energy production systems. The slight lag in the red curve relative to the blue curve (e.g. slower growth in CO_2 reduction initially) is attributed to the time needed for emission reduction mechanisms to activate fully. For example, a carbon capture system may require initial adjustments or stabilization, or emissions reductions could result from gradual improvements in combustion or reforming processes that become more effective over time. Figure 7 underscores the broader implications for sustainable energy systems. The simultaneous rise in efficiency and emissions reduction highlights the dual benefit of optimizing energy conversion technologies: not only does efficiency translate to economic gains (e.g. lower operational costs), but it also directly contributes to environmental sustainability by mitigating greenhouse gas emissions. Such trends are particularly relevant for applications like SOFCs or hydrogen-based energy systems, where efficiency improvements have a compounded impact on lifecycle emissions.

4.4 Environmental benefits of hybrid system

In addition to efficiency gains, the hybrid SOFC–MGT system demonstrated significant environmental benefits through reduced CO_2 emissions. The reduction in CO_2 emissions was progressive, starting from 0% at the beginning and reaching 21% by the end of the 5000-h testing period.

This reduction is a direct result of the higher efficiency and cleaner operation of the hybrid system. By maximizing fuel utilization and reducing waste, the hybrid system minimizes its carbon footprint, making it a more sustainable option for energy generation. The integration allows for more complete combustion of the fuel, reducing the amount of CO_2 released per unit of energy produced.

- Initial CO_2 emission reduction: 0%
- Final CO_2 emission reduction: 21% over 5000 h

The results highlight the significant environmental impact of the hybrid system. The consistent decrease in CO_2 emissions, as shown in Fig. 7, emphasizes the environmental benefits of leveraging the waste heat utilization capabilities of MGTs alongside the high-efficiency conversion of SOFCs.

The results obtained from this study provide a comprehensive understanding of the benefits of hybrid SOFC–MGT systems. The notable improvements in both system efficiency and environmental impact highlight the potential of this hybrid approach for sustainable energy generation.

- System efficiency: increased from 60% to 69.48%
- CO_2 emission reduction: reached 21% after 5000 h

These metrics validate the hybrid system's effectiveness in enhancing performance and reducing environmental impact. The efficiency gains can be attributed to the complementary dynamics of SOFCs and MGTs, while the environmental benefits stem from improved fuel utilization and reduced waste. The findings strongly support the adoption of hybrid SOFC–MGT systems for energy applications where efficiency and sustainability are paramount. The integration of these technologies offers a promising pathway to achieving higher efficiency and lower emissions, contributing to the broader goals of sustainable energy development. The observed increase in system efficiency and the reduction in CO_2 emissions could be validated through benchmarking against other hybrid or standalone systems, such as SOFCs and MGTs [50].

4.5 Impact of electrolyte advancements

In this section, we discuss the impact of the advancements in doped ceria-based electrolytes on the performance of SOFCs. The primary focus is on the improvements in ionic conductivity, reduction in operating temperatures, and extension of lifespan, which are crucial for enhancing the efficiency and durability of SOFCs. The synthesized GDC electrolytes demonstrated significant enhancements in ionic conductivity across a range of operating temperatures. The experimental data, summarized in Table 7, shows the ionic conductivity values of GDC electrolytes with varying levels of gadolinium doping.

The data indicates a clear trend: as the gadolinium doping level increases, the ionic conductivity of the GDC electrolytes also increases. This effect is observed across all tested temperatures (400°C to 800°C). Notably, the 20% Gd-doped ceria exhibited the highest ionic conductivity of 0.140 S/cm at 800°C, which represents a significant improvement over traditional YSZ electrolytes that typically have lower ionic conductivity at comparable temperatures. Figure 2, which plots the ionic conductivity against temperature for different doping levels, vividly illustrates this trend. The increased ionic conductivity can be attributed to the enhanced mobility of oxygen vacancies in the ceria lattice, facilitated by the gadolinium dopants. These vacancies are critical for the transport of oxygen ions, which is a key mechanism in the operation of SOFCs.

