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(ARTICLE)

Energetic, Exergetic, and Economic Analysis of Simple and proposal Combined Cycle Gas Turbine Power Plants: A Case Study of Al-Ruwais Power Station

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تحليل الطاقة والطاقة المتاحة والاقتصاد لمحطات توليد الطاقة ذات الدورة المركبة البسيطة والمقترحة التي تعمل بتوربينات الغاز: دراسة حالة لمحطة الرويس لتوليد الطاقة

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Abstract:

Gas Turbine power plants represent critical energy infrastructure in Libya; however, their performance is highly sensitive to ambient temperature variations. This study investigates the energetic, exergetic, and economic performance of Al-Ruwais Gas Power Plant, which located in Al-Hawamid in the Western Mountain region of Libya, by comparing the existing simple gas turbine configuration (two Siemens SGT5-2000E units) with a proposed Combined Cycle Power Plant integration. Thermodynamic simulations were performed using Aspen Plus over an ambient temperature range of 10–50°C. The CCPP significantly improves plant performance by recovering exhaust-gas heat through the Heat Recovery Steam Generator (HRSG) and generating additional power using the steam turbine. At 10°C, the simple cycle achieves a thermal efficiency of 35.28%, whereas the CCPP about was 49.81%. Moreover, the exergy analysis confirms that the combustion chambers dominate irreversibility losses (82.7%) in the gas cycle, while the HRSG was and condenser (51.4%) and (33.6%) respectively dominate the steam bottoming cycle losses. In addition, the economic assessment confirms that combined-cycle integration provides substantially stronger financial performance, with the Net Present Value (NPV) increasing from $367.41 M to $871.10 M and the Payback Period (PBP) decreasing from 9.19 to 6.21 years.

Keywords: : Gas Turbine; Combined Cycle Power Plant; Exergy Analysis; Aspen Plus; Waste Heat Recovery; Economic Analysis; Libya

الملخص

تُمثل محطات توليد الطاقة بالتوربينات الغازية بنية تحتية حيوية للطاقة في ليبيا؛ إلا أن أداءها يتأثر بشدة بتغيرات درجة الحرارة المحيطة. تُجري هذه الدراسة بحثًا حول الأداء الطاقي والحراري والاقتصادي لمحطة الرويس لتوليد الطاقة بالغاز، الواقعة في منطقة الحواميد بالمنطقة الجبلية الغربية في ليبيا، وذلك من خلال مقارنة التكوين الحالي البسيط للتوربينات الغازية (وحدتان من طراز Siemens SGT5-2000E) مع نموذج مُقترح لمحطة توليد طاقة ذات دورة مركبة. أُجريت محاكاة ديناميكية حرارية باستخدام برنامج Aspen Plus ضمن نطاق درجة حرارة محيطة يتراوح بين 10 و50 درجة مئوية. تُحسّن محطة توليد الطاقة ذات الدورة المركبة أداء المحطة بشكل ملحوظ من خلال استعادة حرارة غازات العادم عبر مولد البخار لاستعادة الحرارة (HRSG) وتوليد طاقة إضافية باستخدام التوربين البخاري. عند درجة حرارة 10 درجات مئوية، تُحقق الدورة البسيطة كفاءة حرارية تبلغ 35.28%، بينما تصل كفاءة محطة توليد الطاقة ذات الدورة المركبة إلى 49.81%. علاوة على ذلك، يؤكد تحليل الطاقة المتاحة أن غرف الاحتراق تُهيمن على خسائر اللاعكوسية (82.7%) في دورة الغاز، بينما تُهيمن مولدات البخار لاستعادة الحرارة (51.4%) والمكثف (33.6%) على خسائر دورة البخار المتبقية. بالإضافة إلى ذلك، يؤكد التقييم الاقتصادي أن دمج الدورة المركبة يُحقق أداءً ماليًا أقوى بكثير، حيث ارتفعت القيمة الحالية الصافية من 367.41 مليون دولار إلى 871.10 مليون دولار، وانخفضت فترة الاسترداد من 9.19 إلى 6.21 سنة.

الكلمات المفتاحية: محطة غازية ;دورة مركبة;تحليل اكسيرجي;اسبن بلس;مبادل حراري;تحليل اقتصادي ;ليبيا

1.Introduction

Gas turbine power plant constitute one of the most important technologies for electricity generation globally and in Libya in particular, owing to their rapid dynamic response and acceptable energy conversion efficiency. In Libya, these stations form a fundamental pillar of the national power generation

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infrastructure, with gas turbine units distributed across several plants, including West Tripoli, South Tripoli, Benghazi, Al-Zawiya, and Al-Ruwais. However, the operational performance of these units is strongly affected by local atmospheric conditions, particularly the elevated ambient temperatures experienced during summer months, which reduce compressor-inlet air density, decrease power output, and increase fuel consumption (Algool et al., 2015; El-Badri et al., 2022; Siemens, 2011).

The Combined Cycle Power Plant (CCPP) is one of the most effective engineering solutions for enhancing gas turbine performance. By recovering exhaust-gas heat through a Heat Recovery Steam Generator (HRSG) to drive an additional steam turbine, the CCPP converts a larger fraction of the fuel energy into useful electrical output and reduces Specific Fuel Consumption (SFC) compared with the simple Gas Turbine (GT) cycle (Batainih & Khaleel, 2020; Eshoul et al., 2025; Hamada et al., 2023).

Energy and exergy analyses provide a systematic methodology for evaluating gas turbine plant performance. Energy analysis quantifies the overall energy balance based on the first law of thermodynamics, whereas exergy analysis identifies the location, magnitude, and causes of thermodynamic irreversibilities within each component. Moreover, the exergy loss ratio of each component reveals where the greatest opportunities for performance improvement exist (Bejan et al., 1995; Dincer & Rosen, 2013). This paper compares two configurations—the existing simple GT cycle (GT×2) and the proposed CCPP-through thermodynamic simulation, exergy analysis, and economic evaluation.

2. Target Gas Power plant

2.1 Description of the SGT5-2000E Gas Turbine

Al-Ruwais Gas Power turbine is located in Al-Hawamid, Western Mountain region (Jebel al-Gharbi), Libya. The plant employs two Siemens SGT5-2000E gas turbine units, each rated at 168 MW under ISO conditions. This model is a single-shaft gas turbine comprising a multi-stage axial compressor, a combustion chamber, and a gas turbine directly coupled to an electric generator, operating on an open Brayton cycle (Algool et al., 2015; Siemens, 2011). Table 1 presents the main operating parameters.

Table 1. Siemens SGT5-2000E Operating Parameters at ISO Conditions

Parameter	Value	Unit
Power Output	168	MW
Thermal Efficiency	34.7	%
Pressure Ratio	12	—
Exhaust Temperature	536	°C
Exhaust Mass Flow	531	kg/s
Ambient Temperature (ISO)	15	°C
Compressor Isentropic Efficiency	85	%
Turbine Isentropic Efficiency	90.5	%

3. Methodology and Thermal Modelling

3.1 Aspen Plus Simulation Software

Aspen Plus is an advanced engineering simulation tool widely used in the analysis and modelling of complex thermal systems. The software provides an integrated environment for simulating thermodynamic processes in energy and industrial applications, relying on precise mathematical models for fluid dynamics, heat transfer, and chemical reactions (AspenTech, 2020; Ibrahim, 2010).

