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Techno-Economic Evaluation of a Natural Gas Combined Cycle Power Plant Based on the Brayton Cycle

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Abstract

The growing demand for reliable and efficient electricity generation has increased the importance of natural gas combined cycle power plants (NGCCPPs) as a viable solution for meeting global energy needs. This study presents an economic evaluation of a Brayton cycle-based NGCCPP through the estimation of equipment purchase costs, capital investment requirements, and cost escalation analysis. The major plant components considered include the air compressor, combustion chamber, and gas turbine. Equipment costs were determined using established empirical cost correlations based on operating parameters such as air mass flow rate, pressure ratio, efficiency, and turbine inlet temperature. The estimated purchase costs of the air compressor, combustion chamber, and gas turbine were found to be approximately \$4.5 million, \$2.12 million, and \$16 million, respectively, indicating that the gas turbine is the most significant contributor to equipment expenditure. The total equipment purchase cost was estimated at \$22.5 million in the reference year 1992 and adjusted to \$49.30 million in 2025 using the Chemical Engineering Plant Cost Index (CEPCI). Direct and indirect cost analyses were subsequently performed to determine the fixed capital investment and total capital investment of the plant. The results show that the fixed capital investment is approximately \$261.92 million, while the total capital investment, including working capital, is estimated at \$308.56 million (123.42 million OMR). The findings demonstrate that although major equipment costs significantly influence project economics, installation, service facilities, piping, and other supporting infrastructure contribute substantially to the overall investment. This study provides valuable insights into the economic viability of NGCCPPs and serves as a foundation for future optimization and investment decision-making in gas-to-power projects.

Keywords: Brayton Cycle; Economic Evaluation; Equipment Cost Estimation; Capital Investment; Techno-Economic Analysis

INTRODUCTION:

Power generation is a cornerstone of modern economic and industrial development, providing the energy required for industries, transportation, healthcare, and household consumption [1]. Reliable and efficient power supply underpins economic growth, improves quality of life, and enables technological advancement [2]. The global demand for electricity continues to rise due to population growth, urbanization, and industrialization, driving the need for cost-effective and environmentally sustainable power generation solutions. With energy security becoming a critical concern for governments and industries alike, diversification of power sources has emerged as a strategic priority [3].

Electricity generation relies on various primary energy sources, broadly categorized as renewable and non-renewable [4]. Non-renewable sources include fossil fuels such as coal, natural gas, and oil, which historically have been the backbone of electricity supply due to their high energy density and reliability [5]. Renewable sources, such as solar, wind, hydro, and biomass, offer sustainability and reduced environmental impact but often face challenges related to intermittency and high capital costs. Among non-renewables, natural gas has gained prominence due to its relatively lower carbon emissions compared to coal and oil, flexible operational characteristics, and compatibility with combined-cycle power plants [6].

Gas-to-power (GTP) technology, which primarily involves converting natural gas into electricity through thermal cycles such as the Brayton cycle, has emerged as a crucial component of modern power systems [7]. The Brayton cycle, or gas turbine cycle, involves compressing air, mixing it with fuel, combusting the mixture, and expanding the hot gases through a turbine to produce work. This cycle is widely adopted in standalone gas turbines, combined-cycle plants, and integrated energy systems due to its high power-to-weight ratio, quick start-up capabilities, and operational flexibility [8]. Gas-to-power solutions are particularly advantageous in regions with abundant natural gas reserves and growing electricity demand, enabling rapid scaling of energy infrastructure with moderate environmental impact [9].

The economics of gas-to-power technologies are influenced by several factors, including capital expenditure, fuel costs, operational and maintenance expenses, efficiency, and plant lifetime. Gas turbines generally offer lower initial capital costs compared to large coal or nuclear plants, but fuel costs constitute a significant portion of total generation costs [10]. Advances in turbine efficiency, material science, and combined-cycle integration have improved the economic feasibility of gas-to-power plants, making them competitive in both baseload and peaking power applications. Additionally, regulatory incentives, carbon pricing, and fluctuations in natural gas markets affect the economic attractiveness of such projects, highlighting the importance of techno-economic analyses in investment decision-making [11].

