TELKOMNIKA Telecommunication Computing Electronics and Control
Vol. 24, No. 5, October 2026, pp. 1805~1815
ISSN: 1693-6930, DOI: 10.12928/TELKOMNIKA.v24i5.27887

Solid oxide fuel cells as next-generation high-efficiency alternatives to combined cycle gas turbines

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Article Info

Article history:

Received Feb 20, 2026
Revised Jun 1, 2026
Accepted Jun 30, 2026

Keywords:

Combined cycle gas turbine
Fuel utilization
Power generation efficiency
Solid oxide fuel cell
Thermodynamic simulation

ABSTRACT

This study provides a direct thermodynamic comparison between a combined cycle gas turbine (CCGT) and a solid oxide fuel cell (SOFC) system, each designed for approximately 450 MW gross output. The benchmark CCGT, based on Siemens STG5-4000F and SST5-5000 units, achieved 61% gross efficiency under baseline conditions, with moderate sensitivity to fuel composition. In contrast, the SOFC system, modeled with an active cell area of 250,000 m², demonstrated superior performance, reaching nearly 70% gross efficiency and exceeding 63% net efficiency, while requiring lower fuel input (18.5 kg/s versus 19.5 kg/s for CCGT). Efficiency trends highlight fundamental differences: CCGT shows incremental gains with increased fuel flow but remains below 57% net efficiency, whereas SOFC sustains higher values despite greater sensitivity to input variations. These findings emphasize SOFC's potential as a next-generation utility-scale power technology, offering higher efficiency and reduced fuel demand, while acknowledging challenges in scalability, durability, and cost that must be addressed for practical deployment.

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1. INTRODUCTION

Combined cycle gas turbine (CCGT) systems represent one of the most mature and efficient conventional power generation technologies, with gross efficiencies exceeding 60% [1]–[5]. A notable configuration is the Siemens STG5-4000F gas turbine integrated with the SST5-5000 steam turbine generator, which achieves approximately 61% gross efficiency at 450 MW output [1]. Thermodynamic simulations of such CCGT plants provide valuable insights into performance characteristics, particularly under variations in fuel input and load scheduling [3], [6], [7].

Solid oxide fuel cells (SOFCs) have recently emerged as a promising alternative for utility-scale generation, extending beyond small-scale applications [8]–[12]. Their efficiency can be further enhanced through hybridization with gas turbines [13]–[19]. However, few studies have directly compared SOFC and CCGT systems at equivalent output scales and under identical fuel assumptions. Addressing this gap, the present work develops a simulation-based model to evaluate both technologies systematically. By applying the same fuel type and varying input flow rates, the analysis enables a rigorous comparison of efficiency outcomes. The novelty of this study lies in its direct thermodynamic comparison of CCGT and SOFC systems at ~450 MW gross output. The results provide new insights into SOFC's feasibility as a next-generation high-efficiency power technology, while recognizing challenges in scalability, durability, and cost.

2. LITERATURE STUDY

CCGT plants have been widely studied due to their maturity and broad industrial use. Recent modeling emphasizes cycle optimization and integration with low-carbon technologies. Rodríguez *et al.* [19] applied an adaptive neuro-fuzzy inference system (ANFIS) to model CCGT operations, identifying key variables that affect efficiency and reliability. Mullen and Lucquiaud [20] examined thermodynamic integration of CCGT with carbon capture, utilization, and storage (CCUS), showing its potential to produce both low-carbon hydrogen and electricity. Reviews of performance analysis confirm that optimization strategies, such as advanced cycle simulations and hybridization, remain central to improving CCGT efficiency under diverse fuel conditions [21]. Overall, these studies indicate that while CCGT technology is stable, its future progress depends on decarbonization and integration with emerging energy systems.

SOFCs have gained attention for their ability to achieve higher efficiencies through direct electrochemical conversion. Marcantonio and Scopel [11] reviewed thermodynamic models for SOFCs, including tubular, planar, and monolithic designs, highlighting the role of internal reforming and transport phenomena. Khan *et al.* [13] assessed SOFC-based hybrid cogeneration systems from thermodynamic, economic, and environmental perspectives, demonstrating the benefits of waste heat recovery for both power and heat production. Other performance studies consistently show improvements in fuel efficiency, current density, and voltage stability, leading to higher overall system efficiency [22]. These findings support the view that SOFCs, when scaled and integrated effectively, can surpass conventional thermal cycles in efficiency and sustainability.

