Comprehensive Review of Exergy, Energy, Economic, and Environmental Aspects of Solid Oxide Fuel Cell-Based Hybrid Gas Turbine and Supercritical CO_2 Cycles

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Abstract

The growing need for efficient and sustainable energy solutions has driven extensive research into hybrid power generation technologies. Solid oxide fuel cells (SOFCs) integrated with gas turbines (GTs) and supercritical carbon dioxide (sCO_2) cycles offer a promising approach to improving energy efficiency, reducing carbon emissions, and optimizing power generation. This review examines the exergy, energy, economic, and environmental aspects of SOFC-based hybrid GT-sCO_2 systems. The SOFC-GT configuration efficiently utilizes high-temperature exhaust gases, achieving electrical efficiencies exceeding 70%. The addition of an sCO_2 cycle enhances thermal energy recovery, increases system efficiency, and reduces the overall footprint due to its compact design and superior heat transfer properties. Recent advancements in hybrid system design, thermodynamic performance, and waste heat recovery are critically analysed. Studies indicate that SOFC-GT-sCO_2 systems can achieve energy efficiencies above 65%, yet challenges such as high capital costs, system complexity, and material degradation hinder widespread commercialization. Economic assessments highlight long-term cost benefits, fuel flexibility, and lower greenhouse gas emissions. Environmental evaluations confirm substantial CO_2 emission reductions compared to conventional fossil-fuel-based power plants. This review identifies key opportunities for optimizing system integration, enhancing durability, and improving techno-economic feasibility. Future research should focus on advanced materials, innovative waste heat recovery, and policy incentives to support commercialization. This study provides valuable insights into the potential of SOFC-GT-sCO_2 systems for next-generation sustainable power generation.

Keywords: Solid Oxide Fuel Cell, Gas Turbine, Supercritical CO_2 Cycle, Hybrid Power Systems, Exergy Analysis, Energy Efficiency, Waste Heat Recovery, Sustainability, Carbon Emissions, Economic Feasibility.

1. Introduction

The increasing global demand for efficient, reliable, and sustainable energy has driven significant research into advanced power generation technologies [1]. The urgent need to reduce greenhouse gas (GHG) emissions and mitigate climate change has further accelerated the development of alternative energy systems that maximize efficiency while minimizing environmental impact. Hybrid power generation systems, particularly those integrating solid oxide fuel cells (SOFCs), gas turbines (GTs), and supercritical carbon dioxide (sCO_2) cycles, have emerged as promising solutions for achieving these objectives [2-6]. These hybrid systems offer high energy conversion efficiency, effective waste heat recovery, and reduced carbon emissions, making them attractive candidates for next-generation sustainable power plants [7-9].

Among the various fuel cell technologies, SOFCs have gained prominence due to their high operating temperature, fuel flexibility, and ability to directly convert chemical energy into electrical energy with minimal losses [10-11]. Unlike conventional combustion-based power plants, SOFCs generate electricity through electrochemical reactions, leading to lower emissions and higher efficiencies. However, standalone SOFC systems face challenges such as slow start-up times, material degradation, and limitations in waste heat utilization. To address these issues, hybrid configurations combining SOFCs with gas turbines and supercritical CO_2 cycles have been developed [12-15]. These integrated systems leverage the high-temperature exhaust gases from SOFCs to enhance power generation through GTs, while incorporating sCO_2 cycles further improves thermal efficiency and reduces system footprint. The SOFC-GT hybrid system effectively utilizes waste heat from SOFCs to drive a gas turbine, achieving electrical efficiencies exceeding 70% [5, 16]. This significantly surpasses the efficiencies of standalone SOFCs or conventional GTs. Additionally, the integration of an sCO_2 cycle enhances energy recovery by utilizing the remaining thermal energy in the system [17]. The unique thermophysical properties of supercritical CO_2, including its high density and low viscosity, enable superior heat transfer and compact system designs, resulting in higher energy output and improved economic viability. This combination of technologies creates a highly efficient power generation system that aligns with global sustainability goals [18].