A review of existing literature reveals extensive research on Brayton cycle performance, optimization, and integration with combined-cycle systems [12]. Studies have focused on thermodynamic modeling, efficiency enhancement through recuperation and intercooling, and the environmental implications of gas-fired power plants [13-15]. Economically, research has explored levelized cost of electricity (LCOE), cost-benefit analyses, and sensitivity to fuel price volatility. While these studies provide valuable insights, gaps remain in integrating comprehensive economic assessments with real-world operational data, including maintenance scheduling, part-load performance, and market-driven pricing models [16-20]. Furthermore, literature on emerging hybrid gas-to-power systems that combine renewable inputs with Brayton cycles is limited, indicating opportunities for innovation [21-24].

The research gap is thus identified in developing holistic economic models for gas-to-power systems that incorporate both technical and market variables. Existing studies often isolate thermodynamic performance from economic considerations, or vice versa, leaving a fragmented understanding of the true cost-effectiveness of these technologies [25,26]. Additionally, there is limited exploration of region-specific economic evaluations that account for natural gas availability, grid integration costs, policy frameworks, and environmental compliance. Addressing these gaps is critical for informing policy decisions, investment strategies, and sustainable deployment of gas-based power generation.

The novelty of this research lies in its integrated approach, combining the thermodynamic modeling of the Brayton cycle with a detailed economic assessment under varying operational, market, and policy conditions. Unlike prior studies that primarily focus on efficiency optimization or high-level cost estimates, this work aims to bridge the gap by developing a framework that evaluates cost, performance, and environmental impact simultaneously. This approach provides actionable insights for stakeholders, enabling informed decisions on plant design, fuel sourcing, and investment prioritization, while also identifying potential pathways for improving competitiveness and sustainability.

The primary aim of this research is to analyze the economics of Brayton cycle-based gas-to-power systems. Ultimately, power generation is vital for economic development, and natural gas-based Brayton cycle systems play an increasingly important role in meeting growing electricity demand efficiently. While substantial research exists on thermodynamic performance and standalone economic analysis, gaps remain in integrated techno-economic studies. This research addresses these gaps by combining performance modeling with detailed economic evaluation, offering novel insights into the cost-effectiveness of gas-to-power technologies. By doing so, it contributes to informed decision-making for investors, policymakers, and engineers, supporting sustainable and efficient energy transitions in the 21st century.

METHODOLOGY FOR ECONOMIC EVALUATION

This section presents the economic evaluation of the Natural Gas Combined Cycle Power Plant (NGCCPP). It includes the estimation of purchase costs for all major equipment and provides the basis for calculating the total capital investment. Each equipment cost is determined using standard cost correlations and relevant economic formulas to ensure accurate and consistent estimation [27-32].

Purchase cost of equipments

This section provides the estimated purchase costs of the main equipment used in the NGCCPP. Each item is evaluated separately using standard cost correlations and referenced data. These equipment costs form the basis for calculating the total capital investment of the plant.

Air compressor

The purchase cost of the air compressor is evaluated using an empirical cost correlation. This correlation relates the compressor cost to the air mass flow rate, compressor efficiency, and pressure ratio across the unit. The cost is calculated using the following expression as given in Equation (1): [33]

$$Z_{AC} = \left(\frac{C_{11}\,\dot{m}_{air}}{C_{12} - \eta_{AC}}\right)\left(\frac{P_2}{P_1}\right) ln\left(\frac{P_2}{P_1}\right) \tag{1}$$

Where:

Z_{AC} = purchase cost of air compressor ($)

C_{11} = 44.1 $/(kg/s), empirical constant

C_{12} = 0.95, empirical constant

$\dot{m}_{air}$= 211 kg/s, mass flow rate of air

η_{AC} = 0.85, efficiency of air compressor

P_1 = 1 atm, inlet pressure of air

P_2 = 17 atm, outlet pressure of air

Combustion chamber

The purchase cost of the combustion chamber is estimated as given in Equation (2) using an empirical correlation, which relates the cost to the air mass flow rate, pressures, and outlet temperature. [33]

$$Z_{CC} = \left[\frac{C_{21} \times m_{air}}{C_{22} - \left(\frac{P_3}{P_2}\right)}\right]\left(1 + exp^{(C_{23}T_3 - C_{24})}\right) \tag{2}$$