The literature suggests that CCGT systems are defined by stability and incremental improvements, mainly through carbon capture and hydrogen integration. In contrast, SOFC systems promise disruptive efficiency gains but face challenges in scalability and durability. Thermodynamic modeling is crucial in both cases: for CCGT, it refines established cycles, while for SOFC, it validates conceptual and hybrid designs. Collectively, these studies provide a strong basis for comparative simulation, reinforcing the argument that SOFCs represent a next-generation technology for high-efficiency, low-carbon power generation.

3. METHOD

This study examines two large-scale power generation systems: a benchmark CCGT and a conceptual SOFC plant. The CCGT configuration is modeled using Siemens STG5-4000F and SST5-5000 units, operating with natural gas (NG) as the standard fuel. The NG composition is CH_4 79%, C_2H_6 13.5%, C_3H_8 3.92%, CO_2 0.64%, and N_2 3.04% [23]. For the SOFC, a hypothetical design is developed to deliver ~450 MW output, enabling direct comparison with the CCGT benchmark. The required active cell area is set to 250,000 m², based on literature values for large-scale stacks [11], [24]–[27]. This choice ensures scalability to utility-level output. Thermodynamic modeling is employed to simulate both systems. For CCGT, established cycle simulation methods are applied, incorporating gas turbine and steam turbine interactions [16]–[20]. For SOFC, modeling is based on electrochemical conversion principles, including reaction kinetics and transport equations, scaled to the reference output. Both models allow systematic variation of input parameters, particularly fuel composition, to observe efficiency responses. Modeling assumptions include steady-state operation, neglect of degradation effects, and idealized scaling of SOFC stacks. Key input parameters are fuel type, fuel composition, and operating conditions such as temperature and pressure. Manufacturer data and literature values are used to establish realistic boundary conditions. The comparative framework focuses on gross and net efficiency as performance indicators, ensuring that both systems are evaluated under equivalent and controlled conditions.

4. RESULTS AND DISCUSSION

4.1. CCGT power plant simulation model

Figure 1 illustrates the integrated thermodynamic design of the benchmark CCGT plant, highlighting the interaction between the Siemens STG5-4000F gas turbine, the heat recovery steam generator (HRSG), and the SST5-5000 steam turbine stages. The schematic shows how natural gas and ambient air are directed into the gas turbine to produce mechanical and electrical power, while the exhaust heat is recovered in the HRSG to generate steam for the steam turbine, which drives the electric generator. Color-coded pathways distinguish hot gas, steam, condensate, and feedwater streams, clarifying the energy conversion process across the cycle. Together with Table 1, the diagram provides a visual confirmation of the simulation framework and reinforces the stability of CCGT performance under varying fuel flow conditions.