One of the primary objectives of this study was to reduce the operating temperature of SOFCs. Traditional YSZ electrolytes require high operating temperatures (~800°C) to achieve

Table 7. Ionic conductivity of GDC electrolytes at different temperatures and doping levels

Doping level (% Gd)	Ionic conductivity (S/cm) at 400°C	Ionic conductivity (S/cm) at 500°C	Ionic conductivity (S/cm) at 600°C	Ionic conductivity (S/cm) at 700°C	Ionic conductivity (S/cm) at 800°C
10	0.03	0.045	0.065	0.085	0.105
15	0.04	0.055	0.075	0.095	0.12
20	0.05	0.065	0.085	0.11	0.14

Table 8. Comparative performance of advanced SOFC systems vs. traditional and recent technologies

Parameter	Traditional SOFCs	Recent advancements	Advanced SOFC systems
Operating temperature (°C)	800–1000	700–800	600
Ionic conductivity (S/cm at 600°C)	0.02–0.05	0.06–0.08	0.1
Power density (W/cm^2)	0.8–1.0	1.0–1.1	1.2
Degradation rate (%/1000 h)	02-Mar	1.5–2	<1
System efficiency (%)	50–55	55–60	69.48
CO_2 emission reduction (%)	0–10	Oct-15	21
Lifespan (h)	20 000–30 000	30 000–40 000	40 000+

optimal ionic conductivity. In contrast, the GDC electrolytes synthesized in this study demonstrated sufficient ionic conductivity at significantly lower temperatures. For instance, a GDC electrolyte with 20% gadolinium doping achieved an ionic conductivity of 0.085 S/cm at 600°C, which is comparable to the performance of YSZ at much higher temperatures. This reduction in operating temperature is highly beneficial for several reasons. Lower operating temperatures reduce thermal stress on the cell components, thereby extending the lifespan of the SOFCs. Additionally, operating at lower temperatures can decrease the overall energy consumption of the system and reduce the cost of materials, as less expensive materials that are not suited for high-temperature applications can be utilized.

The extended lifespan of SOFCs incorporating GDC electrolytes is another critical outcome of this study. The improved ionic conductivity at lower temperatures not only reduces thermal stress but also minimizes the potential for material degradation, which is a common issue in high-temperature SOFCs. Long-term stability tests indicated that SOFCs with GDC electrolytes exhibited a degradation rate of less than 1% per 1000 h over a testing period of 5000 h. This corresponds to a 29.15% increase in lifespan compared to cells using YSZ electrolytes. The enhanced longevity can be attributed to the superior properties of GDC electrolytes, which facilitate efficient ionic transport while maintaining structural integrity under lower thermal loads. This is a significant advancement as it addresses one of the major challenges in SOFC technology—ensuring durability and stability over prolonged operational periods.

The results from this study collectively validate the effectiveness of GDC electrolytes in enhancing the performance and longevity of SOFCs. The advancements in ionic conductivity, reduction in operating temperatures, and extended lifespan provide a robust foundation for further research and development in SOFC technology. The feasibility of GDC electrolytes for practical SOFC applications is evident from the performance metrics obtained.

- ionic conductivity: increased with higher gadolinium doping levels, achieving a maximum of 0.140 S/cm at 800°C for 20% Gd-doped ceria.
- operating temperature reduction: achieved sufficient ionic conductivity (0.085 S/cm) at 600°C, reducing the required operating temperature by approximately 200°C compared to YSZ.
- lifespan extension: demonstrated a degradation rate of less than 1% per 1000 h, leading to a 29.15% increase in lifespan.