3.2 Thermal Model Equations

Table 2. Thermal Model Equations

Parameter	Equation
Net Power (GT)	$\dot{W}\mathrm{net(GT)} = \dot{W}\mathrm{thermal(GT)} - \dot{W}\mathrm{loss(GT)}$
Net Thermal Efficiency	$\eta\mathrm{net(GT)} = \dot{W}\mathrm{net(GT)} / (\dot{m}\mathrm{f} \cdot \mathrm{LHV})$
Specific Fuel Consumption	$\mathrm{HR} = 3600 / \eta\mathrm{net(GT)}$
CO_2 Emissions	$CO_2 = \dot{m}\mathrm{EMISSION} / \eta\mathrm{net(GT)}$
Net Power (CCPP)	$\dot{W}\mathrm{CCPP} = \dot{W}\mathrm{GT} + \dot{W}\mathrm{ST} - \dot{W}\mathrm{aux}$
HRSG Heat Transfer	$\dot{Q}\mathrm{HRSG} = \dot{m}\mathrm{exh} \cdot (\mathrm{hexh,in} - \mathrm{hexh,out})$

3.3 Exergy Analysis Equations

The exergy analysis is based on physical and chemical exergy components. The exergy loss ratio (y_D) for each component expresses its share of the total system exergy destruction, identifying components with the greatest potential for thermodynamic improvement.

Table 3. Exergy Analysis Equations

Parameter	Equation
Total Exergy	$\dot{E}x = \dot{E}x\_ph + \dot{E}x\_ch$
Physical Exergy	$\dot{E}x\_ph = \dot{m}[(h–h_0) - T_0(s–s_0)]$
Exergy Eff. (Turbine)	$\eta\_ex = \dot{W}\mathrm{out} / (\dot{E}\mathrm{xin} - \dot{E}\mathrm{xout})$
Exergy Eff. (Compressor)	$\eta\_ex = (\dot{E}\mathrm{xout} - \dot{E}\mathrm{xin}) / \dot{W}\mathrm{in}$
Exergy Eff. (Combustor)	$\eta\_ex = \dot{E}\mathrm{xout} / (\dot{E}\mathrm{xfuel} + \dot{E}\mathrm{xair})$
Exergy Eff. (HRSG)	$\eta\_ex = (\dot{E}\mathrm{xcold,out} - \dot{E}\mathrm{xcold,in}) / (\dot{E}\mathrm{xhot,in} - \dot{E}\mathrm{xhot,out})$
Exergy Destruction	$\dot{E}\mathrm{xD} = \Sigma\dot{E}\mathrm{xin} - \Sigma\dot{E}\mathrm{xout}$
Exergy Loss Ratio	$y\_D = \dot{E}\mathrm{xD,k} / \dot{E}\mathrm{xD,total} \times 100\%$
Overall Exergy Efficiency	$\eta\_ex = \dot{W}\mathrm{net} / \dot{E}\mathrm{xfuel}$

3.4 Economic Analysis Model

The economic analysis uses Net Present Value (NPV), Payback Period (PBP), Accounting Rate of Return (ARR), and Profitability Index (PI) as the main indicators. These indicators are evaluated over a 25-year project lifetime at a 10% discount rate. Capital cost, fuel cost, and electricity revenue are the primary inputs. Table 4 summarizes the equations used to calculate the economic indicators, while the sensitivity analyses vary the electricity selling price ($0.060–$0.090/kWh) and fuel price ($0.10–$0.22/kg) independently.

Table 4. Economic Analysis Equations

Parameter	Equation
Capital Investment	$C_0 = \Sigma\ \mathrm{Ccap,k}$
Annual Electricity Generation	$\mathrm{Eannual} = \mathrm{Wnet} \times \mathrm{OH}$
Annual Revenue	$\mathrm{Rannual} = \mathrm{Eannual} \times \mathrm{Pe}$
Annual Fuel Cost	$\mathrm{Cfuel} = \dot{m}\mathrm{fuel} \times 3600 \times \mathrm{OH} \times \mathrm{Pfuel}$
Net Annual Cash Flow	$\mathrm{CFt} = \mathrm{Rannual} - \mathrm{Cfuel} - \mathrm{CO\&M}$
Net Present Value (NPV)	$\mathrm{NPV} = -C_0 + \Sigma[t=1 \text{ to } n]\ \mathrm{CFt} / (1 + i)^t$

Payback Period (PBP)	PBP = C_0 / CFannual
Accounting Rate of Return (ARR)	ARR = (Average annual profit / C_0) × 100%
Profitability Index (PI)	PI = PV of future cash flows / C_0

where C_0 is the initial capital investment, Ccap,k is the capital cost of component k, OH is the annual operating hours, Pe is the electricity selling price, Pfuel is the fuel price, CO&M is the annual operation and maintenance cost, i is the discount rate, and n is the project lifetime.

4. Model Validation and System proposal

4.1 Gas Turbine Model Validation

A simulation model of the Siemens SGT5-2000E gas turbine was developed in Aspen Plus under International Organization for Standardization (ISO) conditions. Air enters the compressor at 15°C and 1.013 bar at 520.328 kg/s and reaches 349.6°C at 11.7 bar after compression. Natural gas, represented as Methane (CH_4), enters at 10.762 kg/s and 20 bar. After turbine expansion, the exhaust gas temperature reaches approximately 536.6°C.

Table 5. Model Validation Results

Parameter	ISO Values	Simulation	difference (%)
Power Output (MW)	168	167.65	0.21
Thermal Efficiency (%)	34.7	34.70	0.00
Exhaust Temperature (°C)	536	537	0.19
Exhaust Mass Flow (kg/s)	531	531	0.00
Pressure Ratio	12	12	—
Ambient Temp. (°C)	15	15	—

The validation demonstrates good agreement between the simulation and the manufacturer data: the power output error is 0.21%, the thermal efficiency difference is 0.00%, the exhaust temperature difference is 0.19%, and the exhaust mass-flow difference is 0.00%. These results confirm the reliability of the Aspen Plus model for subsequent parametric and exergy analyses.

4.2 proposal: Linking Two Gas Turbine Units

The first step toward the combined cycle configuration is the simultaneous operation of both SGT5-2000E units. Figure 1 shows the Aspen Plus model for the two gas turbine units (GT×2), providing approximately 335–342 MW net power depending on ambient temperature. Combining both units doubles the available exhaust thermal energy entering the HRSG, enabling a larger and more efficient steam turbine.

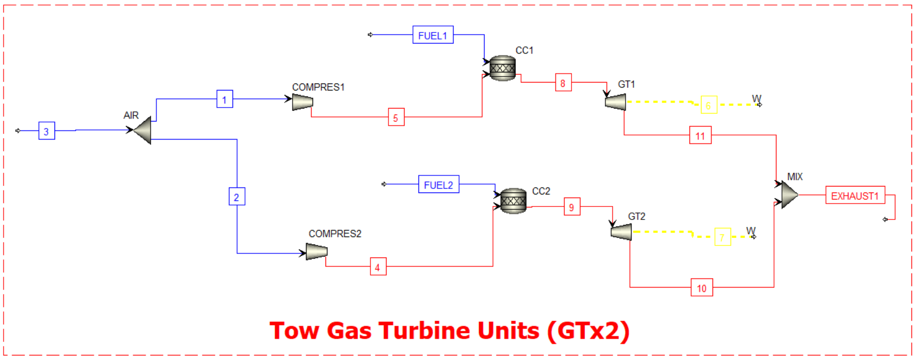

Figure 1. Aspen Plus Simulation Model: Two SGT5-2000E Gas Turbine Units (GT×2)

4.3 Combined Cycle Design

The CCPP design integrates both SGT5-2000E units with a common HRSG and a single steam turbine bottoming cycle. Combining the exhaust streams approximately doubles the thermal energy entering the HRSG, enabling a steam turbine that adds approximately 140 MW at ISO conditions. Figure 2 shows the complete Aspen Plus model of the combined cycle configuration.