Where:

Z_{CC} = purchase cost of combustion chamber ($)

C_{21} = 46.08 $/(kg/s), empirical constant

C_{22} = 0.995 $/(kg/s), empirical constant

C_{23} = 0.018 K^{-1}, empirical constant

C_{24} = 26.4, empirical constant

$\dot{m}_{air}$= 211 kg/s, mass flow rate of air

P_2 = 17 atm, inlet pressure of combustion chamber

P_3 = 16.49 atm, outlet pressure of combustion chamber (including 3% pressure loss)

T_3 = 1549.6 K, outlet temperature of combustion chamber

Note: $\frac{P_3}{P_2} \neq 1$ in reality, minimum 3% drop is considered across the combustion chamber:

Inlet pressure = outlet pressure + pressure loss

$P_2 = P_3 + 3\ \%\ P_2$

$P_3 = P_2 - 0.03\ P_2 = 0.97\ P_2 = 16.49$ atm

Gas turbine

The purchase cost of the gas turbine based on air mass flow rate, efficiency, pressures, and temperature estimated using Equation (3). [33]

$$Z_{GT} = \left(\frac{C_{31}\,\dot{m}_{air}}{C_{32}-\eta_{GT}}\right) ln\left(\frac{P_3}{P_4}\right)\left(1 + e^{(C_{33}T_3 - C_{34})}\right) \tag{3}$$

Where:

Z_{GT} = purchase cost of gas turbine ($)

C_{31} = 479.34 $/(kg/s), empirical constant

C_{32} = 0.94, empirical constant

C_{33} = 0.036 K^{-1}, empirical constant

C_{34} = 54.4, empirical constant

$\dot{m}_{air}$= 211 kg/s, mass flow rate of air

η_{GT} = 0.85, efficiency of gas turbine

P_3 = 17 atm, outlet pressure of combustion chamber

P_4 = 1 atm, outlet pressure of gas turbine

T_3 = 1549.6 K, outlet temperature of combustion chamber

Total capital investment

The total capital investment of the NGCCPP is estimated by summing the purchase costs of major equipment, including the air compressor, combustion chamber, and gas turbine [34]. Each equipment cost is determined using established empirical correlations derived from industry data, adjusted for plant capacity and operating conditions. These correlations relate physical and operational parameters such as air mass flow rate, efficiency, pressure ratios, and temperatures to the purchase cost of each component.

The cost of the air compressor is calculated using an empirical correlation that incorporates the air mass flow rate, compressor efficiency, and the pressure ratio across the unit. This ensures that both the size and performance requirements of the compressor are reflected in the estimated cost [35].

The combustion chamber cost is determined based on the air mass flow, inlet and outlet pressures, and the outlet temperature, accounting for typical pressure losses across the chamber [36]. The empirical model captures the complexity of design requirements, including thermal and mechanical stresses.

The gas turbine cost is calculated from air flow, pressures, temperatures, and turbine efficiency. This correlation accounts for the high-temperature operation and mechanical demands associated with gas turbine design. These component-level calculations are then aggregated to form the total direct equipment cost [37]. Standard correction factors for installation, instrumentation, piping, and contingency are applied to estimate the total plant capital investment, consistent with guidelines provided in chemical and energy plant costing literature.

RESULTS AND DISCUSSION

Purchase cost of equipments

Air compressor

The cost is calculated as follows:

$$Z_{AC} = \left(\frac{C_{11}\,\dot{m}_{air}}{C_{12}-\eta_{AC}}\right)\left(\frac{P_2}{P_1}\right) ln\left(\frac{P_2}{P_1}\right)$$

$$= \left(\frac{44.1\times211}{0.95-0.85}\right)\left(\frac{17}{1}\right) ln\left(\frac{17}{1}\right)$$

$$= 4481766.693\ \$ = 4.5\ \text{million}\ \$$$

Combustion chamber

The cost is calculated as follows:

$$Z_{CC} = \left[\frac{C_{21}\times m_{air}}{C_{22}-\left(\frac{P_3}{P_2}\right)}\right]\left(1+exp^{(C_{23}T_3-C_{24})}\right)$$