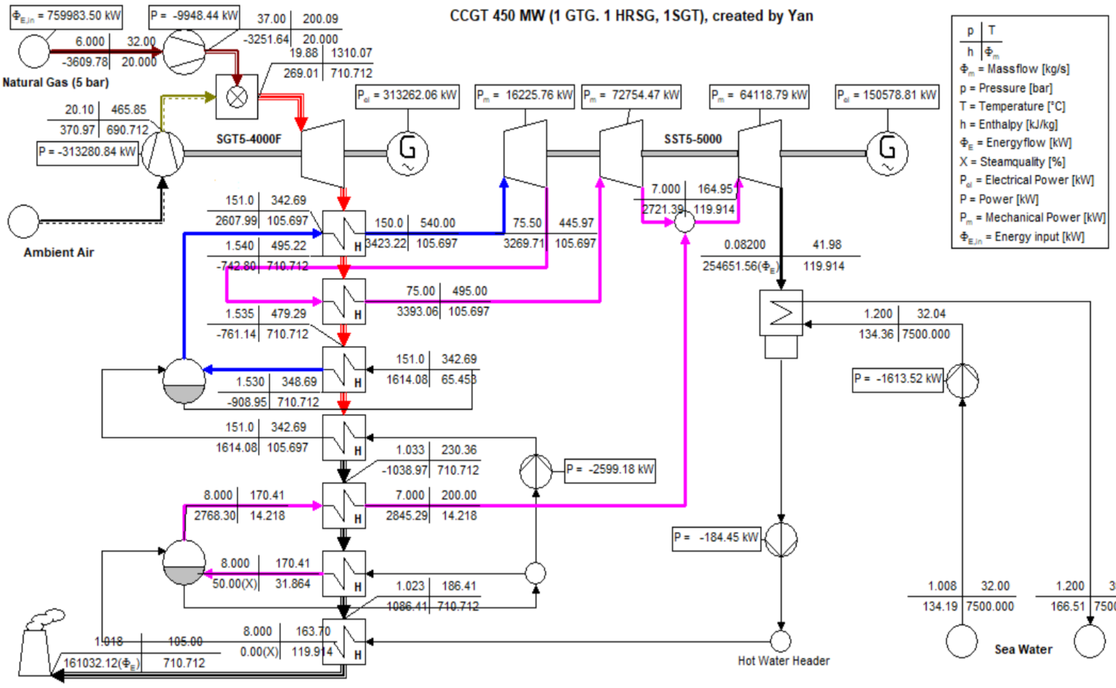

Figure 1. CCGT power plant thermodynamics design simulation

Table 1. CCGT power plant simulation result

Apparatus	Unit	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11
Fuel flow	Kg/s	15	15.5	16	16.5	17	17.5	18	18.5	19	19.5	20
NG tank	MW	570.0	588.9	608.0	627.0	646.0	665.0	684.0	703.0	722.0	741.0	760.0
GTG power	MW	236.5	242.8	250.6	258.4	266.3	274.1	281.9	289.8	297.6	305.4	313.3
STG power	MW	110.3	114.8	118.7	122.7	126.6	130.6	134.6	138.5	142.5	146.5	150.4
Gross power	MW	346.7	357.5	369.3	381.1	392.9	404.7	416.5	428.3	440.1	451.9	463.7
Cooling water	kW	1614	1614	1614	1614	1614	1614	1614	1614	1614	1614	1614
Gas compress	kW	7461	7710	7959	8207	8456	8705	8954	9202	9451	9700	9948
LP boiler pump	kW	138	143	148	152	157	162	166	171	175	180	185
HP boiler pump	kW	1948	2021	2086	2151	2216	2281	2346	2412	2477	2542	2607
Cranking GTG	kW	3500	3500	3500	3500	3500	3500	3500	3500	3500	3500	3500
Fan cooling GTG	kW	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
Close c. pump	kW	200	200	200	200	200	200	200	200	200	200	200
Oil pump	kW	50	50	50	50	50	50	50	50	50	50	50
Desal demin pump	kW	400	400	400	400	400	400	400	400	400	400	400
Air compressor	kW	300	300	300	300	300	300	300	300	300	300	300
Auxiliary p. plant	kW	150	150	150	150	150	150	150	150	150	150	150
Miscellaneous	kW	150	150	150	150	150	150	150	150	150	150	150
Total aux power	kW	16910	17237	17556	17874	18193	18511	18830	19148	19467	19785	20104
Net power	MW	329.8	340.3	351.8	363.3	374.7	386.2	397.7	409.2	420.6	432.1	443.6
Gross eff.	(%)	60.83	60.71	60.75	60.79	60.82	60.86	60.89	60.93	60.96	60.98	61.01
Net eff.	(%)	57.86	57.79	57.86	57.94	58.01	58.08	58.14	58.20	58.26	58.31	58.37

The thermodynamic simulation of this benchmark plant confirmed a gross efficiency of approximately 61% at an output of ~450 MW under baseline conditions. Variations in fuel composition exhibited only moderate sensitivity, with efficiency changes remaining within a narrow band. This outcome reflects the maturity and stability of CCGT technology, which has been refined through decades of industrial application. Figure 1 and Table 1 collectively present the design and results, demonstrating consistent performance across natural gas fuel flow rates ranging from 15 to 20 kg/s, thereby establishing a reliable baseline for comparison with emerging power generation technologies.