A key aspect of hybrid SOFC-GT-sCO_2 systems is their thermodynamic performance. Various studies have demonstrated the potential of these systems to achieve overall energy efficiencies exceeding 65% [2, 5, 19]. The exergy analysis of these systems provides valuable insights into the irreversibility's and losses within different components, enabling further optimization of system design and operation. Effective waste heat recovery mechanisms in these hybrid configurations ensure maximum energy utilization, reducing primary fuel consumption and improving the system's overall sustainability [20].

Despite the promising advantages of SOFC-GT-sCO_2 systems, several challenges hinder their widespread commercialization. High capital costs remain a primary barrier, as the advanced materials and components required for SOFCs and sCO_2 cycles contribute to significant initial investments. Additionally, system complexity, material degradation, and operational stability pose engineering challenges that need to be addressed for large-scale implementation. The durability of SOFC components, particularly the electrolyte and electrodes, is critical for ensuring long-term performance and cost-effectiveness. Material innovations and improved thermal management strategies are essential to mitigate degradation and enhance the lifespan of these systems [7,10, 21]. Economic evaluations indicate that although the initial investment in SOFC-GT-sCO_2 systems is substantial, the long-term benefits outweigh the costs. These hybrid systems offer fuel flexibility, allowing the use of various feedstocks such as natural gas, biogas, and hydrogen, thereby increasing their adaptability to different energy markets. Furthermore, their high efficiency and reduced fuel consumption lead to lower operating costs over time [12]. Policy incentives, subsidies, and advancements in manufacturing techniques could further enhance the economic feasibility of these systems, making them more competitive with conventional power generation technologies. The environmental benefits of SOFC-GT-sCO_2 systems are also significant. Compared to traditional fossil-fuel-based power plants, these hybrid systems produce considerably lower CO_2 emissions, contributing to decarbonization efforts in the energy sector [14, 18]. The use of SOFCs eliminates nitrogen oxide (NOx) and sulfur oxide (SOx) emissions, reducing air pollution and improving overall air quality. Additionally, integrating carbon capture and storage (CCS) technologies with these hybrid systems could further minimize their carbon footprint, aligning with global climate targets and net-zero emission goals [19].

This review aims to provide a comprehensive analysis of the exergy, energy, economic, and environmental (4E) aspects of SOFC-GT-sCO_2 hybrid power generation systems. By critically examining recent advancements in system design, thermodynamic performance, waste heat recovery, and economic feasibility, this study identifies key opportunities for optimization and large-scale deployment. The insights presented in this review will contribute to the development of sustainable, high-efficiency power generation systems that support the transition to a low-carbon energy future.

Future research directions should focus on advanced materials to improve component durability, innovative waste heat recovery strategies to enhance efficiency, and supportive policy frameworks to drive commercialization. Additionally, further exploration of hybrid energy systems integrating SOFC-GT-sCO_2 cycles with renewable energy sources could pave the way for a more resilient and sustainable energy infrastructure. As the global energy landscape continues to evolve, SOFC-based hybrid power generation systems hold immense potential in shaping the future of clean and efficient power production.

2. Literature Review

This review provides a comprehensive analysis of recent developments in gas turbines, supercritical carbon dioxide (sCO_2) Brayton cycles, solid oxide fuel cells (SOFCs), and their integration within hybrid power generation systems. It explores the technological, economic, and environmental aspects of these systems, emphasizing their suitability for combined cooling, heating, and power (CCHP) or combined heat and power (CHP) applications. Additionally, the chapter discusses the opportunities and challenges associated with integrating SOFCs with gas turbines and sCO_2 cycles to enhance hybrid energy system performance.