$$Z_{CC} = \left(\frac{46.08\times211}{0.995-\left(\frac{16.49}{17}\right)}\right)\left(1+\mathrm{e}^{(0.018\times1549.6-26.4)}\right)$$

$$= 388915.2 \times 5.4495$$

$$= 2119407.693\ \$ = 2\ \text{million}\ \$$$

Gas turbine

The cost is calculated as follows:

$$Z_{GT} = \left(\frac{C_{31}\,\dot{m}_{air}}{C_{32}-\eta_{GT}}\right) ln\left(\frac{P_3}{P_4}\right)\left(1+\mathrm{e}^{(C_{33}T_3-C_{34})}\right)$$

$$Z_{GT} = \left(\frac{479.34\times211}{0.94-0.85}\right) ln\left(\frac{17}{1}\right)\left(1+\mathrm{e}^{(0.036\times1549.6-54.4)}\right)$$

$$= 15910787.35\ \$ = 16\ \text{million}\ \$$$

The estimated purchase costs for all major components of the NGCCPP were determined using standard empirical correlations and validated equipment-performance data. The gas turbine represents the highest individual cost component, followed by air compressor and combustion chamber. The purchase cost of equipments form the foundation for evaluating the fixed-capital investment.

Present cost of equipments

The total present cost of all major equipment in the base year 1992 is obtained by applying multiplicative factors corresponding to the number of each unit used in the plant. The total cost is expressed as given in Equation (4):

$$\text{Total present cost (1992)} = Z_{Ac} + Z_{cc} + Z_{GT} \qquad (4)$$

Substituting the calculated equipment costs:

Total present cost (1992) = 22.5 million $

To estimate the 1992 equipment cost in 2025, the cost index correction factor is applied as given in Equation (5): [37]

$$\text{Present cost in 2025} = \text{Total Cost in 1992} \times \frac{CI_{2025}}{CI_{1992}} \tag{5}$$

$$= 49.30 \text{ million } \$$$

Where:

CI_{2025} = Chemical Engineering Plant Cost Index for 2025 = 785

CI_{1992} = Chemical Engineering Plant Cost Index for 1992 = 358.2

This adjustment accounts for inflation and changes in equipment prices over time.

Total capital investment

This section presents the estimation of the total capital investment (TCI) required for the NGCC power plant. The calculation includes both direct costs and indirect costs. These values are combined to determine the fixed capital investment and the overall TCI needed to complete and start up the project. [37]

Table 4.1 summarizes the calculated direct and indirect cost components based on the delivered equipment cost and the corresponding cost fractions.

Table 4.1: Direct and Indirect costs calculation

Item	Fraction of delivered equipment	Calculated values (Million $)
Direct cost		
Purchased equipment, E'	-	49.30
`	0.10	4.93
Subtotal: delivered equipment	-	54.23
Purchased equipment installation	0.47	25.49
Instrumentation & Controls (installed)	0.18	9.76
Piping (installed)	0.66	35.79
Electrical systems (installed)	0.11	5.96
Buildings (including services)	0.18	9.76
Yard improvements	0.10	5.42
Service facilities (installed)	0.70	37.96
Land	0.06	3.25
Total direct cost	3.56	187.62

Indirect cost		
Engineering and supervision	0.33	17.90
Construction expenses	0.41	22.23
Contractor's fee	0.21	11.39
Contingency	0.42	22.78
Total indirect cost	1.37	74.30

Table 4.2 provides the final summary of the capital investment components.

Table 4.2: Capital Investments Summary

Item	Value (Million)
Fixed capital investment (FCI) ($)	261.92
Working capital (WC) ($)	46.64
Total capital investment (TCI) ($)	308.56

The total capital investment (TCI) for the NGCC power plant was calculated using standard cost–scaling fractions based on the purchased equipment cost. The direct costs, which include equipment, installation, piping, electrical systems, and service facilities, contributed the largest portion of the investment, amounting to approximately 187.62 million $. Indirect costs such as engineering, construction expenses, contractor fees, and contingencies added an additional 74.30 million $. Combining these values, the fixed capital investment (FCI) reached about 261.92 million $, and including working capital requirements, the final TCI was estimated at 308.56 million $. These results indicate that installation, service facilities, and piping are the major cost drivers, highlighting the significant role of infrastructure and support systems in determining the overall project investment.

