© SEP 2026 | IRE Journals | Volume 10 Issue 3 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV10I3-1722800

Development And Validation of A Simulation Model for Performance Optimization of An Integrated Biogas and Natural Gas Combined-Cycle Power Plant

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Abstract- This study develops and validates a thermodynamic simulation model of an integrated biogas-natural gas combined-cycle gas turbine (CCGT) power plant. First-law mass and energy conservation principles were used to model the air compressor, combustion chamber, gas turbine, and heat recovery steam generator (HRSG), integrated into a unified system-level framework in Aspen HYSYS (v21.0.4) via a sequential modular, iterative approach. Validation against published GE LM2500+ operational data yielded errors below 1.6% across net power output, thermal efficiency, exhaust temperature, and HRSG steam production. Parametric analysis across biogas-natural gas blend ratios (0-100%) showed that a 50% biogas blend reduced thermal efficiency by 3.3% and power output by 11-12%, while cutting fossil-derived CO2 emissions by nearly 50%. Raising turbine inlet temperature from 1200 K to 1600 K substantially recovered this performance penalty. The validated model provides a practical decision-support tool for optimizing hybrid biogas-natural gas plant design, particularly in biomass-rich, gas-dependent economies such as Nigeria.

Keywords: biogas; natural gas; combined-cycle gas turbine; simulation; Aspen HYSYS; thermal efficiency; emissions; model validation

I. INTRODUCTION

Rising climate concerns are pushing power generation away from fossil fuels toward renewables, but intermittency issues favour hybrid systems pairing renewables with conventional fuels (1–4). Biogas derived from organic waste is a promising complement to natural gas in CCGT plants, especially in Nigeria, which has substantial untapped potential (542.5 million tonnes of organic waste/year, 25.5 billion m³ of biogas) (5,6).

This study fills that gap by developing and validating a thermodynamic model of an integrated biogas-NG CCGT plant, covering: (i) component-level modelling of the compressor, combustor, turbine, and HRSG (7,8); (ii) system-level integration (9–11); (iii) validation against industrial reference data (12); and (iv) a parametric study of blend ratio and operating parameters on performance and emissions (13–15), aiming to provide a practical decision-support tool for hybrid plant adoption.

II. METHOD

This study adopted a quantitative, simulation-based research approach, in which thermodynamic component models were mathematically formulated, integrated into a system-level model, implemented in commercial process simulation software, validated against published reference data, and subsequently used to perform parametric sensitivity analysis.

2.1 System Description and Conceptual Model

The integrated power plant under study comprises a Brayton-cycle gas turbine topping cycle coupled with a Rankine-cycle steam bottoming cycle through a heat recovery steam generator (HRSG), forming a combined-cycle gas turbine (CCGT) configuration. The plant was designed to accept a variable fuel blend consisting of Nigerian natural gas, modelled primarily as methane with a typical lower heating value (LHV) of approximately 36 MJ/m³, and biogas, modelled as a mixture of methane and carbon dioxide (typically 60% CH_4 and 40% CO_2) reflecting local feedstock composition. The conceptual block diagram of the integrated model links the air compressor, combustion chamber, gas turbine, and HRSG sequentially, with the output state variables (temperature, pressure, and mass flow rate) of each component serving as inputs to the next.

2.2 Mathematical Modeling of Components

2.2.1 Fuel Input Modeling

The lower heating value of the fuel blend was calculated as the mole-weighted average of the LHVs of its constituent species:

$$LHV_{blend} = \Sigma x_i \cdot LHV_i \quad (1)$$

where xi is the mole fraction and LHVi is the lower heating value of component i (e.g., CH_4, CO_2, N_2). The specific heat capacity and enthalpy of the fuel mixture and combustion products were calculated as functions of temperature and composition using established thermophysical property correlations.