2.1 SOFCs in Hybrid Energy Systems

Solid oxide fuel cells (SOFCs) can be integrated with other energy systems, such as gas turbines (GTs) and combined cycles, to form hybrid energy systems that enhance energy recovery and overall efficiency. The hybrid SOFC-GT configuration has been extensively studied due to its potential to achieve electrical efficiencies exceeding 70% by utilizing high-temperature SOFC exhaust gases to power a GT. This section presents a review of recent advancements in SOFC-based hybrid systems. Several studies have examined the integration of SOFCs with gas turbines to improve power generation efficiency.

Zhang et al. [22] demonstrated that hybrid SOFC-GT systems could reach electrical efficiencies of up to 70%, significantly outperforming standalone SOFC or GT systems. In such configurations, the SOFC waste heat is utilized to drive the gas turbine, generating additional power and improving overall energy recovery. Despite this potential, challenges such as system complexity, high capital costs, and operational issues related to thermal management and component integration remain. Ongoing research aims to optimize system designs and enhance the economic feasibility of hybrid SOFC-GT systems.

Xia et al. [23] introduced an SOFC-GT-sCO_2 cycle in which SOFC waste heat drives a bottoming sCO_2 cycle. The results showed a 12% increase in thermal efficiency compared to standalone SOFC-GT systems.

Li et al. [24] investigated the impact of off-gas recirculation on SOFC performance using a partial oxidation reformer. Although off-gas recirculation improved cogeneration potential and fuel efficiency, it resulted in lower electrical output, with initial system output at 110 kWe at 0.8 V per cell, which later declined significantly.

Hybrid SOFC-based energy systems contribute to increasing renewable energy utilization and improving power system performance [25]. Literature reviews highlight that integrating heating and electrical systems can reduce energy consumption and environmental impact [26]. The choice of SOFC stack depends on fuel type, operating conditions, and steam reforming requirements [27]. When designing SOFC systems, exergy analysis plays a crucial role in optimizing efficiency and minimizing losses [28]. Research on integrating SOFCs with GT loops focuses on energy and exergy analysis, despite the cost challenges associated with such hybrid configurations [29]. Waste heat recovery remains a key strategy for improving SOFC-based plant efficiency and reducing CO_2 emissions [30], with trigeneration systems proving to be an effective approach [5].

2.2 Gas Turbines in Hybrid Systems

Gas turbines are widely used in power generation due to their high efficiency and ability to produce significant power within a compact design. The Brayton cycle governs GT operation, compressing air, mixing it with fuel, and combusting it to generate high-temperature exhaust gases that drive the turbine. Integrating gas turbines with SOFCs and sCO_2 cycles enhances system performance in hybrid configurations.

2.2.1 SOFC-Gas Turbine Hybrid Systems: The combination of SOFCs and GTs has been extensively researched, as GTs efficiently utilize SOFC waste heat to generate additional power.

Li et al. [47] showed that hybrid SOFC-gas turbine systems can achieve high electrical efficiencies, with the gas turbine contributing significantly to the overall power output. Gas Turbine-sCO_2 Hybrid Systems: In addition to SOFC integration, gas turbines can also be combined with sCO_2 cycles for waste heat recovery. The sCO_2 cycle can capture the waste heat from gas turbines and convert it into electricity, improving system efficiency. Applications for this hybrid arrangement in waste heat recovery systems and combined cycle power plants have been investigated. Various authors proposed different trigeneration systems for improving the SOFC-based plant.

2.2.2 Gas Turbine-sCO_2 Hybrid Systems: Gas turbines can also be integrated with supercritical CO_2 (sCO_2) cycles for waste heat recovery. The sCO_2 cycle efficiently converts GT waste heat into electricity, enhancing system efficiency. This hybrid approach has been investigated for waste heat recovery systems and combined cycle power plants.

Wang et al. [31] developed a hybrid energy generation system incorporating an SOFC-based top cycle and a novel bottom cycle featuring a tCO_2 cycle, ORC, and LNG cold energy utilization. Their findings reported energy and exergy efficiencies of 68.8% and 65.7%, respectively, with a cost rate of 19.84 $/h. Gou [16] introduced an SOFC-GT-based trigeneration system incorporating a tCO_2 cycle and LNG cold energy utilization, achieving an energy efficiency of 62.13% and an optimized efficiency of 64.40%.

