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(ARTICLE)

Feasibility Study of Steam Injection and Combined Cycle Technologies Based on Economic Analysis

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دراسة جدوى تقنيتي حقن البخار والدورة المركبة استنادًا إلى التحليل الاقتصادي

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Abstract:
This study aims to evaluate the economic feasibility of Steam Injection Gas Turbine (SIGT) and Combined Cycle Power Plant (CCPP) technologies when applied to two Siemens SGT5-2000E gas turbine units. An integrated economic model was developed based on key financial performance indicators, including Capital Cost, Net Present Value (NPV), Payback Period (PBP), Annual Rate of Return (ARR), and Profitability Index (PI). In addition, the impact of variations in electricity selling prices and fuel prices on the economic performance of the studied systems was investigated. The results showed that the steam injection technology achieved the best economic performance compared with both the combined cycle and simple cycle configurations. The capital cost increased by only 4.1% relative to the base case, while the technology achieved the highest NPV of USD 1,845.71 million, the shortest payback period of 0.61 years, the highest ARR of 71.0%, and the highest PI of 5.97. In contrast, the combined cycle technology required a substantial increase in capital cost of 50%, which adversely affected its economic feasibility indicators despite the noticeable improvement in overall performance. Sensitivity analysis further revealed that increasing the electricity selling price from 0.055 to 0.08 USD/kWh improved all economic indicators for the three systems. However, steam injection consistently maintained the highest NPV, ARR, and PI values, in addition to the shortest payback period across all electricity price levels considered. Conversely, increasing the fuel price from 0.019 to 0.079 USD/kg reduced the economic performance of all systems; nevertheless, steam injection demonstrated the greatest resilience to fuel price fluctuations, maintaining superior investment returns and the best profitability and economic efficiency indicators. The findings confirm that steam injection technology represents the most economically viable option for upgrading SGT5-2000E gas turbine power plants, providing an optimal balance between investment cost and economic return while ensuring rapid capital recovery and greater resistance to variations in energy and fuel prices. These results provide valuable decision-support guidance for policymakers, planners, and energy-sector stakeholders in selecting appropriate technologies to enhance the economic performance of gas turbine power plants.

Keywords: Gas Power Plants, Steam Injection Technology, combined cycle technology, Economic Feasibility, Aspen Plus.

الملخص
تهدف هذه الدراسة إلى تقييم الجدوى الاقتصادية لتقنيتي حقن البخار (SIGT) والدورة المركبة (CCPP) عند تطبيقهما على وحدتين غازيتين من نوع Siemens SGT5-2000E. تم تطوير نموذج اقتصادي متكامل يعتمد على مؤشرات الأداء المالية الرئيسة، تشمل تكلفة رأس المال (Capital Cost)، والقيمة الحالية الصافية (NPV)، وفترة استرداد رأس المال (PBP)، ومعدل العائد السنوي (ARR)، ومؤشر الربحية (PI)، بالإضافة إلى دراسة تأثير تغير أسعار الكهرباء والوقود على الأداء الاقتصادي للأنظمة المدروسة. أظهرت النتائج أن تقنية حقن البخار حققت أفضل أداء اقتصادي مقارنة بالدورة المركبة والدورة البسيطة، حيث ارتفعت تكلفة رأس المال بنسبة محدودة

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بلغت 4.1% فقط مقارنة بالحالة الأساسية، في حين حققت أعلى قيمة حالية صافية بلغت 1845.71 مليون دولار، وأقصر فترة استرداد بلغت 0.61 سنة، وأعلى معدل عائد سنوي بلغ 71.0%، بالإضافة إلى أعلى مؤشر ربحية بلغ 5.97. في المقابل، تطلبت تقنية الدورة المركبة زيادة كبيرة في تكلفة رأس المال بلغت 50%، مما انعكس على مؤشرات الجدوى الاقتصادية رغم التحسن الملحوظ في الأداء. كما أظهرت تحليلات الحساسية الاقتصادية أن ارتفاع سعر بيع الكهرباء من 0.055 إلى 0.08 USD/kWh أدى إلى تحسين جميع المؤشرات الاقتصادية للأنظمة الثلاثة، بينما حافظت تقنية حقن البخار على أعلى قيم للقيمة الحالية الصافية ومعدل العائد السنوي ومؤشر الربحية، إلى جانب أقصر فترة استرداد عند جميع مستويات الأسعار المدروسة. ومن ناحية أخرى، بينت النتائج أن ارتفاع سعر الوقود من 0.019 إلى 0.079 USD/kg أدى إلى تراجع الأداء الاقتصادي لجميع الأنظمة، إلا أن تقنية حقن البخار أظهرت أعلى قدرة على مقاومة تأثير تقلبات أسعار الوقود، محافظةً على أعلى عائد استثماري وأفضل مؤشرات ربحية وكفاءة اقتصادية. تؤكد نتائج الدراسة أن تقنية حقن البخار تمثل الخيار الأكثر جدوى من الناحية الاقتصادية لتطوير محطات التوليد الغازية من نوع SGT5-2000E، حيث توفر توازناً مثالياً بين التكلفة الاستثمارية والعائد الاقتصادي، وتحقق استرداداً سريعاً لرأس المال مع قدرة أكبر على مواجهة تغيرات أسعار الطاقة والوقود. وتمثل هذه النتائج أداة دعم مهمة لصناع القرار والمخططين في قطاع الطاقة عند اختيار التقنيات المناسبة لتحسين الأداء الاقتصادي لمحطات التوليد الغازية.