2.2.2 Air Compressor

The axial-flow compressor was modelled as a polytropic compression process (7,8). The compressor power, Wc, is a function of air mass flow rate and the specific enthalpy change across the compressor:

$$W_c = m_a(h_2 - h_1) = m_a \cdot c_{p,a} \cdot (T_2 - T_1) \quad (2)$$

The compressor outlet temperature was determined from the compressor pressure ratio (CPR = P2/P1) and the isentropic efficiency, ηc:

$$T_2 = T_1[1 + (1/\eta_c)(CPR^{((\gamma_a-1)/\gamma_a)} - 1)] \quad (3)$$

2.2.3 Combustion Chamber

The combustor was modelled as a constant-pressure control volume governed by mass and energy conservation (16,17). A stoichiometric combustion equation, formulated for the specific fuel blend composition, was used to determine the theoretical air requirement, and the actual air-fuel ratio was set by the excess air required to control the turbine inlet temperature (TIT). The TIT (state 3) was obtained from the first law of thermodynamics:

$$m_f(LHV_{blend} + h_f) + m_a \cdot h_2 = (m_a + m_f) \cdot h_3 + Q_{loss} \quad (4)$$

This equation was solved iteratively for T3, since the enthalpy of the exhaust gas, h3, depends strongly on temperature.

2.2.4 Gas Turbine

The gas turbine was modelled as a polytropic/isentropic expansion process (7,8). The gross turbine power output is:

$$W_T = m_g(h_3 - h_4) = m_g \cdot c_{p,g} \cdot (T_3 - T_4) \quad (5)$$

with the turbine outlet (exhaust) temperature obtained from the turbine pressure ratio (TPR) and isentropic efficiency, ηt:

$$T_4 = T_3[1 - \eta_t(1 - 1/TPR^{((\gamma_g-1)/\gamma_g)})] \quad (6)$$

The net gas turbine power output is the difference between turbine work and compressor work, WGT,net = WT - WC.

2.2.5 Heat Recovery Steam Generator (HRSG)

The HRSG was modelled using the pinch-point method, with three sections represented: economizer, evaporator, and superheater (9,11,18). Energy balances applied across each section were solved simultaneously, subject to pinch-point and approach-point temperature constraints, to obtain the steam mass flow rate and final stack gas temperature.

2.3 System Integration and Simulation Strategy

The individual component models were integrated into a cohesive system-level simulation using Aspen HYSYS (version 21.0.4), selected for its robust numerical solver and graphical block-diagram modeling environment (9,11,19). Component blocks were connected sequentially, with an iterative solution procedure employed to reconcile interdependent variables; for instance, the combustor model adjusted the air-fuel ratio iteratively until the target turbine inlet temperature was achieved, ensuring thermodynamic consistency across the system

$$\eta_{th,overall} = (W_{GT,net} + W_{ST}) / (m_f \cdot LHV_{blend}) \quad (7)$$

2.4 Model Validation

The developed model was validated by configuring its inputs (ambient conditions, fuel composition, compressor pressure ratio of 23:1, turbine inlet temperature of 1500 K) to match published operational data for a reference industrial gas turbine, the GE LM2500+, under ISO conditions (288.15 K, 101.3

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kPa, 60% relative humidity) (12). Simulated key performance indicators (KPIs) — net power output, overall thermal efficiency, turbine exhaust temperature, and HRSG steam production — were compared against reference data using the percentage error:

Error (%) = |Valuesimulated - Valuereference| / Valuereference × 100% *(8)*

The model was considered successfully validated where the percentage error for major KPIs fell within an acceptable margin of ±5%, a tolerance commonly applied in process simulation studies.

2.5 Parametric Analysis

Following validation, a one-factor-at-a-time (OFAT) parametric analysis was conducted to investigate plant performance under varying conditions. Two categories of variables were examined: (i) fuel composition, with the biogas-to-natural-gas ratio varied from 0% to 100% biogas in 10% increments (and up to a 50% blend for detailed analysis), and (ii) operating parameters, namely compressor pressure ratio (CPR), turbine inlet temperature (TIT), and ambient air temperature. The dependent variables monitored were overall plant thermal efficiency, net power output, fuel consumption, stack exhaust temperature, and CO2 emissions profile, calculated from combustion stoichiometry.

III. RESULTS AND DISCUSSION

This section presents the principal findings of the simulation study, organized around model component parameters, plant-level integration results, model validation, and parametric sensitivity analysis.

3.1 Model Component Parameters

Table 1 summarizes the key operating and design parameters used in developing the thermodynamic models for the individual plant components, selected to reflect realistic industrial conditions for the integrated biogas-natural gas system.

Table 1: Summary of key component design and operating parameters.