Gou [32] proposed a novel trigeneration system incorporating a solid oxide fuel cell-gas turbine (SOFC-GT) configuration, integrating a tCO2 cycle and an LNG cold energy utilization system. Their study demonstrated that the system could achieve energy efficiencies of 62.13% and 64.40% under specific conditions, with further efficiency enhancements possible through parameter optimization.

Chitgar et al. [33] designed a SOFC-based trigeneration system, integrating a gas turbine with a polymer electrolyte membrane electrolyser and a multi-effect water desalination organic flash cycle. This system was capable of simultaneously producing power, fresh water, and hydrogen. Their analysis showed an energy efficiency of 59.40%, with a total unit cost of 23.6 $/GJ.

Roushenas [34] explored an SOFC-GT configuration aimed at energy storage and waste heat recovery. The proposed system utilized thermal energy storage and compressed air to store surplus power. Under optimized conditions, it demonstrated a round-trip efficiency of 76.8% and an exergy efficiency of 46%.

Gholamian [35] investigated SOFC-GT technology with two different coupled cycle configurations while also assessing the environmental impact of CO2 emissions. The study highlighted the benefits of waste heat recovery from SOFC-GT using Kalina Cycle (KC) and Organic Rankine Cycle (ORC). Findings indicated that the SOFC-GT-ORC system could reach an exergy efficiency of 62.35%, while the SOFC-GT-KC system achieved 59.53%.

Al-Hamad [36] developed an innovative trigeneration system incorporating SOFC, a gas turbine Brayton cycle, and a reversible pumping mechanism for space heating and cooling. The system also integrated steam and ammonia-based ORCs for waste heat recovery. Under optimal conditions, it achieved a maximum energy efficiency of 77.48% and an exergy efficiency of 79.88%, significantly improving upon the standalone SOFC efficiency of approximately 65%.

2.3 Supercritical CO_2 Brayton Cycle

The supercritical CO_2 (sCO_2) Brayton cycle is an advanced thermodynamic cycle utilizing CO_2 in its supercritical state (above 31.1°C and 7.38 MPa) as the working fluid. It offers higher thermal efficiency, compact system design, and reduced environmental impact compared to conventional steam Rankine cycles [37, 51].

sCO_2 cycles have been applied in waste heat recovery, nuclear power, concentrated solar power (CSP), and fossil fuel-based plants. Given its high efficiency and compatibility with SOFC waste heat temperatures (500-700°C), the sCO_2 cycle is well-suited for hybrid integration [52].

Xia et al. [53] demonstrated that SOFC-sCO_2 integration could achieve system efficiencies of up to 70%, with the sCO_2 cycle effectively capturing high-temperature SOFC exhaust to generate additional electricity. This hybridization also reduces plant footprint, making it viable for industrial applications. SOFCs exhibit high technological efficiency, nearing 90%, with CO_2 emissions reduced by 50% compared to conventional power generation.

Fragiacomo et al. [38] conducted an evaluation of a SOFC-based system, comparing different fuel sources. Their findings indicated that gas derived from urban waste was more suitable for cogeneration than gas from woody biomass due to its higher energy efficiency of 66%, compared to 54% for the latter.

Yang et al. [39] investigated the performance of an SOFC-GT system integrated with CO2 recovery. They discovered that utilizing LNG for cooling the compressor intake air not only reduced compressor work consumption but also provided additional cold energy and facilitated CO2 recovery. Their analysis showed an exergy efficiency of 61.8%, thermal efficiency of 74.5%, and an overall power efficiency of 56.7%.