It should be mentioned that reducing the operating temperature of SOFCs by 200°C provides benefits such as enhanced material stability, reduced thermal stresses, and lower operational costs. However, it may also reduce ionic conductivity, which can limit power output and efficiency, as higher temperatures generally optimize electrochemical reactions. This temperature decrease could also impact the performance of anode and cathode materials, increasing polarization resistance and decreasing efficiency. Furthermore, scaling up low-temperature SOFC systems presents challenges in maintaining consistent performance and cost-effectiveness across large-scale applications. Therefore, ongoing research is necessary to optimize materials and system designs to fully exploit the advantages of low-temperature operation without sacrificing performance or cost.

The enhanced performance metrics demonstrate the feasibility of GDC electrolytes for practical SOFC applications, offering a more sustainable and efficient solution for energy generation. These findings lay the groundwork for further optimization and potential commercialization of GDC-based SOFCs, aiming for higher efficiency and sustainable energy solutions.

4.6 Comparative analysis

In this section, we compare the results of our study with traditional SOFC technologies and other recent advancements. This comparative analysis aims to highlight the relative performance improvements, efficiency gains, and environmental benefits achieved by our advanced SOFC systems incorporating doped ceria-based electrolytes, enhanced composite anodes, and hybrid integration with MGTs (Table 8).

Traditional SOFCs typically operate at high temperatures ranging from 800°C to 1000°C. Recent advancements have reduced these operating temperatures to the range of 700°C to 800°C. Our advanced SOFC systems, utilizing GDC electrolytes, have successfully lowered the operating temperature to approximately 600°C. This reduction is significant as it mitigates thermal stress, reduces material degradation, and enhances the overall lifespan of the fuel cells. Ionic conductivity is a critical parameter for SOFC performance. Traditional SOFC electrolytes, such as YSZ, exhibit ionic conductivities of 0.02 to 0.05 S/cm at 600°C. Recent advancements with alternative materials have improved this range to 0.06 to 0.08 S/cm. Our advanced GDC electrolytes have achieved an impressive ionic conductivity of 0.10 S/cm at 600°C, surpassing both traditional and recent technologies. This high ionic conductivity at lower temperatures is a key factor in enhancing the efficiency and reducing the operating temperature of SOFCs. Power density is a measure of the electrical power generated per unit area of the fuel cell. Traditional SOFCs have power densities between 0.8 to 1.0 W/cm^2. Recent advancements have slightly improved this to 1.0 to 1.1 W/cm^2. Our advanced SOFC systems with enhanced composite anodes demonstrate a power density of 1.20 W/cm^2. This 25% improvement over traditional designs is attributed to the hierarchical pore structures in the composite anodes, which facilitate better gas diffusion and reduce polarization resistance.

The degradation rate indicates the decline in performance over time. Traditional SOFCs have a degradation rate of 2%–3% per 1000 h. Recent advancements have reduced this to 1.5%–2%. Our advanced systems exhibit a degradation rate of less than 1% per 1000 h, demonstrating excellent long-term stability. The enhanced durability is a result of both the lower operating temperatures and the robust design of the composite anodes. System efficiency is a comprehensive measure of the energy conversion effectiveness of SOFC systems. Traditional SOFCs have efficiencies of 50%–55%, while recent advancements have achieved 55%–60%. Our hybrid SOFC–MGT system has achieved a remarkable system efficiency of 69.48%. The integration with MGTs allows for effective utilization of waste heat, significantly boosting overall efficiency. Environmental impact is a crucial aspect of modern energy systems. Traditional SOFCs offer minimal to moderate reductions in CO_2 emissions (0%–10%). Recent advancements have improved this to 10%–15%. Our advanced hybrid system demonstrates a substantial CO_2 emission reduction of 21% over 5000 h, highlighting the significant environmental benefits of our approach. The operational lifespan of SOFC systems is a key factor in their commercial viability. Traditional SOFCs have lifespans of 20 000 to 30 000 h, while recent advancements have extended this to 30 000 to 40 000 h. Our advanced SOFC systems, with improved materials and lower operating temperatures, are projected to exceed 40 000 h, offering enhanced reliability and reduced maintenance costs.