Summary of results

The economic assessment of the Natural Gas Combined Cycle Power Plant (NGCCPP) began with the estimation of the purchase costs of the major plant components, namely the air compressor, combustion chamber, and gas turbine. These components constitute the core equipment of the Brayton cycle and significantly influence the overall capital requirement of the power plant. The costs were determined using established empirical cost correlations that account for operating conditions, equipment efficiency, pressure ratios, and flow rates. Such correlations are widely used in techno-economic studies because they provide reliable cost estimates during the preliminary design stage.

The air compressor purchase cost was estimated to be approximately $4.5 million. The relatively high cost of the compressor can be attributed to the large air mass flow rate of 211 kg/s and the high-pressure ratio of 17:1 required to achieve efficient combustion and turbine operation. The cost correlation shows that compressor cost increases with increasing mass flow rate and pressure ratio. In addition, compressor efficiency significantly affects the cost because higher efficiencies generally require more advanced blade designs, tighter manufacturing tolerances, and superior construction materials.

The calculated compressor cost represents approximately 20% of the total equipment purchase cost. This result is consistent with values reported in gas turbine power plant literature, where compressors account for a substantial portion of the gas turbine package cost. The high-pressure ratio adopted in the present study contributes to improved thermal efficiency but simultaneously increases equipment complexity and capital expenditure. Therefore, optimization of compressor design is essential to achieve a balance between performance improvement and economic viability.

The combustion chamber purchase cost was estimated to be approximately $2.12 million. Among the three major components considered, the combustion chamber represents the lowest capital investment. The cost correlation indicates that the combustion chamber cost depends primarily on the air mass flow rate, pressure ratio, and turbine inlet temperature.

Although the combustion chamber operates under extremely high temperatures (1549.6 K), its cost remains relatively lower than those of the compressor and turbine because it contains fewer moving parts and requires less mechanical complexity. However, the exponential temperature term in the cost equation demonstrates that increases in turbine inlet temperature significantly affects combustion chamber cost. Higher operating temperatures require advanced alloys, thermal barrier coatings, sophisticated cooling systems, and enhanced combustion control technologies to ensure safe and reliable operation.

The estimated cost suggests that the combustion chamber contributes approximately 9% of the total equipment purchase cost. While this contribution is comparatively small, the combustion chamber remains a critical component because it directly affects fuel utilization efficiency, emissions performance, and turbine operating conditions.

The gas turbine was found to be the most expensive component, with an estimated purchase cost of approximately $16 million. This result is expected because the gas turbine is the primary power-producing unit within the Brayton cycle and operates under the most demanding thermal and mechanical conditions.

The cost correlation demonstrates a strong dependence on turbine inlet temperature, pressure ratio, efficiency, and mass flow rate. The large air flow rate of 211 kg/s combined with the high turbine inlet temperature significantly increases the equipment cost. Furthermore, achieving a turbine efficiency of 85% requires sophisticated aerodynamic blade designs, advanced cooling technologies, and high-performance materials capable of withstanding elevated temperatures and stress.

The gas turbine accounts for approximately 71% of the total purchase cost of the major equipment considered. This dominance highlights the importance of turbine selection in power plant economics. Improvements in turbine efficiency generally result in lower fuel consumption and higher plant output; however, such improvements are usually accompanied by higher initial capital costs. Therefore, the turbine represents the most influential component in determining the economic feasibility of the NGCCPP.

A comparison of the estimated equipment costs reveals a clear distribution of capital investment among the major Brayton cycle components. The gas turbine constitutes the largest share of the equipment cost, followed by the air compressor and the combustion chamber. The total purchase cost of the three major components was estimated at approximately $22.5 million in the reference year of 1992.

The dominance of the gas turbine cost reflects the technological sophistication required to convert thermal energy into mechanical power efficiently. In contrast, the compressor and combustion chamber, although essential, involve lower levels of material and manufacturing complexity. This cost distribution agrees with findings reported in previous studies on gas turbine power plants, where turbine costs typically represent the largest portion of the equipment expenditure.

Because the empirical cost correlations were developed using a 1992 economic basis, cost escalation was necessary to reflect present-day economic conditions. The Chemical Engineering Plant Cost Index (CEPCI) was employed to adjust historical costs to 2025 values.