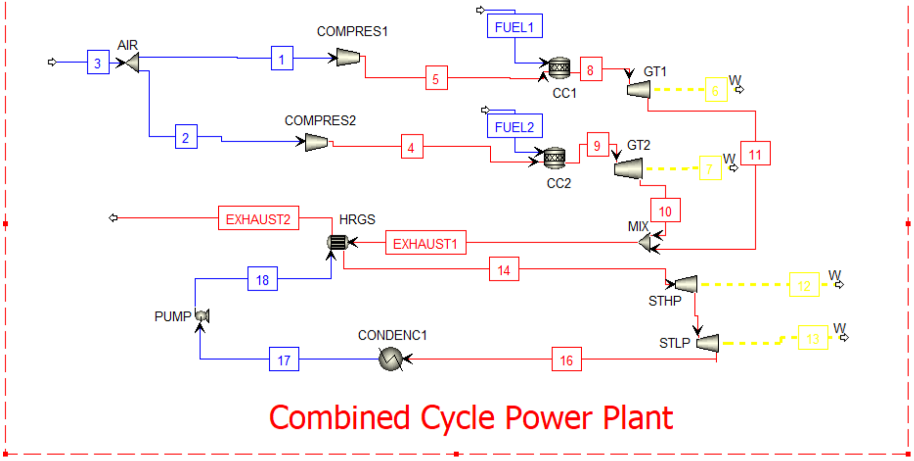

Figure 2. Final Combined Cycle Power Plant (CCPP): Two Gas Turbines + HRSG + Steam Turbine

Table 6. Key proposal Parameters — Final CCPP Configuration

Component	Parameter	Value
GT Units (×2)	Gross Power per unit	168 MW (ISO)
HRSG	Combined Exhaust Flow	1062 kg/s
HRSG	Steam Pressure (HP)	12.44 bar
Steam Turbine	Additional Power	140 MW
CCPP Total	Net Power (at 15°C)	477 MW
CCPP Total	Thermal Efficiency (at 15°C)	49.2%

5. Results and Discussion

5.1 Effect of Ambient Temperature on Thermal Efficiency

This section evaluates the influence of ambient temperature on the thermal efficiency of the simple and combined cycle configurations. The comparison clarifies how exhaust heat recovery helps maintain higher efficiency as compressor-inlet temperature increases.

Figure 3 presents the thermal efficiency of both configurations across an ambient temperature range of 10-50°C.

The simple cycle (GT×2) efficiency declines from 35.28% at 10°C to 30.17% at 50°C a reduction of 14.5% driven by reduced air density at the compressor inlet, which increases compression work and lowers net output for the same fuel input. The CCPP maintains a consistent advantage of approximately 14.5 percentage points across the entire temperature range, declining from 49.81% to 44.70%. This persistent gap demonstrates the effectiveness of the HRSG in converting exhaust heat that would otherwise be rejected into useful electrical work via the steam turbine.

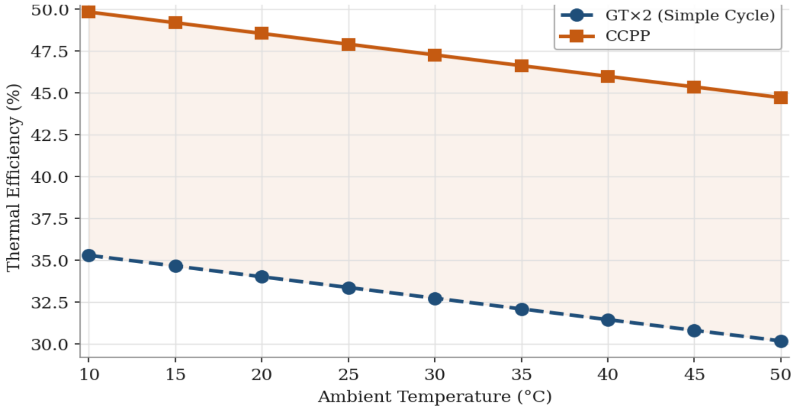

Figure 3. Thermal Efficiency Comparison: GT×2 vs CCPP

5.2 Effect of Ambient Temperature on Net Power Output

This section examines how the net electrical power output responds to increasing ambient temperature. The analysis highlights the reduction in gas turbine output and quantifies the additional power supplied by the steam bottoming cycle.

Figure 4 compares the net electrical power output of both configurations across the ambient temperature range.

The simple cycle net power decreases from 341.68 MW at 10°C to 292.16 MW at 50°C — a decline by about 14.49%. The CCPP the difference between output decreases from 482.43 MW to 432.91 MW over the same range. The gap of approximately 140–141 MW between the two curves at all temperatures represents the additional generation capacity contributed by the steam turbine bottoming cycle, maintained consistently regardless of ambient temperature.

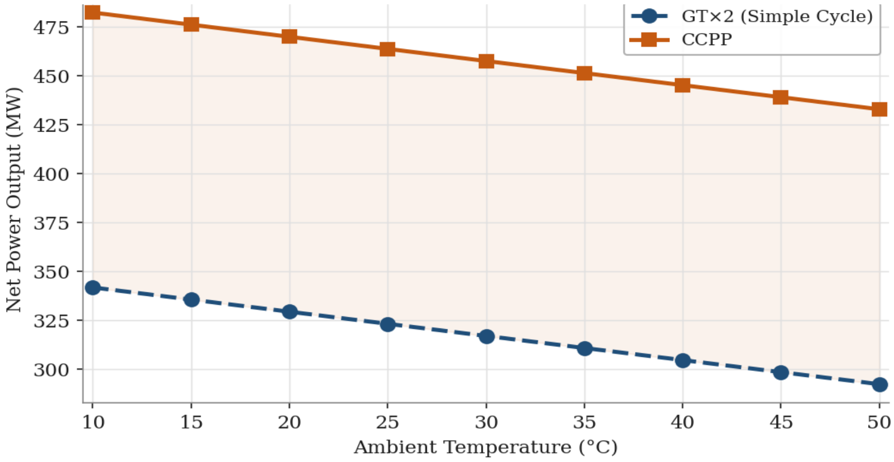

Figure 4. Net Power Output Comparison: GT×2 vs CCPP

5.3 Effect of Ambient Temperature on Specific Fuel Consumption

This section presents the variation of Specific Fuel Consumption (SFC) with ambient temperature. The discussion focuses on how the combined cycle reduces fuel consumption per unit of generated electricity compared with the simple cycle.

Figure 5 shows the specific fuel consumption (SFC) of both configurations in kg of fuel per MWh of electrical output.

The CCPP achieves markedly lower SFC because the same fuel input yields more electrical output. The simple cycle SFC rises from 226.73 kg/MWh at 10°C to 265.16 kg/MWh at 50°C — an increase of

16.95%. also CCPP SFC rises from 160.58 to 178.95 kg/MWh over the same range, representing a consistent reduction of approximately 29% compared with the simple cycle at all temperature points.

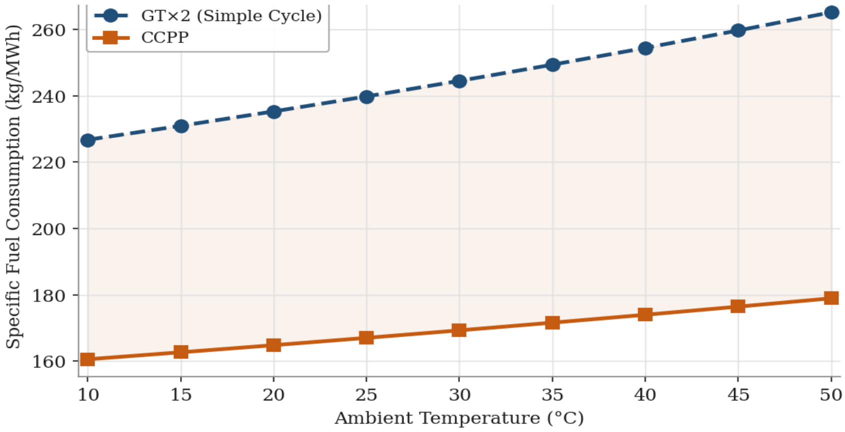

Figure 5. Specific Fuel Consumption Comparison: GT×2 vs CCPP

5.4 Effect of Ambient Temperature on CO_2 Emissions

This section analyses the specific Carbon Dioxide (CO_2) emission intensity of the two configurations. The results are interpreted in relation to fuel consumption and the improvement achieved through combined-cycle heat recovery.