4.2. SOFC power plant simulation model

Building upon this baseline analysis, the SOFC power plant simulation adopts the design concept model illustrated in Figure 2, incorporating criteria such as the use of a flue gas heater as the balance of plant (BoP) unit for fuel preheating, air supply, and water evaporation. System pressure and temperature are defined according to Figure 2. The primary output analyzed is SOFC efficiency, benchmarked against the CCGT system at an equivalent gross power of 450 MW. The SOFC simulation is based on variations in fuel flow rate, consistent with the CCGT system, and equivalent power is obtained by adjusting the active cell area as specified in the design of Figure 2.

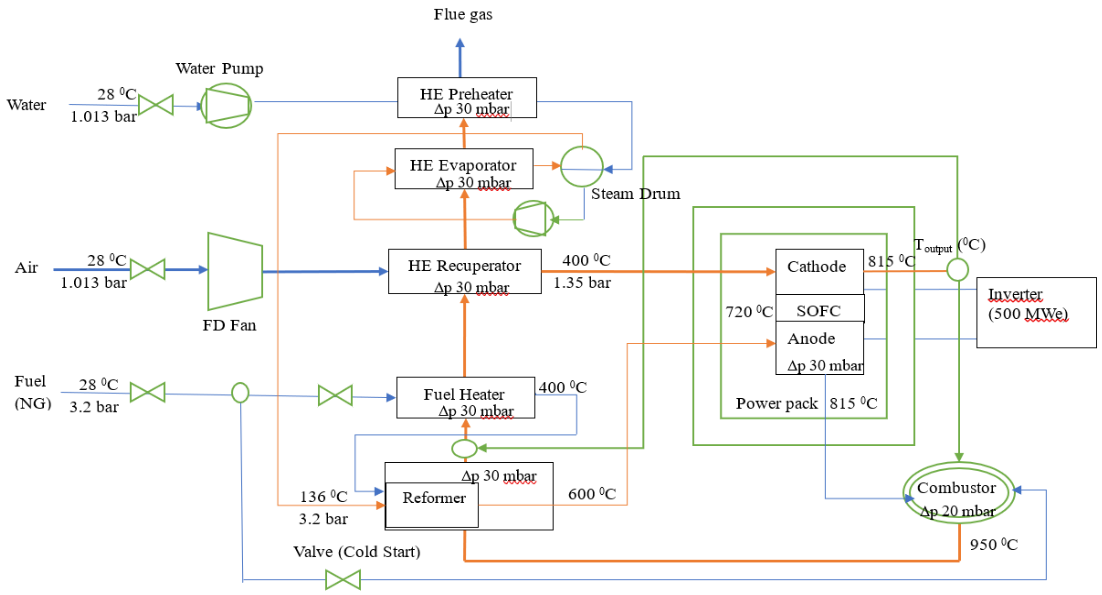

Figure 2. Modeling of SOFC power plant thermodynamics design simulation

To further refine this comparison, analysis using the SOFC model focused on determining the appropriate cell area required to achieve output power comparable to CCGT, approximately 450 MW. Assuming an SOFC active cell power density of 2 kW/m², within a conversion range of 2–20 kW/m², the required minimum active area is approximately 200,000 m². Using a CCGT fuel flow rate of 19.5 kg/s for a gross output of 450 MW, a simulation was conducted for SOFC active areas ranging from 200,000 m² to 360,000 m². Partial results are presented in Table 2, while the efficiency versus active area curve is shown in Figure 3. Figure 3 shows the increase in efficiency with the active area of the SOFC cell.

Table 2. Simulation results of changes in the SOFC cell area for efficiency

SOFC area (m^2)	200000 kW	210000 kW	220000 kW	230000 kW	240000 kW	250000 kW	260000 kW	270000 kW	38000 kW	290000 kW	300000 kW	310000 kW
NG fuel power	741023	741023	741023	741023	741023	741023	741023	741023	741023	741023	741023	741023
Gross power	461903	467261	472098	476480	480464	484097	487420	490467	493266	495843	498220	500417
Air compr.	31383.1	30820	30312	29852	29433	29051	28702	28382	28088	27817	27568	27337
Water pump	15.68	15.68	15.68	15.68	15.68	15.68	15.68	15.68	15.68	15.68	15.68	15.68
W. feed pump	5.41	5.41	5.41	5.41	5.41	5.41	5.41	5.41	5.41	5.41	5.41	5.41
Total aux. power	31399	30836	30328	29867	29449	29067	28718	28398	28104	27833	27583	27353
Net power	430504	436426	441770	446612	451015	455030	458702	462069	465163	468010	470637	473064
Gross efficiency (%)	62.33	63.06	63.71	64.30	64.84	65.33	65.78	66.19	66.57	66.91	67.23	67.53
Net efficiency (%)	58.10	58.90	59.62	60.27	60.86	61.41	61.90	62.36	62.77	63.16	63.51	63.84