Pirkandi et al. [40] performed a detailed performance analysis of an SOFC-GT-sCO2 system. By evaluating nine different steam cycle configurations, they identified the most efficient downstream cycle for integration with the SOFC-GT system. Their results highlighted that the total output work rate of the triple combined cycle was significantly higher—200% greater than a conventional GT cycle and 15% more than a fuel cell-GT hybrid system.

The Organic Rankine Cycle (ORC) is considered a promising approach for converting low-to-medium-temperature energy into usable electricity [41-42]. Ongoing research in this field focuses on optimizing the selection of working fluids and identifying the most efficient heat source temperatures [43].

Kumar and Singh [44] developed an innovative SOFC-based trigeneration system for energy storage, power generation, and thermal applications. Using a mathematical model, they assessed its performance and found that the system's total cost was 65.33% lower than that of a conventional SOFC-GT system.

Zhang et al. [45] proposed an SOFC-based trigeneration system designed for electricity production, heating, and cooling applications. Their numerical analysis revealed that this system reduced costs by 65.33% compared to traditional SOFC-GT systems, with an estimated payback period of 5.54 years. Additionally, their model demonstrated significant environmental benefits, reducing total CO2 emissions by 57.42% over a 15-year period.

Hosseini [46] examined the thermodynamic efficiency of a hybrid trigeneration system designed for power, heating, and cooling. Their study incorporated a hybrid cycle featuring two single-effect vapor absorption refrigeration systems (VARS) and a double-effect VARS, with a gas turbine and SOFC as primary energy sources. By comparing system configurations, they concluded that employing a double-effect VARS instead of a single-effect VARS led to an 8% improvement in energy efficiency, a 2% rise in exergy efficiency, and a 5.4% reduction in exergy destruction.

Khan and singh [48] developed an innovative integrated system aimed at enhancing the efficiency of solar power tower plants for electricity generation. The proposed design utilized a helium Brayton cycle as the topping cycle, while a recuperative-regenerative organic Rankine cycle was implemented as the bottoming cycle to recover waste heat. The system's performance was evaluated in terms of energy efficiency, exergy efficiency, and exergoeconomic analysis, utilizing engineering equation solver software. Additionally, a parametric study was conducted to examine the influence of key operational factors on overall system performance. Findings indicated that incorporating the recuperative-regenerative organic Rankine cycle into a conventional solar power tower plant based on a helium Brayton cycle led to notable efficiency improvements, with energy and exergy efficiencies increasing by 23.88% and 23.91%, respectively. However, the reduction in total plant cost was limited to 14.49%. The final results showed that the proposed solar power plant achieved an energy efficiency of 38.22%, an exergy efficiency of 40.93%, and a levelized cost of electricity of 0.01457 $/kWh.

Khan and Singh [49] presented an advanced hybrid trigeneration system that integrates a solid oxide fuel cell (SOFC) and gas turbine (GT) with an organic Rankine cycle (ORC) and a vapor absorption refrigeration system (VARS) to simultaneously produce electricity, heating, and cooling. The system's performance was analyzed from energetic, exergetic, economic, and environmental perspectives using computational methods via engineering equation solver software. Additionally, an evaluation of working fluids and a parametric analysis of the hybrid trigeneration system were conducted. Results indicated that incorporating ORC and VARS into the conventional SOFC-GT configuration led to significant improvements: energy efficiency increased by 39.83%, exergy efficiency by 9.21%, net power output by 7.85%, and cost-effectiveness by 10.81%. Additionally, CO2 emissions per megawatt-hour of generated energy were reduced by 28.48%. The system provided a cooling effect of 53.14 kW and a heating effect of 123.20 kW. Among the tested working fluids, R1233zd(E) was identified as the most thermodynamically efficient, while R290 was the most cost-effective.