Figure 6 shows the specific CO_2 emission intensity of both configurations in kg of CO_2 per MWh of electrical output.

Because natural gas combustion releases CO_2 in fixed proportion to the fuel burned, CO_2 intensity follows the same trend as SFC. The simple cycle CO_2 intensity rises from 622.04 kg/MWh at 10°C to 727.47 kg/MWh at 50°C.but The CCPP reduces CO_2 intensity from 440.56 to 490.95 kg/MWh, achieving approximately a 29.2% reduction at every temperature point compared with the simple cycle.

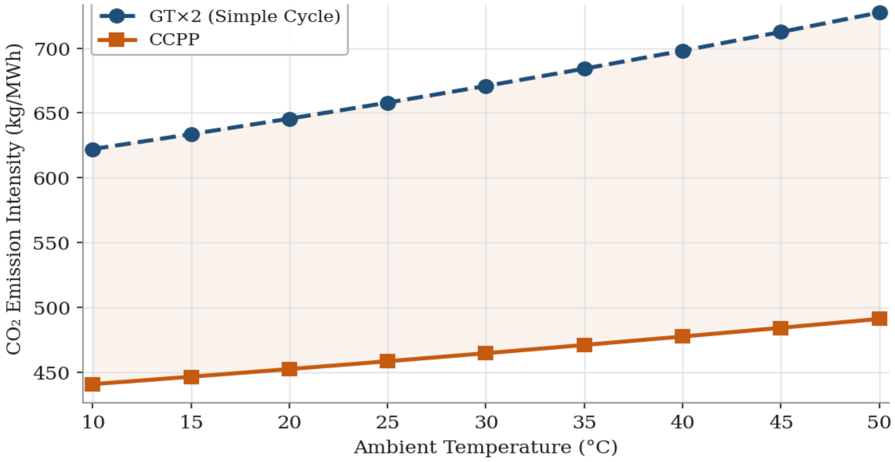

Figure 6. CO_2 Emission Intensity Comparison: GT×2 vs CCPP

5.5 Exergy Analysis

Exergy is defined as the maximum theoretical useful work that can be obtained from a system as it comes into thermodynamic equilibrium with a specified reference environment. It represents the quality or availability of energy, rather than merely its quantity, and indicates the portion of energy that can be converted into useful work under ideal reversible conditions.In thermodynamic analysis, exergy is a powerful measure because it identifies the real losses caused by irreversibilities such as friction, combustion, heat transfer through finite temperature differences, mixing, and pressure drops. Unlike energy, which is conserved according to the First Law of Thermodynamics, exergy is not conserved; it is destroyed due to entropy generation. Therefore, exergy analysis is mainly based on both the First and Second Laws of Thermodynamics.

This section evaluates the exergetic performance of the studied configurations. The analysis identifies the main sources of exergy destruction and explains how combined-cycle integration improves the quality of energy conversion.

5.5.1 Exergy Efficiency Comparison

Figure 7 presents the exergy efficiency of both configurations, quantifying how effectively each system converts the maximum theoretically available work (fuel exergy input) into actual net power output.

The simple cycle exergy efficiency decreases from 34.58% at 10°C to 29.82% at 50°C, while the CCPP exergy efficiency decreases from 48.56% to 43.80% — a consistent advantage of approximately 14 percentage points. The CCPP achieves higher exergy efficiency because the HRSG recovers exhaust-stream exergy that would otherwise be rejected to the environment, reducing total cycle irreversibility.

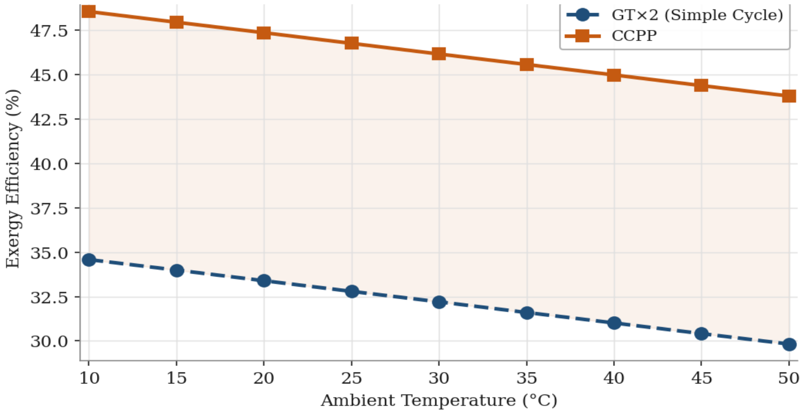

Figure 7. Exergy Efficiency Comparison: GT×2 vs CCPP

5.5.2 Exergy Loss Ratio - Simple Gas Turbine Cycle

Figure 8 shows the distribution of exergy losses across the components of the simple gas turbine cycle (GT×2). The exergy loss ratio (y_D) of each component expresses its percentage share of total system exergy destruction.

The combustion chambers (CC1+CC2) dominate exergy destruction, accounting for 82.7% of total losses. This large fraction is an inherent consequence of the irreversible chemical reaction and the large temperature difference between the flame and the working fluid; it cannot be significantly reduced within the framework of an open Brayton cycle operating on natural gas. The gas turbines (GT1+GT2) contribute 9.0% of exergy destruction, primarily due to aerodynamic irreversibilities. The compressors (GT1+GT2) contribute the smallest share at 8.3%, reflecting their relatively high isentropic efficiency. These results confirm that combustion irreversibility is the fundamental thermodynamic barrier in the simple gas turbine cycle.

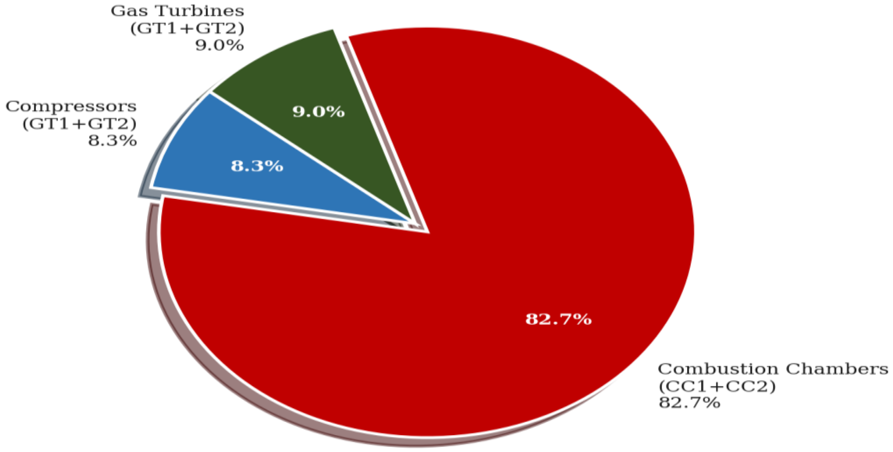

Figure 8. Exergy Loss Distribution - Simple Gas Turbine Cycle (GT×2)

5.5.3 Exergy Loss Ratio - Steam Bottoming Cycle (CCPP)

Figure 9 shows the distribution of exergy losses across the components of the steam bottoming cycle in the CCPP.

The HRSG dominates exergy destruction in the steam bottoming cycle, accounting for 51.4% of losses. This reflects the unavoidable temperature difference between the hot exhaust gas and the steam being generated. The condenser contributes 33.6%, representing heat rejected to the cooling medium at near-ambient temperature - thermodynamically unrecoverable exergy. Steam Turbine 1 accounts for 11.8%, while Steam Turbine 2 contributes 3.0%. The water pump contributes a negligible 0.2%. HRSG design optimisation - through minimising the temperature approach or using multi-pressure steam generation - offers the greatest potential for improving CCPP bottoming cycle performance.