Figure 3 demonstrates the positive correlation between SOFC cell active area and system efficiency. As presented in Tables 1 and 2, when the gross output of a CCGT system reaches 450 MW, the SOFC net efficiency becomes comparable once the cell area approaches approximately 210,000 m². Further expansion of the active area results in net efficiencies surpassing the CCGT benchmark.

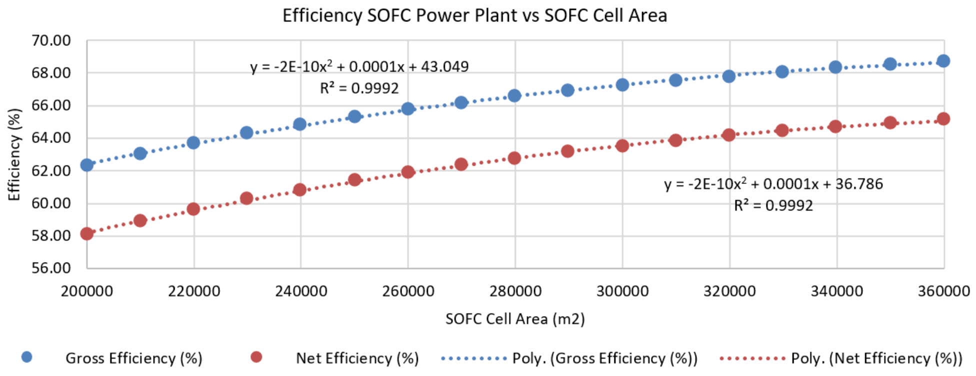

Figure 3. Curve of efficiency vs SOFC active area cell

Given that fuel flow rate directly influences electrochemical conversion, where higher flow rates increase current density but simultaneously reduce conversion efficiency, additional simulations were conducted. To preserve favorable efficiency characteristics, an active cell area of 250,000 m² was selected as the reference case. Subsequent analyses varied the fuel flow rate, with CCGT serving as the benchmark, and both gross and net efficiencies were systematically evaluated against the previously simulated CCGT system.

Extending this framework, Figure 4 presents a detailed thermodynamic simulation of an SOFC power plant with a cell area parameter of 250,000 m², developed as an extension of the conceptual framework illustrated in Figure 2. While Figure 2 outlines the general flow of water, air, and natural gas through key components such as the preheater, reformer, SOFC stack, and combustor, Figure 4 translates this schematic into a comprehensive numerical model. It includes precise data for mass flow, pressure, temperature, enthalpy, entropy, and power output across each subsystem, enabling a full-scale simulation of SOFC performance at 450 MWe. By referencing the structural layout in Figure 2, the simulation in Figure 4 validates the operational feasibility of the design and quantifies its efficiency under varying conditions, reinforcing the scalability and optimization potential of SOFC-based power generation.