الكلمات المفتاحية: محطات الطاقة الغازية، تقنية حقن البخار، تقنية الدورة المركبة، الجدوى الإقتصادية، Aspen Plus.

Introduction

Gas turbine power plants are among the most efficient sources of electricity generation worldwide, characterized by their high efficiency and ability to respond rapidly to increasing energy demands [1]. In Libya, these plants are an integral part of the national electricity generation system, with several gas-fired power plants installed, including the Western Tripoli Gas Power Plant, Southern Tripoli Power Plant, Benghazi Power Plant, Zawiya Power Plant, and others. However, the efficiency of these plants is significantly affected by local environmental factors such as temperature and relative humidity, which undergo noticeable variations between seasons [2, 3]. These factors necessitate improving the efficiency of gas turbine power plants in order to reduce fuel consumption and harmful emissions while maintaining a high level of performance [4]. In this context, several advanced technologies contribute to achieving these objectives. Among these technologies, combined cycle and steam injection stand out as effective solutions for improving the efficiency of gas turbine power plants [5]. Combined cycle technology utilizes the heat of the exhaust gases produced by the gas turbine to generate steam, which is used to operate an additional steam turbine, resulting in increased energy production and improved plant efficiency. Although this technology is effective in improving performance, it requires significant investments in infrastructure [6, 7]. Another study focused on the thermodynamic simulation of a combined cycle power plant (CCPP), investigating the effects of economic strategies and design factors on improving plant performance. The results showed that changes in economic factors affect the balance between cash flows and fixed costs at the optimum point [8]. In contrast, steam injection technology introduces a specific amount of steam into the combustion chamber of the gas turbine, thereby increasing the volume and density of the gas flowing through the turbine [1, 7, and 9]. In this paper, the economic feasibility of both combined cycle and steam injection technologies will be investigated through a practical case study of SGT5-2000E gas turbines under identical operating conditions for both technologies.

2. Methodology

Results and discussion

1.1. Aspen Plus Program

Aspen Plus is a comprehensive simulation tool widely used in engineering applications to simulate and analyze thermodynamic processes, particularly in energy applications and industries. The program enables users to simulate a wide range of systems, including power plants. It is distinguished by its ability to simulate complex processes, evaluate performance, and optimize designs, making it a powerful tool for studying energy systems and their economic impacts [10]. In power plant simulations, Aspen Plus is frequently used to simulate both simple gas cycles and combined cycles, as well as steam injection in gas turbine plants, enabling engineers to evaluate different operational strategies and configurations to achieve optimal economic and environmental outcomes [11]. Aspen Plus utilizes advanced mathematical techniques to solve the equations governing system behavior. This ensures that the simulations converge to accurate solutions, even for complex systems with interconnected components.

The program's property libraries also enable accurate calculations of physical properties, ensuring that the models reflect real-world behaviour and provide accurate predictions of system performance [12]. In addition to thermodynamic calculations, Aspen Plus also provides tools for economic analysis, allowing users to evaluate the cost implications of different design choices and operational strategies [11].

1.2. Microsoft Excel Program

Microsoft Excel is a popular and effective tool for data calculations and performing complex mathematical operations in many engineering applications. In this study, Excel was primarily used to analyze data related to economic feasibility. Excel is used for these operations due to its powerful capabilities in performing advanced calculations and processing data quickly and flexibly, facilitating the handling of large and complex datasets [13]. It also enables accurate calculations. Using advanced mathematical formulas and graphical representations, Excel was used to provide predictions regarding economic feasibility [14].

1.3. Economic Analysis

- The Payback Period (PBP) is defined as the time required to recover the total capital invested (TCI) through annual net cash flows (CFN). The payback period is calculated using Equation (1) [19-21].

$$TCI = \sum_{j=1}^{PBP} CFN_j \quad \text{(1)}$$

- TCI: Total Capital Invested.
- CFN: Recurring Net Cash Flow, representing the difference between annual revenues and operating costs.