Component	Parameter	Value	Unit
Biogas feed	Temperature / Pressure	55 / 3	°C / bar
Air compressor	Adiabatic / Polytropic efficiency	88 / 91.6	%
Air compressor	Compression ratio	21	—
Gas turbine	Adiabatic / Polytropic efficiency	90 / 87.4	%
Gas turbine	Duty	2000	kW
HRSG sections	ΔP shell / tube; ΔT	0.1-0.2; 200	bar; °C
Steam turbine	Adiabatic / Polytropic efficiency	90 / 89	%
Overall CCGT	Combined-cycle efficiency (ηccgt)	43.5	%

The air compressor's adiabatic and polytropic efficiencies (88% and 91.6%) and compression ratio of 21 are consistent with values reported for small-to-medium CCGT systems, confirming the model's fidelity in simulating compressor work and heat input requirements. The gas turbine's 90% adiabatic efficiency and 2000 kW duty indicate effective translation of chemical energy from mixed-fuel combustion into mechanical power, with a Gibbs reactor used to represent the combustor and accommodate variable gas compositions under thermodynamic equilibrium. Within the HRSG, the small pressure drops (0.1-0.2 bar) and large temperature differences (200°C) across the economizer, evaporator, and superheater sections reflect effective heat transfer with minimal flow losses, while the steam turbine duty of 268.8 kW contributed to an overall combined-cycle efficiency of 43.5%.

3.2 CCGT Power Plant Simulation Result

Integration of the component models into the unified Aspen HYSYS framework yielded the optimized steady-state parameters summarized in Table 2.

Table 2: Optimized parameters from CCGT plant simulation.

Component	Optimised Parameter
Natural gas	185.1 kg/h @ 20 bar, 25°C
Biogas	50 kg/h @ 20 bar, 25°C
Air flow	9800 kg/h @ 1 bar, 25°C
Air compressor	ηadiabatic = 88%, ηpolytropic = 91.6%, duty = 1277 kW
Gas turbine	ηadiabatic = 90%, duty = 2000 kW
Steam turbine	ηadiabatic = 90%, duty = 268.8 kW
Overall efficiency	ηccgt = 43.5%

The results indicate that a biogas-to-natural-gas blend of approximately 1:3.7 provided stable combustion and efficient energy conversion. The air flow rate of 9800 kg/h ensured complete combustion and consistent turbine inlet conditions, while compressor and turbine efficiencies (88-90%) aligned with standard industrial benchmarks. The steam turbine output of 268.8 kW from waste heat recovery confirmed effective coupling between the Brayton and Rankine cycles, validating the integrated model as a robust and realistic platform for subsequent parametric and environmental analysis.

3.3 Model Validation

The model was validated against published operational data for the GE LM2500+ industrial gas turbine. Table 3 compares the simulated key performance indicators with reference values.

Table 3: Comparison of simulated results with reference data for model validation.

Performance Indicator	Reference (GE, 2020)	Simulated Value	Error (%)
Net power output (MW)	30.2	29.85	-1.16
Overall thermal efficiency (%)	39.5	38.9	-1.52
Turbine exhaust temperature (K)	823	831	+0.97
HRSG steam production (kg/s)	12.5	12.3	-1.60

The percentage error for all primary KPIs was below 1.6%, well within the ±5% margin generally considered acceptable for process simulation validation. The model slightly under-predicted power output and efficiency, plausibly attributable to conservative assumptions on auxiliary power consumption or minor discrepancies in modelled specific heat capacities, while the turbine exhaust temperature was marginally over-predicted, consistent with the slightly lower work extraction predicted by the model. The strong agreement in HRSG steam production further validated the energy balance across the integrated system. Given this close agreement, the model was deemed successfully validated and suitable for parametric analysis.

3.4 Effect of Biogas-to-Natural-Gas Ratio

Increasing biogas share in the fuel blend steadily lowered thermal efficiency (~3.3% drop pure NG to pure biogas, in line with literature's 3-5%) (14,14,20) and net power output, since biogas's lower calorific value reduces turbine expansion heat (21). Total CO2 fell sharply (~50% at pure biogas, matching reported 45-55%) (14,17), while fuel mass flow rose over 150% at 50% blend to maintain turbine inlet temperature with implications for fuel system sizing (15,20). Exhaust temperature rose only slightly (831→845 K), and the higher exhaust mass flow partly offset losses by boosting HRSG/steam turbine output.