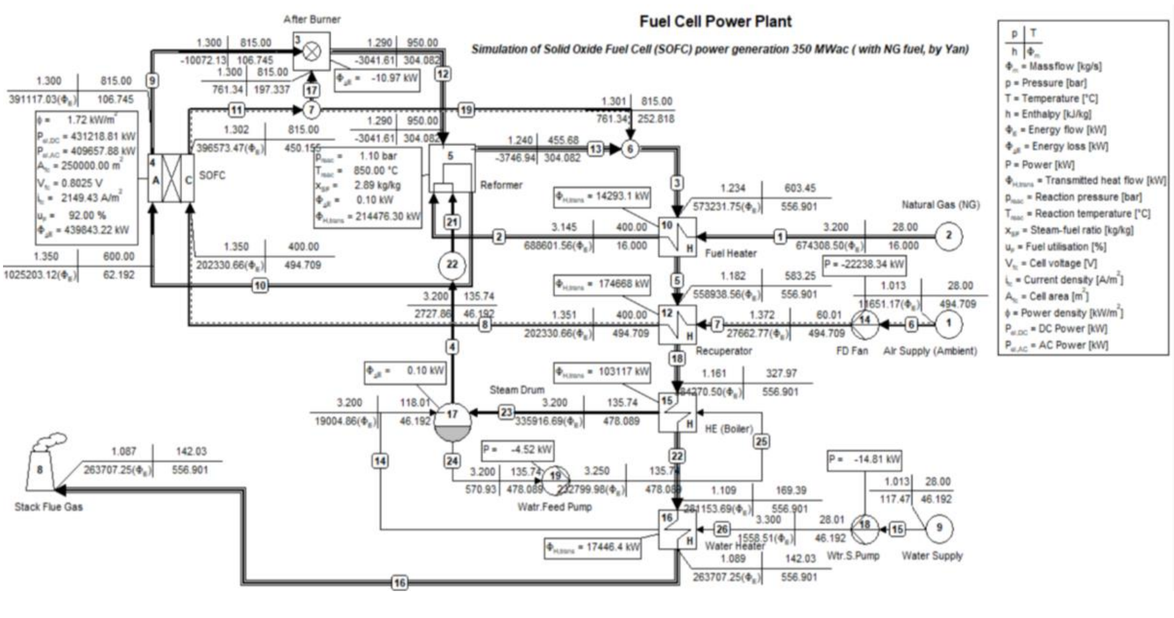

Figure 4. SOFC power plant thermodynamics design simulation

Accordingly, using Table 3 as a reference, with an active SOFC cell area of 250,000 m², the simulation results demonstrate that the SOFC achieves superior gross and net efficiencies compared to the CCGT. As illustrated in Figure 5, at a gross power output of approximately 450 MW, SOFCs deliver higher gross efficiency than CCGTs. To reach this level of power, a CCGT requires a NG fuel flow of about 19.5 kg/s, whereas an SOFC achieves the same output with only 18.5 kg/s of NG fuel flow, highlighting its efficiency advantage.

Table 3. SOFC power plant simulation result

Apparatus	Unit	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11
Fuel input	Kg/s	15	15.5	16	16.5	17	17.5	18	18.5	19	19.5	20
Fuel input power	MW	570.0	589.0	608.0	627.0	646.0	665.0	684.0	703.0	722.0	741.0	760.0
Gross power	MW	387.2	398.5	409.7	420.7	431.6	442.3	453	463.5	473.8	484.1	494.2
Air compr.	MW	20.5	21.4	22.3	23.1	24	24.9	25.8	26.8	27.7	28.7	29.7
Wtr. s. pump	kW	12.1	12.5	12.9	13.3	13.7	14.1	14.5	14.9	15.3	15.7	16.1
Whb. c. pump	kW	4	4	5	5	5	5	5	5	5	5	6
Total aux. power	kW	20.5	21.4	22.3	23.1	24	24.9	25.8	26.8	27.7	28.7	29.7
Net power	MW	366.7	377.1	387.4	397.5	407.5	417.4	427.1	436.7	446.1	455.9	464.5
Eff. gross	%	67.93	67.66	67.38	67.09	66.80	66.51	66.22	65.93	65.63	65.33	65.03
Eff. net	%	64.33	64.03	63.72	63.40	63.08	62.76	62.44	62.11	61.79	61.45	61.12

4.3. Comparing of efficiency CCGT vs SOFC power plant simulation model

This trend is further clarified in Figure 5, which illustrates a clear performance advantage of SOFCs over CCGTs in both gross and net efficiency across a range of fuel input values. SOFC gross efficiency starts high and declines gradually as fuel input increases, following a downward polynomial trend with an R^2 of 1, indicating a perfect fit. Net efficiency for SOFC also follows a similar trend, remaining consistently above 57% even at higher fuel flows. In contrast, CCGT gross efficiency shows a slight upward trend with increasing fuel input, but its net efficiency declines, peaking below 57%. This suggests that while CCGT systems benefit marginally from increased fuel input, their overall fuel-to-power conversion remains less efficient than SOFCs under comparable conditions. Nevertheless, these trend curves are essential for power systems scheduling, which will be useful for future studies if SOFCs are to be introduced into electrical power systems.