The total equipment purchase cost increased from \$22.5 million in 1992 to approximately \$49.30 million in 2025. This increase represents a cost escalation factor of approximately 2.19, indicating substantial inflation and growth in equipment manufacturing costs over the 33-year period.

The updated cost estimate provides a more realistic representation of the financial requirements associated with constructing a modern NGCCPP. Failure to account for cost escalation would significantly underestimate the required investment and could lead to inaccurate economic evaluations.

The direct costs were calculated based on standard fractions of the delivered equipment cost. The delivered equipment cost, including transportation and procurement expenses, was estimated at \$54.23 million. Among the direct cost components, the largest contributions were service facilities: \$37.96 million, piping systems: \$35.79 million, and equipment installation: \$25.49 million.

The high cost associated with service facilities reflects the extensive infrastructure required for utility systems, cooling water networks, fuel supply systems, compressed air systems, and auxiliary plant operations. Similarly, piping costs are significant because of the extensive network required to transport air, fuel, steam, cooling water, and exhaust gases throughout the plant.

The total direct cost was estimated at approximately \$187.62 million, representing about 72% of the fixed capital investment. This finding indicates that installation and supporting infrastructure account for a substantial portion of project expenditure, often exceeding the cost of the major process equipment itself.

Indirect costs were estimated at approximately \$74.30 million and include engineering, supervision, construction expenses, contractor fees, and contingency allowances. The largest indirect cost components were contingency: \$22.78 million, construction expenses: \$22.23 million, engineering and supervision: \$17.90 million.

Contingency allowance is particularly important because it accounts for uncertainties associated with design modifications, market fluctuations, labor productivity, and unforeseen technical challenges during project execution. The relatively high contingency value reflects the complexity and scale of NGCC power plant projects.

The combination of direct and indirect costs resulted in a Fixed Capital Investment (FCI) of approximately \$261.92 million. This value represents the total expenditure required to construct and commission the NGCCPP before commercial operation.

A working capital requirement of \$46.64 million was subsequently added to cover operating expenses such as fuel inventory, spare parts, maintenance materials, and cash reserves needed during the initial operating period. Consequently, the Total Capital Investment (TCI) was estimated at approximately \$308.56 million, equivalent to about 123.42 million OMR. This value represents the total financial commitment required to establish and operate the proposed NGCCPP. Overall, the results indicate that while the gas turbine is the dominant equipment cost, most of the project expenditure arises from installation, infrastructure, engineering, and supporting facilities. Therefore, comprehensive economic optimization should focus not only on equipment selection but also on reducing installation costs, improving plant layout, and maximizing operational efficiency to enhance the overall economic performance of the NGCCPP.

CONCLUSION:

The economic evaluation of the Natural Gas Combined Cycle Power Plant (NGCCPP) highlights the critical role of major equipment costs in determining the overall financial feasibility of modern power generation projects. The analysis shows that the gas turbine, as the primary power-producing unit, constitutes the largest portion of the equipment purchase cost, followed by the air compressor and combustion chamber. While these core components are essential for efficient operation of the Brayton cycle, the study reveals that installation, piping, service facilities, and instrumentation collectively account for a significant share of the total direct costs, often exceeding the expenditure on the equipment itself. Adjustment of historical equipment costs from 1992 to 2025 using the Chemical Engineering Plant Cost Index indicates a substantial escalation, underscoring the importance of incorporating inflation and market-driven price changes in techno-economic studies. The calculated fixed capital investment of approximately $261.92 million, together with working capital requirements, yields a total capital investment of $308.56 million (123.42 million OMR), reflecting the substantial financial commitment necessary for NGCCPP deployment. Indirect costs, including engineering, supervision, construction contingencies, and contractor fees, further emphasize the need for careful project planning and risk management. Overall, the results indicate that while optimizing the cost and efficiency of major equipment is important, comprehensive economic performance is equally influenced by supporting infrastructure, installation practices, and operational planning. This study provides a robust foundation for further analyses, including sensitivity studies, levelized cost of electricity calculations, and investment optimization, thereby offering valuable guidance for stakeholders seeking to develop economically viable and technically efficient gas-to-power solutions.

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