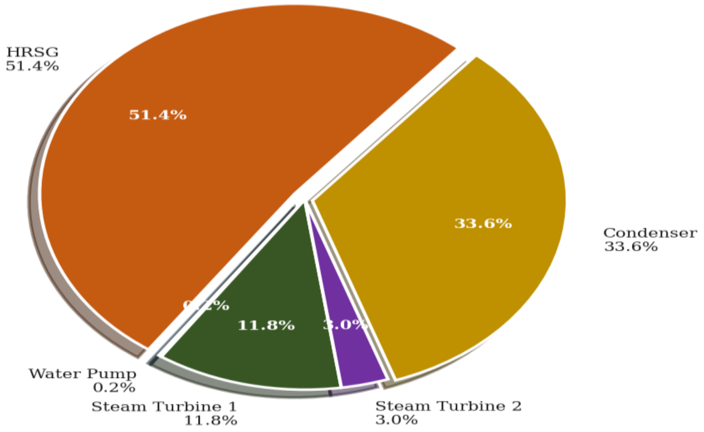

Figure 9. Exergy Loss Distribution - Steam Bottoming Cycle (CCPP)

5.5.4 Total Exergy Destruction Comparison

Figure 10 compares total exergy destruction for both configurations at selected ambient temperatures.

The CCPP consistently achieves lower total exergy destruction than the simple cycle at every temperature point. At 10°C, total exergy destruction reduces from 657.2 MW (simple cycle) to 514.8 MW (CCPP) - a reduction of 142.4 MW corresponding to the additional net power extracted by the steam turbine. The

HRSG introduces additional exergy destruction due to finite-temperature-difference heat transfer, but this is far outweighed by the elimination of exhaust-heat rejection to the environment that occurs in the simple cycle.

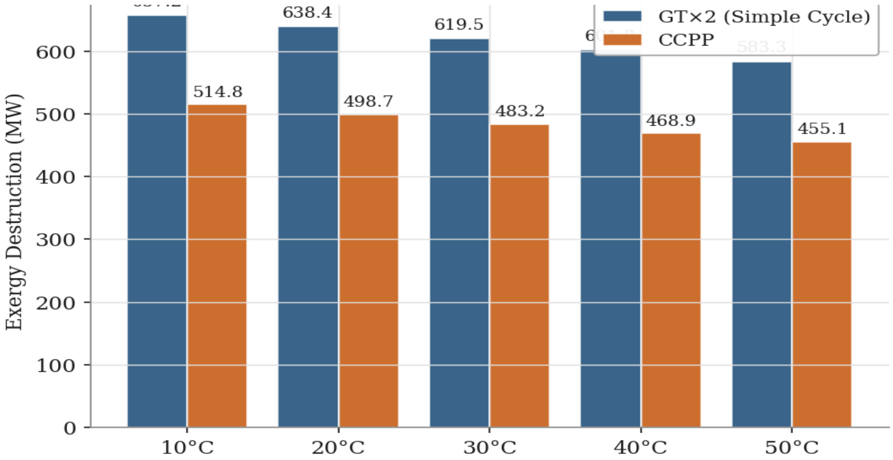

Figure 10. Total Exergy Destruction Comparison: GT×2 vs CCPP

6. Economic Analysis

The economic analysis evaluates the financial viability of both the simple gas turbine cycle (GT×2) and the CCPP over a 25-year project lifetime at a 10% discount rate. The base-case electricity price is \$0.070/kWh, while the fuel-price sensitivity reported in the thesis covers \$0.10–\$0.22/kg. The analysis assesses the effect of these assumptions on Net Present Value (NPV), Payback Period (PBP), Accounting Rate of Return (ARR), and Profitability Index (PI).

6.1 Base-Case Comparative Economic Indicators

This subsection compares the main base-case economic indicators for the simple cycle and combined cycle configurations. The analysis focuses on capital cost, profitability, and the ability of each configuration to recover the initial investment.

Although the CCPP requires a higher capital investment (\$567.06 M compared with \$392.40 M for GT×2), it delivers substantially stronger financial returns. NPV increases from \$367.41 M to \$871.10 M, while PBP decreases from 9.19 to 6.21 years. Moreover, ARR improves from 18.31% to 23.95%, and PI rises from 1.00 to 1.60. These values confirm that the combined cycle provides a higher return per unit of invested capital despite its larger initial cost.

Table 7. Comparative Economic Indicators: GT×2 vs CCPP

Economic Indicator	GT×2 (Simple Cycle)	CCPP
Capital Cost (M$)	392.40	567.06
NPV (M$)	367.41	871.10
PBP (Years)	9.19	6.21
ARR (%)	18.31	23.95
PI	1.00	1.60

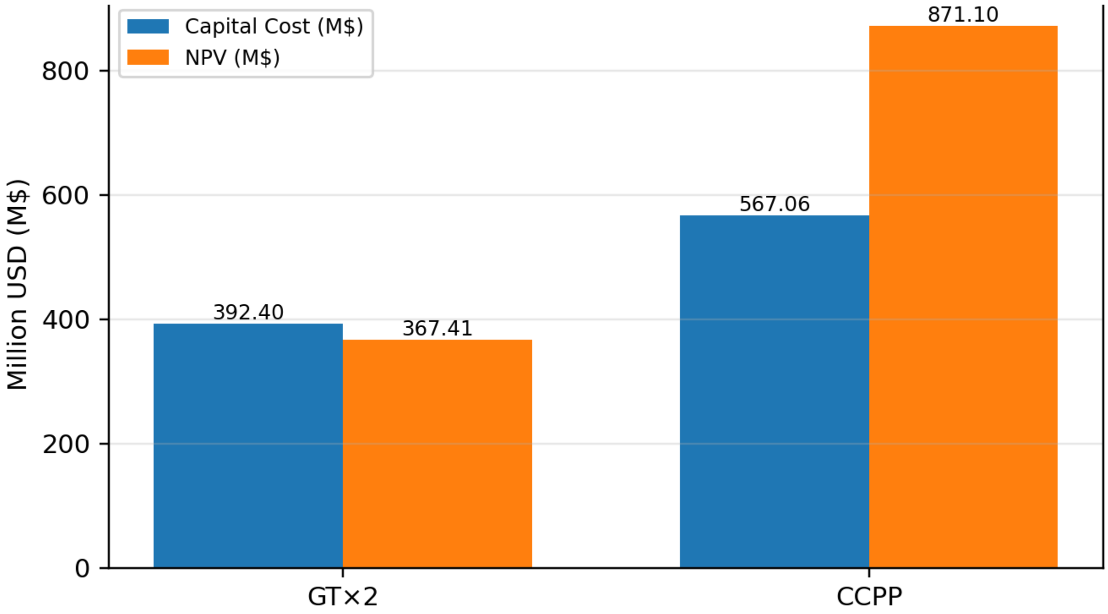

Figure 11. Capital Cost and NPV Comparison: GT×2 vs CCPP

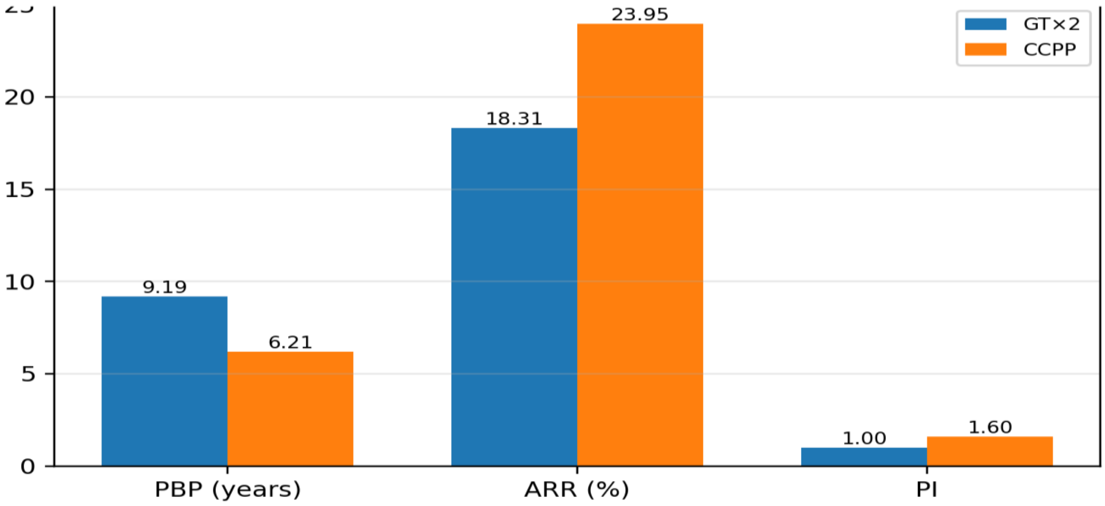

Figure 12. Financial Indicators (PBP, ARR, PI): GT×2 vs CCPP

6.2 Sensitivity Analysis: Electricity Selling Price

This subsection evaluates how changes in the electricity selling price affect the financial performance of both the simple gas turbine cycle (GT×2) and the combined cycle power plant (CCPP). The comparison clarifies how the additional power generated by the steam bottoming cycle strengthens the economic response of the CCPP to higher electricity tariffs.