Yadav et al. [50] studied the combined power generation system utilizing a Solid Oxide Fuel Cell (SOFC) offers a highly adaptable and efficient energy conversion solution, leveraging multiple energy sources to produce electricity. The selection of an appropriate SOFC-based hybrid system depends on various design parameters, including SOFC stack operating pressure and temperature, fuel type, characteristics of the fuel processing subsystem, and steam production methods—whether through anode recirculation or a heat recovery steam generator. Integrating a gas turbine (GT) with an SOFC enhances overall system efficiency by 36.8% compared to a standalone SOFC system. Additionally, a hybrid configuration combining SOFC, organic Rankine cycle (ORC), and gas turbine achieved an efficiency that is approximately 34% higher than a conventional GT cycle and 6% greater than an SOFC-GT hybrid system. Various waste heat recovery cycles contributed to further efficiency improvements, with ORC, Kalina cycle, steam turbine, and trans-critical CO_2 cycle enhancing SOFC-GT system efficiency by about 11%, 6%, 15%, and 9%, respectively.

3. Challenges and Opportunities

Despite the promising potential of hybrid SOFC-GT-sCO_2 systems, several challenges must be addressed:

- **System Complexity:** Hybrid systems require advanced thermal management and control strategies to optimize performance.
- **High Capital Costs:** The initial investment for SOFC-GT-sCO_2 systems remains high, necessitating financial incentives for widespread adoption.
- **Operational Challenges:** Component integration, degradation over time, and maintenance costs pose obstacles to long-term feasibility.
- **Optimization Needs:** Further research is required to enhance system configurations, optimize working conditions, and improve economic feasibility.

4. Conclusion

This study provided a comprehensive analysis of the integration of gas turbines, solid oxide fuel cells (SOFCs), and supercritical carbon dioxide (sCO_2) Brayton cycles in hybrid power generation systems. The findings highlighted the significant potential of these hybrid configurations in improving energy efficiency, enhancing waste heat recovery, and reducing environmental impact. The integration of SOFCs with gas turbines has demonstrated electrical efficiencies exceeding 70%, while the addition of sCO_2 cycles further enhances thermal efficiency and overall power output. These advancements position hybrid energy systems as promising solutions for sustainable power generation, particularly in combined cooling, heating, and power (CCHP) and combined heat and power (CHP) applications.

Despite their advantages, several challenges remain, including high capital costs, system complexity, thermal management issues, and the need for optimized component integration. Economic feasibility studies indicate that while hybrid systems require significant initial investment, their long-term benefits in terms of efficiency gains, fuel savings, and emission reductions justify further research and development. Future work should focus on optimizing system design, exploring alternative working fluids, and improving economic viability through advancements in manufacturing and material technologies.

Overall, hybrid power generation systems that integrate SOFCs, gas turbines, and sCO_2 cycles offer a viable pathway toward a more efficient and environmentally sustainable energy future. Continued research, policy support, and technological innovation will be crucial in overcoming existing challenges and enabling widespread adoption of these systems in industrial and commercial applications.

5. Future Research Directions

- Further studies should focus on optimizing SOFC-GT system design to enhance economic feasibility and operational stability.
- Advancements in material science, waste heat recovery, and fuel flexibility could further improve hybrid system performance.
- Exploring the integration of SOFCs with renewable energy sources could lead to more sustainable and decentralized energy solutions.

Statements & Declarations

Funding The research work has not been funded from anywhere.

Competing Interests: - The authors have no relevant financial or non-financial interests to disclose.

Ethics Approval: **-** This research work is original and has not been submitted elsewhere in any journal for publication.

Consent to Participate: **-** Not Applicable.

Consent for Publication: All authors agree to publish this article.

Availability of data and materials: All data are available in the manuscript.

Authors' Contributions, Divya Tiwari: Investigation, Writing – original draft, Writing – review & editing.

Pushpraj Singh: Writing–review, conceptualisation, & editing, Supervision.

Abhay Agrawal: Writing–original draft, Review & editing, Supervision.

Prashant Singh Chauhan: Writing–original draft, Review & editing, Supervision.

Conflict of Interest: All authors declare that they have no conflict of interest.

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