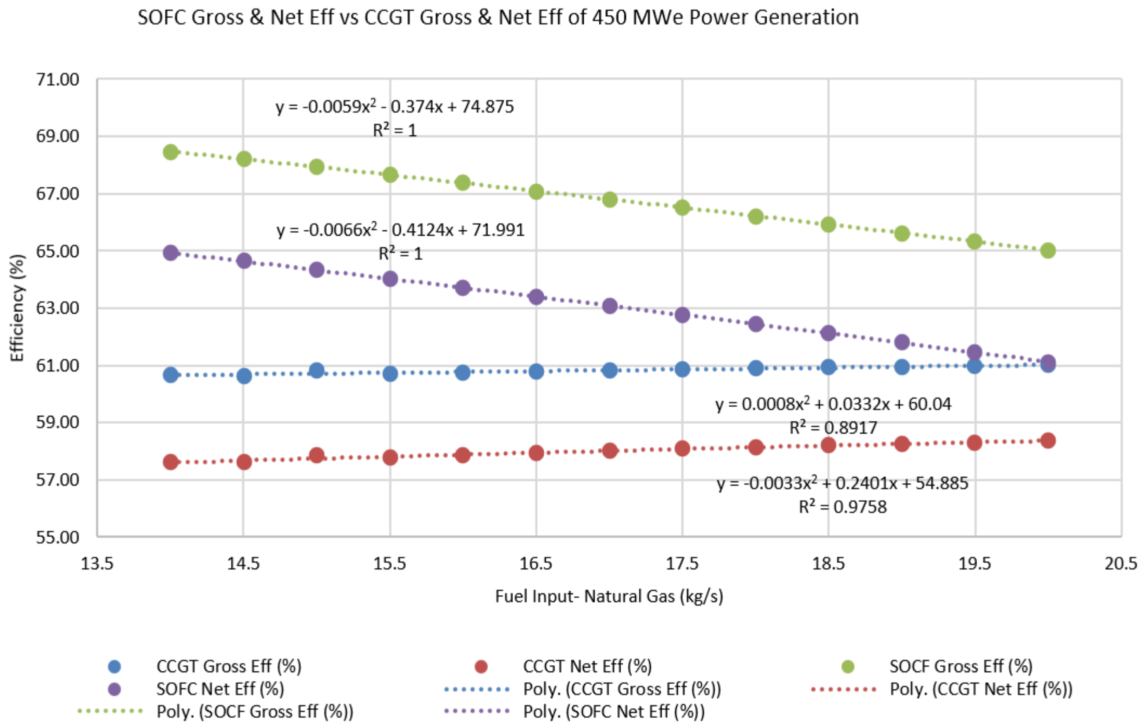

Figure 5. Comparison of CCGT efficiency with SOFC power plant at the same fuel flow

Taken together, the thermodynamic simulations highlight fundamental differences between CCGT and SOFC systems in terms of efficiency and fuel utilization. CCGT, as a mature technology, demonstrates stable performance with only moderate sensitivity to variations in fuel flow. This reflects decades of optimization of the Brayton–Rankine cycle, which has established CCGT as a reliable option for large-scale power generation. However, despite its consistency, CCGT net efficiency remains below 57%, indicating limited potential for further improvement within conventional cycle boundaries.

In contrast, SOFC exhibits superior efficiency through direct electrochemical conversion. The simulations show that with a cell area of approximately 250,000 m², SOFC can achieve gross output levels around 450 MW, with gross efficiency approaching 70% and net efficiency exceeding 63%. This performance advantage is reinforced by lower fuel demand, requiring only 18.5 kg/s of natural gas compared to 19.5 kg/s for CCGT. Nevertheless, SOFC's higher sensitivity to input variations and the complexity of system integration present challenges in scalability, durability, and cost. These factors must be addressed to ensure the practical deployment of SOFC technology on a utility scale.

As shown in Table 4, the comparative summary reinforces the analytical findings by clearly illustrating SOFC's superior efficiency and reduced fuel demand relative to CCGT. While the CCGT remains a mature and reliable technology with proven industrial stability, its efficiency ceiling limits further performance gains. In contrast, the SOFC demonstrates consistently higher gross and net efficiencies, even under varying fuel input conditions, positioning it as a transformative pathway for next-generation power generation. This side-by-side comparison underscores the potential of SOFC to surpass conventional thermal cycles, provided that challenges in scalability, durability, and cost are effectively addressed.