- The Net Present Value (NPV) is defined as the difference between the sum of future net cash flows and the initial investment cost, with all values discounted to the present time. This value is used to evaluate whether a project generates profits exceeding its costs. The NPV is calculated using Equation (2).

$$NPV = \sum_{j=1}^{t} \frac{CFN_j}{(1+r)^j} - TCI \quad \text{(2)}$$

- r : Discount rate, which reflects the return relative to expenditures.
- n : Project lifetime.

If the NPV is positive, this indicates that the project is profitable; if it is negative, the project should be reconsidered or avoided.

- The Average Rate of Return (ARR) is defined as the ratio of the average annual net profit to the total capital invested, as expressed by Equation (3).

$$ARR = \frac{N\,P}{TCI} \quad \text{(3)}$$

- NP: Average Annual Net Profit.

- The Profitability Index (PI) represents the economic feasibility of a project based on the ratio between the present value of net cash flows and the total capital invested. It is calculated using Equation (4).

$$PI = \frac{NPV}{TCI} \quad \text{(4)}$$

A PI value greater than 1 indicates that the project is profitable and economically worthwhile, whereas a value less than 1 indicates that the project may not be economically feasible.

2. Initial Cost Estimates:

Evaluating the financial feasibility of new projects requires a comprehensive economic analysis to ensure the selection of the most economically efficient option. The study is based on economic indicators such as the Payback Period (PBP), Annual Rate of Return (ARR), Net Present Value (NPV), and Profitability Index (PI). The initial capital cost of each system was estimated based on official data and previous studies. Profitability was then calculated based on operating and maintenance (O&M) costs and net revenues from electricity sales, assuming a project lifetime of 20 years, an interest rate of 5%, and an annual operating capacity factor of 85%. Databases managed by engineering companies were used to determine equipment costs. The estimates included the Siemens SGT5-2000E gas turbine power plant with a capacity of 166 MW, both without steam injection and with steam injection technology, to provide a comprehensive assessment of the economic feasibility of each system.

2.1. Cost of Constructing and Operating Two Gas Turbine Units, Each with a Capacity of 166 MW

The cost estimation of the gas turbine power plant was based on a study conducted by GHD Group, a global engineering consultancy, and published in 2023 under the title "Power Station and Associated Costs Benchmark Reserve Capacity Price 2023." The study determined the construction cost of a 166 MW gas-fired power plant using a methodology that includes both fixed and variable costs. The total cost was estimated at approximately 896 USD/kW, corresponding to USD 148.58 million per gas turbine unit, resulting in a total cost of approximately USD 297 million for two units. These estimates include all engineering components, including equipment, civil and mechanical works, and electrical systems. GHD's assessment was based on a detailed analysis of engineering and economic parameters, taking into account variations in prices, inflation, and environmental and operational costs. Annual operation and maintenance costs were also estimated at 2% of the total capacity, including periodic maintenance but excluding emergency maintenance costs [15, 16].

2.2. Cost of Constructing and Operating the Steam Turbine in the Combined Cycle

As part of the cost assessment for constructing and operating the two gas turbine units using steam turbines, a comprehensive analytical study conducted by the U.S. Energy Information Administration (EIA) was adopted. The EIA is one of the leading international organizations in the field of energy and economic analysis, with more than 45 years of experience in providing detailed and accurate data on the construction and operation costs of energy projects. This study provides reliable estimates for various steam power plants in global energy markets.

For the cost analysis of the steam turbine connected to a combined-cycle power plant, a combination of operational data and fixed costs provided by the organization was used. According to the study published in 2022, the total cost of constructing and operating the steam turbine was calculated based on prices recorded in energy markets. Based on the study entitled "Cost and Performance Characteristics of New Generating Technologies, Annual Energy Outlook 2022," published by the U.S. Energy Information Administration (EIA), the cost of a combined-cycle system was estimated at approximately 1,062 USD/kW using the "Combined-cycle - multi-shaft" technology. According to the U.S. Energy Information Administration methodology, this configuration uses two gas turbines to operate the combined cycle, taking into consideration that costs may vary depending on the project location and size [17]. Based on this reference cost and the additional power generated by the steam turbine in the combined-cycle system, the cost of the steam turbine can be calculated. In the studied case, the total capacity of the two gas turbines was 332 MW, which increased to 468 MW after adding the steam turbine, indicating that the steam turbine contributes approximately 136 MW of additional capacity. The cost of the steam turbine was calculated based on its capacity in kilowatts:

$$136,000\ 144.43 = 1,060 \times M$$

According to the studies conducted by the U.S. Energy Information Administration, which provide data supporting a comprehensive assessment of the construction and operation costs of steam turbines, the cost of the steam turbine added to the combined-cycle system using two gas turbine units can therefore be estimated at approximately USD 144.43 million.