Figures 13–16 analyse the effect of varying the electricity selling price from \$0.060/kWh to \$0.090/kWh on the four key financial indicators for both configurations.

As the electricity selling price rises from \$0.060/kWh to \$0.090/kWh, the CCPP NPV increases from \$496.4 M to \$1620.5 M, while GT×2 NPV increases from \$126.0 M to \$816.0 M. The CCPP columns remain consistently and substantially higher than the GT×2 columns, demonstrating that its higher power output amplifies the financial benefit of higher tariffs.

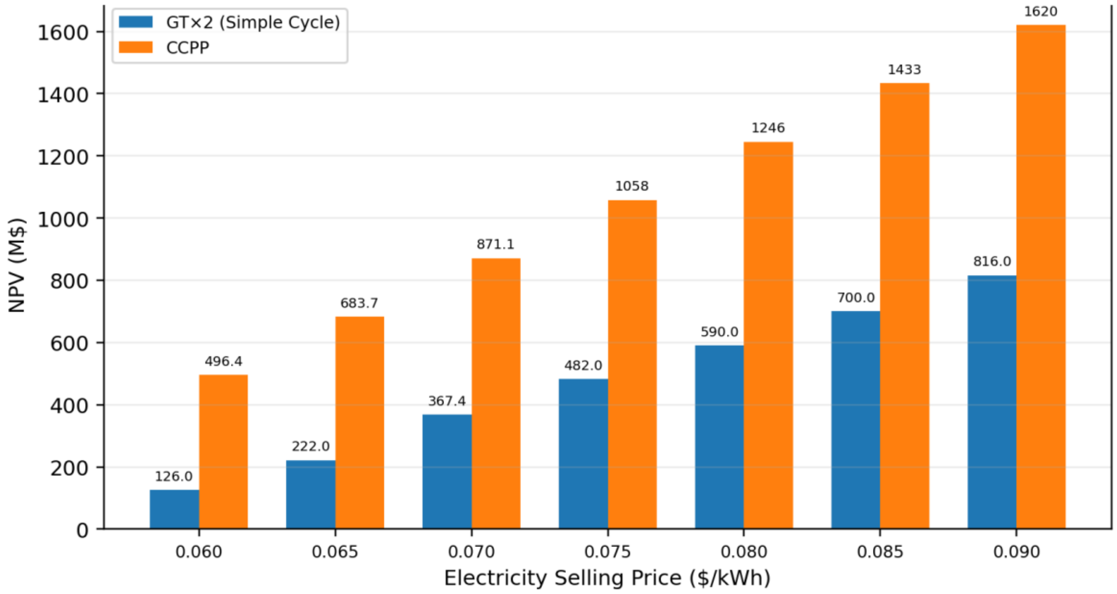

Figure 13.the Effect of Electricity Selling Price on NPV

The CCPP payback period decreases from 9.60 years at $0.060/kWh to 2.90 years at $0.090/kWh, whereas the GT×2 payback period decreases from 14.5 years to 5.0 years over the same range. At the base-case electricity price of $0.070/kWh, the CCPP payback period is approximately 6.2 years, nearly 3 years shorter than that of the simple cycle.

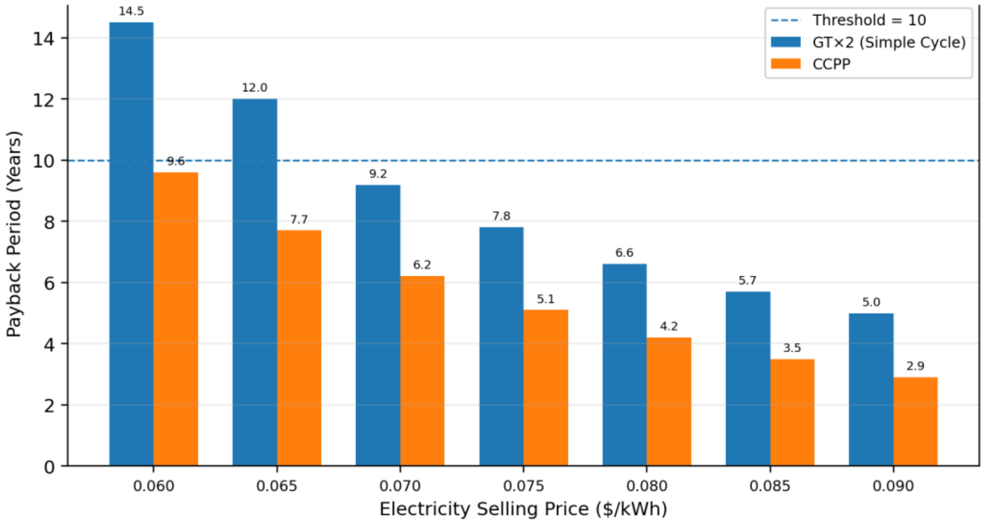

Figure 14.the Effect of Electricity Selling Price on Payback Period

The CCPP ARR increases from 17.7% at $0.060/kWh to 36.5% at $0.090/kWh, consistently outperforming GT×2, whose ARR increases from 10.5% to 29.2% across the same range. Moreover, both configurations exceed the 10% discount-rate benchmark above $0.065/kWh, while the CCPP maintains the stronger profitability margin.

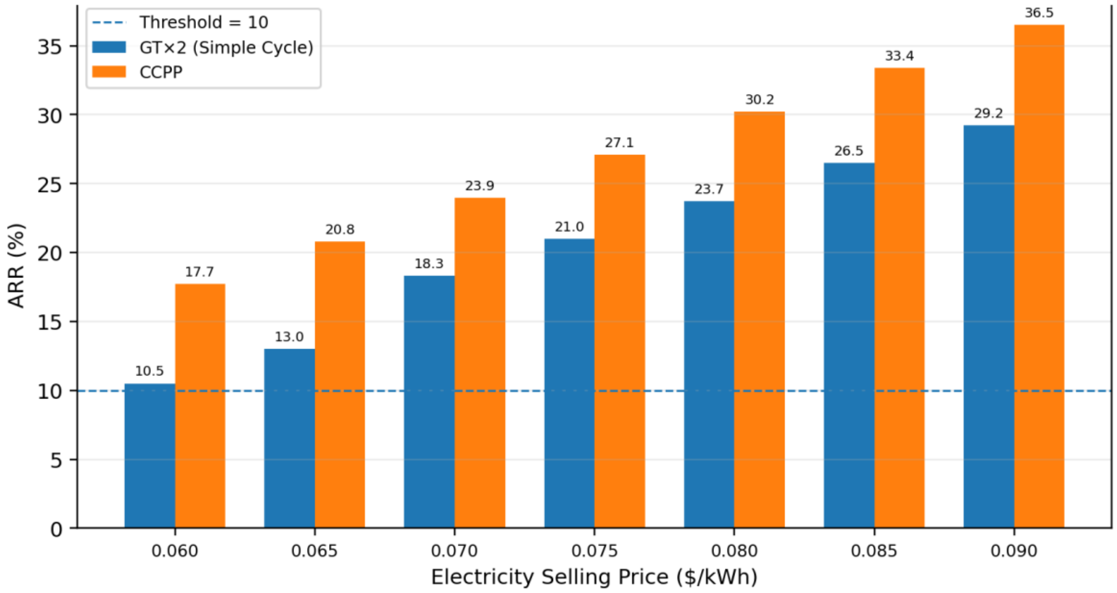

Figure 15.the Effect of Electricity Selling Price on ARR

The CCPP PI increases from 0.90 at \$0.060/kWh to 2.90 at \$0.090/kWh, exceeding the viability threshold (PI ≥ 1.0) for all prices above \$0.065/kWh. At the base-case price of \$0.070/kWh, the CCPP PI reaches 1.60 compared with 1.00 for GT×2, confirming that the combined cycle generates substantially more present-value return per dollar of capital invested.