Table 4. Summary comparison of CCGT vs SOFC (450 MW simulation)

Parameter	CCGT (Siemens STG5-4000F + SST5-5000)	SOFC (active cell area 250,000 m²)
Gross output	~450 MW	~450 MW
Fuel flow (natural gas)	19.5 kg/s	18.5 kg/s
Gross efficiency	~61%	~67–70%
Net efficiency	~58% (maximum)	~63% (average)
Trend vs fuel flow	Net efficiency tends to decline, stabilizing below 57%	Net efficiency remains above 63%, though more sensitive to input variations
Strengths	Mature technology, stable, widely proven in industry	Higher efficiency, lower fuel demand
Limitations	Efficiency ceiling of thermal cycles, limited improvement potential	Challenges in scalability, durability, and cost

4.4. Closing statement

Overall, the comparative thermodynamic simulations underscore the distinct advantages and limitations of CCGT and SOFC technologies. CCGT remains a robust and well-established option for large-scale power generation, characterized by stable performance and decades of optimization within the Brayton–Rankine cycle. However, its efficiency ceiling, particularly in terms of net efficiency, highlights the constraints of conventional thermal cycles. By contrast, SOFC demonstrates significant potential for next-generation power systems, offering superior gross and net efficiencies through direct electrochemical conversion and reduced fuel demand. The findings suggest that SOFC technology, when scaled to an active cell area of approximately 250,000 m², can surpass CCGT benchmarks in both efficiency and fuel utilization. Therefore, while CCGT continues to serve as a reliable baseline for utility-scale applications, SOFC represents a transformative pathway toward higher efficiency and lower fuel consumption. Addressing challenges related to scalability, durability, and cost will be critical to realizing SOFC's promise as a viable alternative for sustainable and efficient power generation in the future.

4.5. Implications for future research

The comparative analysis of CCGT and SOFC systems underscores SOFC's superior efficiency and reduced fuel demand, while also highlighting critical challenges in scalability, durability, and cost. Future research should therefore prioritize hybrid SOFC–CCGT integration, materials and design innovations to enhance long-term durability, system-level optimization under real operating conditions, and comprehensive techno-economic and lifecycle assessments. Investigations into modular scalability will also be essential to support utility-scale deployment. In summary, SOFC represents a promising pathway for next-generation power generation, yet its practical realization demands interdisciplinary collaboration bridging thermodynamics, materials science, control systems, and economic analysis to establish it as a viable alternative or complement to CCGT.

In addition, this study provides valuable insight into the relationship between fuel input and output efficiency in SOFC-based power plants. The efficiency curve of SOFCs exhibits an inverse trend compared to CCGTs: SOFC efficiency declines with increasing fuel consumption, whereas CCGT efficiency rises modestly under similar conditions. This contrasting behavior suggests that future research could explore the integration of SOFCs into hydrothermal scheduling frameworks, enabling more sophisticated optimization of electrical power systems that combine conventional and advanced generation technologies.

5. CONCLUSION

The comparative simulations demonstrate clear differences between CCGT and SOFC systems in efficiency and fuel utilization: CCGT remains a mature baseline technology with stable but limited net efficiency, while SOFC indicates higher efficiency potential under equivalent operating conditions. Rather than repeating numerical outcomes, the analysis highlights trends CCGT efficiency improves only incrementally with increased fuel flow, whereas SOFC sustains higher values despite greater sensitivity to input variations. Achieving net efficiency above 63% at utility scale is significant, as it implies reduced fuel demand and meaningful contributions to decarbonization strategies. Overall, the study indicates that SOFC offers a promising pathway toward sustainable, high-efficiency power generation, though practical deployment will depend on overcoming challenges in scalability, durability, and cost.

ACKNOWLEDGMENTS

This research was conducted within the framework of research collaboration between Politeknik Negeri Bandung and PT PLN (Persero), division Litbang.

FUNDING INFORMATION

This research was funded by PT PLN (Persero) decision Litbang as a collaboration between PT PLN (Persero) Litbang and Bandung State Polytechnic.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

DATA AVAILABILITY

Data availability does not apply to this paper as no new data was created or analyzed in this study.

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