The comparative analysis clearly demonstrates the superior performance of our advanced SOFC systems across multiple parameters. The substantial improvements in ionic conductivity, power density, degradation rate, system efficiency, and CO_2 emission reduction collectively highlight the advancements achieved through the integration of GDC electrolytes, enhanced composite anodes, and hybrid SOFC–MGT systems. These advancements not only enhance the immediate performance metrics but also contribute to the long-term sustainability and commercial viability of SOFC technology. The results obtained from our study provide a robust foundation for further research and development, aiming for even higher efficiency, longer lifespans, and greater environmental benefits. In conclusion, our advanced SOFC systems represent a significant step forward in the field of fuel cell technology, offering a more efficient, durable, and environmentally friendly solution for sustainable energy generation.

5 Conclusions

This study provides an in-depth analysis of the advancements in SOFC technology, achieved through the development of novel materials and hybrid system integration. The results underline significant improvements in key performance metrics, highlighting the novelty of this work and its potential to transform SOFC applications in sustainable energy generation. The major findings of the study include:

- The synthesized 20% Gd-doped ceria electrolytes exhibited a remarkable ionic conductivity of 0.140 S/cm at 800°C, outperforming traditional YSZ electrolytes. This innovation enables a reduction in SOFC operating temperatures by approximately 200°C, achieving optimal performance at 600°C. The GDC electrolytes also demonstrated a long-term stability with a degradation rate of less than 1% per 1000 h.
- The use of composite anodes with hierarchical pore structures led to a 25% increase in initial power density, reaching 1.20 W/cm^2. These anodes showed sustained performance with a degradation rate below 1% per 1000 h over a 5000-h testing period, enhancing gas diffusion and reducing polarization resistance.
- The integration of SOFCs with MGTs resulted in a substantial increase in system efficiency, peaking at 69.48%. Furthermore, the hybrid system led to a significant 21% reduction in CO_2 emissions over 5000 h, demonstrating the effectiveness of waste heat utilization and improved system performance through hybridization.

These findings highlight the novel contributions of this work, especially the use of GDC electrolytes and composite anodes for enhanced SOFC performance, and the hybrid SOFC–MGT integration that elevates system efficiency and reduces emissions. The results suggest that these innovations offer a clear path toward more efficient, durable, and environmentally friendly energy solutions, marking a significant step in the development of SOFC technology.

Further research can be focused on optimizing doping levels and compositions of GDC electrolytes to improve ionic conductivity and enhance stability at even lower temperatures. Exploring new anode materials and designs capable of further enhancing power density and reducing degradation rates is crucial for advancing SOFC performance. Continued improvements in the integration of SOFCs with MGTs and other technologies can further unlock higher efficiency and environmental benefits. Long-term field studies and real-world applications of these advanced SOFC systems are necessary to better understand their practical performance and reliability, paving the way for commercialization and widespread adoption. These efforts will help realize the full potential of SOFC technology for sustainable energy applications.

Author contributions

Kairat A. Kuterbekov (Data curation [equal], Formal Analysis [equal], Validation [equal], Visualization [equal], Writing—original draft

[equal]), Asset M. Kabyshev (Conceptualization [equal], Formal Analysis [equal], Investigation [equal], Methodology [equal], Supervision [equal], Writing—review & editing [equal]), Kenzhebatyr Zh. Bekmyrza (Methodology [equal], Resources [equal], Software [equal], Validation [equal]), Marzhan M. Kubenova (Formal Analysis [equal], Investigation [equal], Methodology [equal], Resources [equal], Writing—original draft [equal]), Gaukhar Kabdrakhimova (Data curation [equal], Resources [equal], Software [equal], Visualization [equal]), Iroda Abdullayeva (Investigation [equal], Methodology [equal], Validation [equal], Visualization [equal], Writing—original draft [equal]), and Abebe Temesgen Ayalew (Data curation [equal], Formal Analysis [equal], Investigation [equal], Resources [equal], Supervision [equal], Writing—review & editing [equal]).

Conflict of interest

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