Separating fossil from biogenic CO2, fossil emissions dropped proportionally with biogas share even as total stack CO2 rose with fuel consumption confirming the core trade-off: a 50% blend roughly halves fossil CO2 but costs 11-12% in power output (14,17).

3.5 Effect of Key Operating Parameters

Increasing the turbine inlet temperature (TIT) from 1100°C to 1250°C improved overall efficiency from 40.1% to 43.2%, while reducing specific fuel consumption from 0.284 to 0.251 kg/kWh, consistent with Brayton cycle principles (8). At a fixed 50/50 biogas-natural gas blend, overall plant efficiency increased continuously with compressor pressure ratio (CPR), rising from approximately 30% at CPR 15 to over 38% at CPR 35, since a higher pressure ratio raises the average temperature of heat addition in the combustor (8,22). Net specific power, in contrast, peaked at a CPR of approximately 28-30 before declining at higher ratios, reflecting the increasing compressor work and reduced margin for heat addition at very high pressure ratios. These results confirm that the design trade-off between peak efficiency (favoring high CPR) and peak specific power (favoring moderate CPR) persists even when the plant is operated on a biogas blend (7,15).

Raising TIT from 1200 K to 1600 K produced an almost linear increase in both net power output and overall efficiency, the most direct mechanism for improving gas turbine performance, since a higher TIT increases the enthalpy available for expansion work without increasing compressor work input (8,22). Notably, the efficiency loss associated with a 50% biogas blend could be substantially recovered by raising TIT from approximately 1400 K to 1550 K, underscoring the critical role of turbine materials technology in enabling high-TIT operation on biogas-blended fuels (15,20).

3.6 Summary of Findings

Biogas integration reduces fossil CO2 emissions but comes at the cost of lower thermal efficiency and power output, owing to biogas's lower calorific value (14,20). This trade-off can be largely mitigated through high-pressure-ratio compressors and advanced turbine materials (8,15), and the validated model offers a practical design tool for balancing environmental and performance goals in plants like Nigeria's (4,5).

IV. CONCLUSION

This study successfully developed and validated a thermodynamic simulation model for an integrated biogas and natural gas combined-cycle power plant. Detailed mathematical models of the compressor, combustor, gas turbine, and HRSG were formulated from fundamental mass and energy conservation principles and explicitly accounted for variable fuel calorific value associated with biogas-natural gas blending. These component models were integrated into a cohesive, sequentially modular system-level simulation in Aspen HYSYS, accurately capturing the dynamic coupling, mass flows, and energy balances across the plant. Validation against published operational data for a reference industrial gas turbine (GE LM2500+) yielded percentage errors below 1.6% for all major performance indicators, confirming the model's fidelity and establishing its credibility as a reliable analytical tool.

The validated model revealed that increasing the biogas fraction in the fuel blend to 50% produced a near-linear decrease in net power output (approximately 11%) and overall thermal efficiency (approximately 3.3%), while reducing fossil-derived CO_2 emissions by nearly half. The parametric analysis further demonstrated that this performance penalty could be substantially mitigated through design optimization, particularly by increasing compressor pressure ratio and turbine inlet temperature. Overall, the developed framework provides a robust, validated platform for evaluating the performance and environmental implications of biogas co-firing in CCGT plants, offering practical value for engineers, plant operators, and policymakers pursuing the integration of renewable fuels into existing gas-fired power infrastructure, particularly in biomass-rich developing economies. Future work should extend the model to capture transient/dynamic plant behaviour, incorporate detailed chemical-kinetics-based emissions modeling (including NO_x and CO), integrate techno-economic cost analysis, and pursue experimental validation specifically under biogas-blended operating conditions.

V. DECLARATIONS

Author Contributions

Chika Enwere: Conceptualization, methodology, investigation, data collection, simulation, formal analysis, validation, visualization, writing – original draft, writing – review and editing.

Ethical Approval

This study did not involve human participants, animals, or identifiable personal data. Therefore, ethical approval and informed consent were not required.

Conflict of Interest

The author declares that there are no known financial or personal conflicts of interest that could have influenced the work reported in this manuscript.

Funding

This research received no external funding.

Consent to participate

Not applicable.

Consent to publish

Not applicable.

Availability of Data and Materials

Not applicable.

Competing Interests

All authors have declared that they have no competing interests

Acknowledgements

Not Applicable

Clinical Trial Number

Not Applicable

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