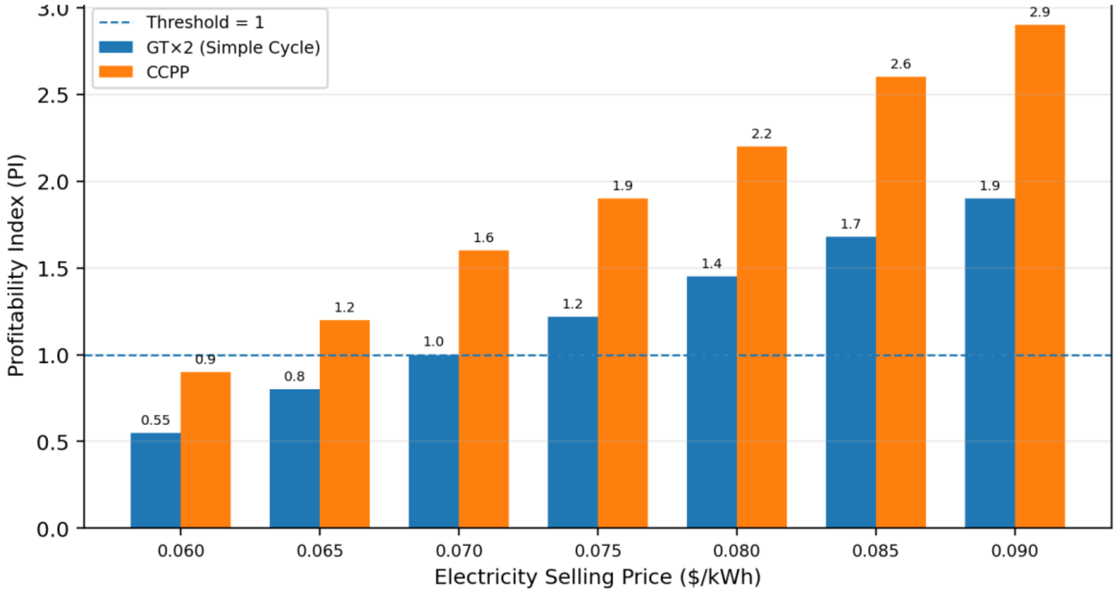

Figure 16.the Effect of Electricity Selling Price on Profitability Index

6.3 Sensitivity Analysis: Fuel Price

This subsection examines the sensitivity of both configurations to fuel price variation. The analysis clarifies whether the lower specific fuel consumption of the CCPP improves economic resilience relative to the simple gas turbine cycle under increasing fuel-cost conditions.

Figures 17–20 analyse the effect of varying the fuel price from \$0.10/kg to \$0.22/kg on the four key financial indicators for GT×2 and CCPP, with the electricity selling price held at the base-case value of \$0.070/kWh.

As fuel price rises from $0.10/kg to $0.22/kg, the CCPP NPV decreases from $1308.3 M to $569.4 M, while GT×2 NPV decreases from $820.0 M to $210.0 M. The CCPP consistently outperforms the simple cycle at all fuel prices because its lower specific fuel consumption limits the impact of fuel-cost escalation on operating profit.

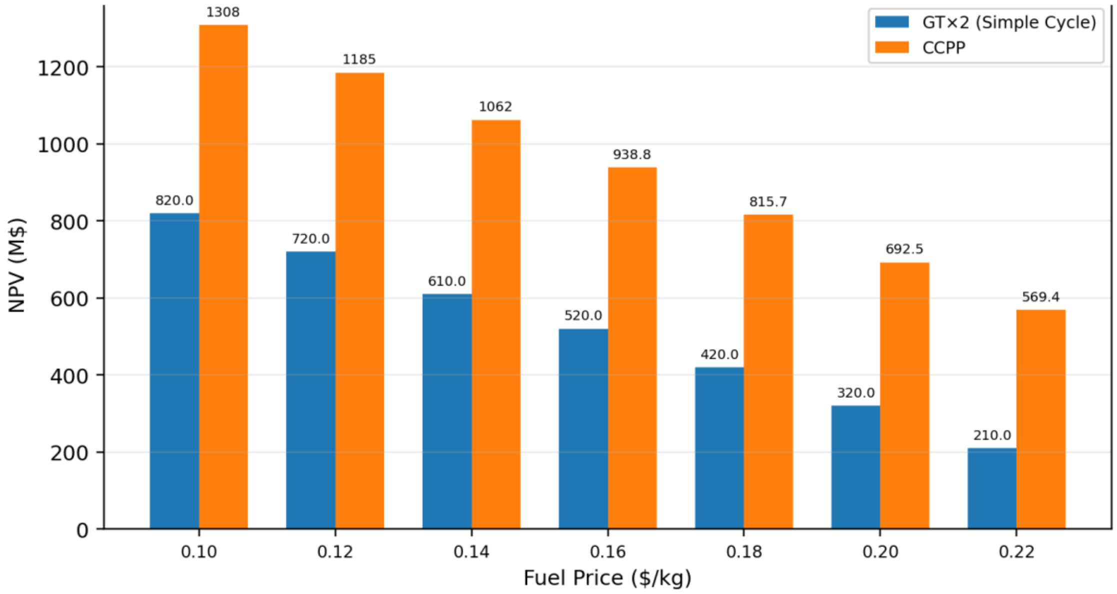

Figure 17.the Effect of Fuel Price on NPV

The CCPP payback period increases from 4.00 years at $0.10/kg to 8.80 years at $0.22/kg, whereas the GT×2 payback period increases more steeply from 6.5 to 15.0 years. At the highest fuel price studied, the CCPP remains well below the GT×2 payback period, demonstrating superior resilience to fuel-cost escalation.

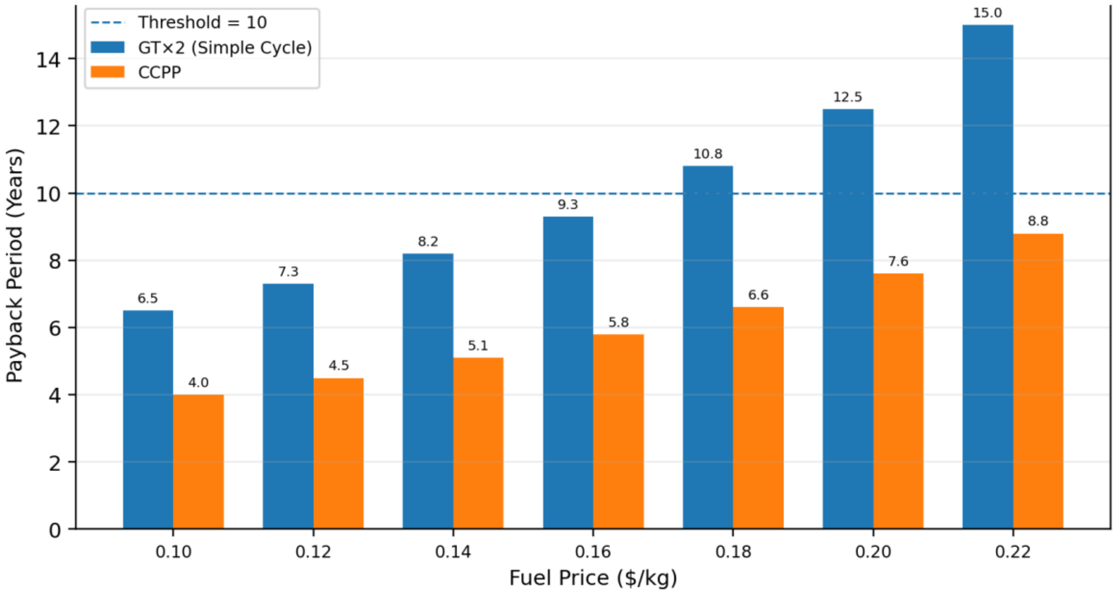

Figure 18.The Effect of Fuel Price on Payback Period

The CCPP ARR decreases from 31.3% at $0.10/kg to 18.9% at $0.22/kg, remaining above the 10% discount-rate benchmark across the full fuel-price range. By comparison, GT×2 ARR decreases from 24.0% to 11.0%, approaching the viability threshold at the highest fuel price; therefore, the CCPP maintains a consistent ARR advantage.

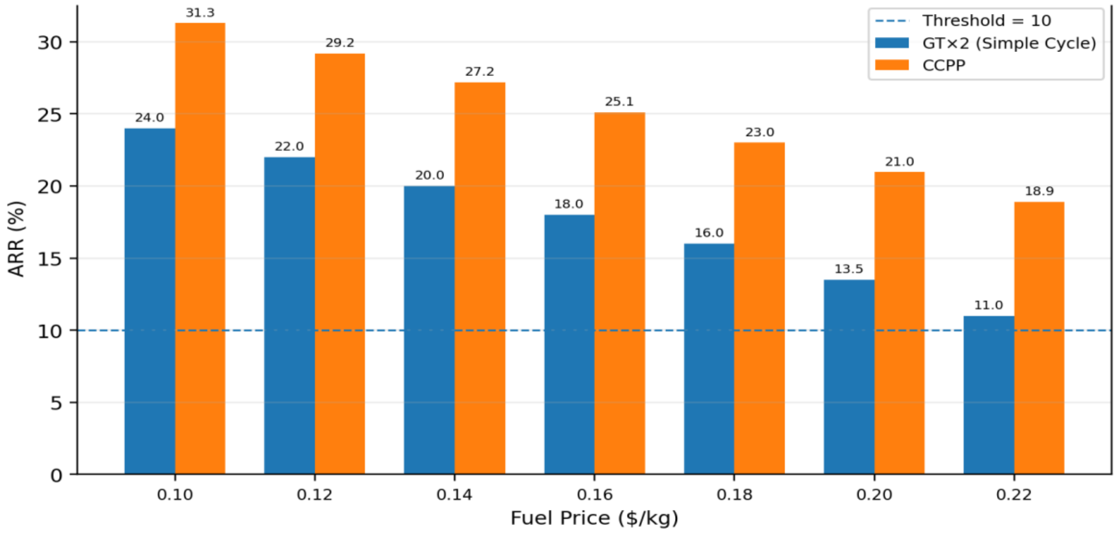

Figure 19.The Effect of Fuel Price on ARR

The CCPP PI decreases from 2.3 at $0.10/kg to 1.0 at $0.22/kg, remaining at or above the viability threshold (PI ≥ 1.0) across the entire studied range. In contrast, the GT×2 PI decreases from 1.5 to 0.6 and falls below the viability threshold at higher fuel prices, confirming that the simple cycle becomes economically less attractive when fuel costs increase.

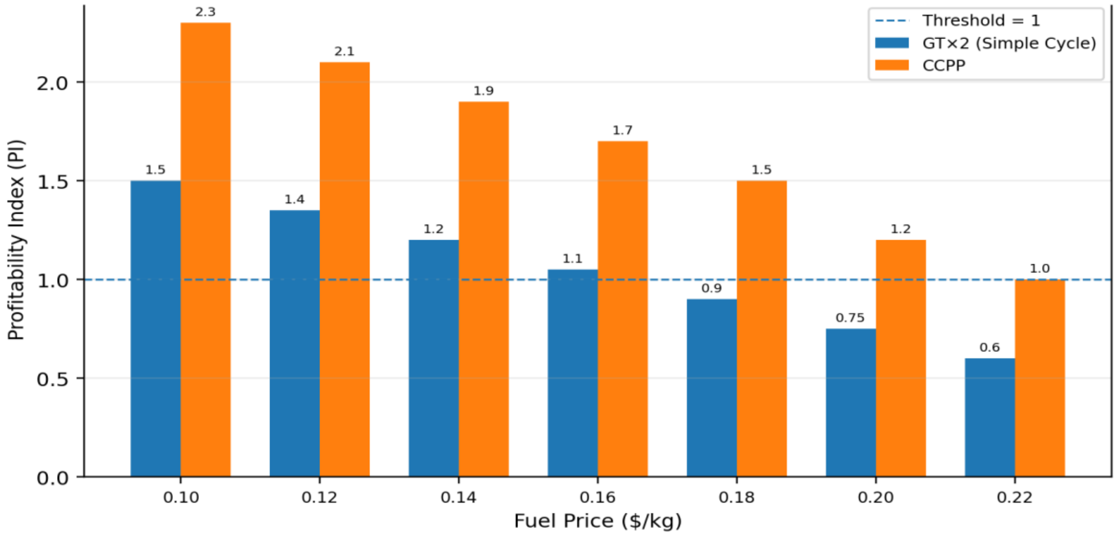

Figure 20.The Effect of Fuel Price on Profitability Index

7. Conclusions

This study carried out a comprehensive energetic, exergetic, and economic comparison between the simple gas turbine cycle (GT×2) and a proposal combined cycle power plant (CCPP) for Al-Ruwais Gas Power plant. The thermodynamic simulation results demonstrated that the simple cycle is highly sensitive to ambient temperature, with thermal efficiency declining from 35.28% at 10°C to 30.17% at 50°C and net power falling from 341.68 MW to 292.16 MW. Combined-cycle integration raises electrical efficiency to 49.81% at 10°C and maintains 44.70% at 50°C, adding approximately 140 MW of additional generation capacity at all ambient temperatures by recovering exhaust heat through the HRSG and converting it into useful work in the steam turbine. The CCPP also reduces specific fuel consumption and CO_2 emission intensity by approximately 29% at every temperature point compared with the simple cycle, confirming its thermodynamic and environmental superiority.

The exergy analysis revealed that combustion chambers are the dominant source of irreversibility in the gas turbine cycle, accounting for 82.7% of total exergy destruction — an inherent limitation of the open Brayton cycle operating on natural gas. Within the steam bottoming cycle of the CCPP, the HRSG accounts for 51.4% of exergy losses and the condenser for 33.6%, identifying heat-transfer temperature differences and condenser rejection as the primary targets for further improvement. Overall, the CCPP achieves consistently higher exergy efficiency (48.56% vs 34.58% at 10°C) and lower total exergy destruction (514.8 MW vs 657.2 MW at 10°C) compared with the simple cycle.

The economic analysis confirmed the financial viability of combined-cycle integration across a wide range of electricity and fuel price scenarios. At the base-case conditions, the CCPP NPV increases from $367.41 M to $871.10 M — an improvement of 137% — while the payback period decreases from 9.19 to 6.21 years and the profitability index rises from 1.00 to 1.60. Sensitivity analysis demonstrated that the CCPP maintains financial viability across electricity prices from $0.060 to $0.090/kWh and fuel prices from $0.10 to $0.22/kg, whereas the simple cycle falls below the viability threshold at higher fuel prices. On the basis of all thermodynamic, exergetic, and economic evidence presented, conversion of Al-Ruwais Gas Power Station to a combined cycle configuration is strongly recommended as a technically sound and economically justified investment.

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