2.3. Cost of the Heat Recovery Steam Generator (HRSG) in Combined Cycle and Steam Injection Technologies

The cost of the Heat Recovery Steam Generator (HRSG) was estimated based on an engineering analysis involving its dimensions, operating characteristics, and the type of materials used. The study considered an exhaust gas pressure of 12 inches of water and the high temperatures generated by the gas turbine, which affect the design and material selection. High-performance materials capable of withstanding pressure and temperature were selected, while manufacturing and installation costs and long-term economic factors such as inflation were also considered. Based on reference data, the cost of an HRSG for a 166 MW power plant was estimated at approximately USD 6.1 million. Since two gas turbine units are used, the total cost of the two HRSG units was estimated at USD 12.2 million. Comparison with reference data for similar plants confirmed the accuracy of these estimates, as the selected values were consistent with the capacity and cycle efficiency of the target plant, supporting the validity of the adopted cost estimates [18].

3. Validation of the Siemens SGT5-2000E Gas Turbine Power Plant Model

The Siemens SGT5-2000E gas turbine is a single-shaft unit equipped with a combustion chamber featuring a two-can configuration for efficient fuel combustion and reduced nitrogen oxide and carbon dioxide emissions. It also consists of a compressor and a four-stage turbine. The Siemens SGT5-2000E is a distinctive gas turbine configuration in which the generator is connected to the shaft located adjacent to the compressor. The model is characterized by its ability to operate reliably under high-load conditions and its capability to burn both liquid and gaseous fuels. The Siemens SGT5-2000E gas turbine power plant operates according to the Brayton cycle [2, 3].

The manufacturer’s operating data under International Organization for Standardization (ISO) conditions are presented in Table (1).

Table (1): Operating data of the Siemens SGT5-2000E gas turbine power plant under ISO conditions [22].

Siemens Performance SGT5-2000E Series	ISO Conditions
Grid Frequency (Hz)	50
Power (MW)	166
Thermal Efficiency (%)	34.7
Heat Rate(kJ/kWh)	10,375
Heat Rate(Btu/kwh)	9,834
Turbine Exhaust Temperature (°C/°F)	541/1,005
Exhaust mass flow rate (kg/s)	525
Pressure ratio	12

When the gas turbine operates under design conditions, these conditions are referred to as ISO conditions. When the power plant operates under conditions that differ from the ISO specifications, its performance is considered to be under off-design conditions. To validate the model, a model for power generation and thermal efficiency was developed using the professional Aspen Plus software for the power plant. The Siemens SGT5-2000E turbine was simulated using the ambient air temperature and pressure, pressure ratio, exhaust mass flow rate, and exhaust gas temperature provided in Table (1). The isentropic efficiencies of the compressor and turbine used in the model were 85% and 90%, respectively. The mechanical efficiency of the turbine and compressor shaft was 98.5%, while the mechanical efficiency of the generator shaft was 99%, as specified for the power plant by the manufacturer and supported by previous studies [2, 3, and 22].

Table (2) presents the validation data for the target gas turbine power plant model. All results were obtained using the analysis tools integrated into Aspen Plus for the gas turbine power plant components and were validated using Microsoft Excel by comparing the calculated values, including efficiency, generated electrical power, exhaust temperature, and heat rate [23]. Equation (5) can be used to calculate the error percentage of the developed model [3].

$$Model_{Eror} = \frac{(Actual\ data - Model\ data) * 100}{Actual\ data} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

Table (2): Validation results of the gas turbine plant model using manufacturer operating data.

NO	Parameters	ISO Conditions	Aspen Plus	Diff	Error%
1	Power (MW)	166	165.68	0.31	0.18
2	Thermal Efficiency (%)	34.7	34.7	0	0
3	Turbine Exhaust Temperature (C)	541	542	1	0.18
4	Exhaust mass flow rate (kg/s)	525	525	0	0
5	Heat Rate(kJ/kWh)	10375	10372.4	2.58	0.02

The results showed good agreement with the manufacturer's operating data. This agreement demonstrates that the model is capable of accurately simulating the performance of the gas turbine power plant, making it a reliable tool for evaluating advanced technologies such as steam injection and combined cycle systems. Based on these results, the model can be used to investigate the economic feasibility and application of different technologies.

3.1. Simulation of the Target Gas Turbine Power Plant Using Steam Injection Technology (SIGT)

Following the validation of the gas turbine power plant model, the study focused on applying Steam Injection Gas Turbine (SIGT) technology to two Siemens SGT5-2000E gas turbine units. Figure (1) illustrates the process details within the two gas turbine units. The simulation was performed using Aspen Plus based on actual operating data for the two Siemens SGT5-2000E gas turbine units.

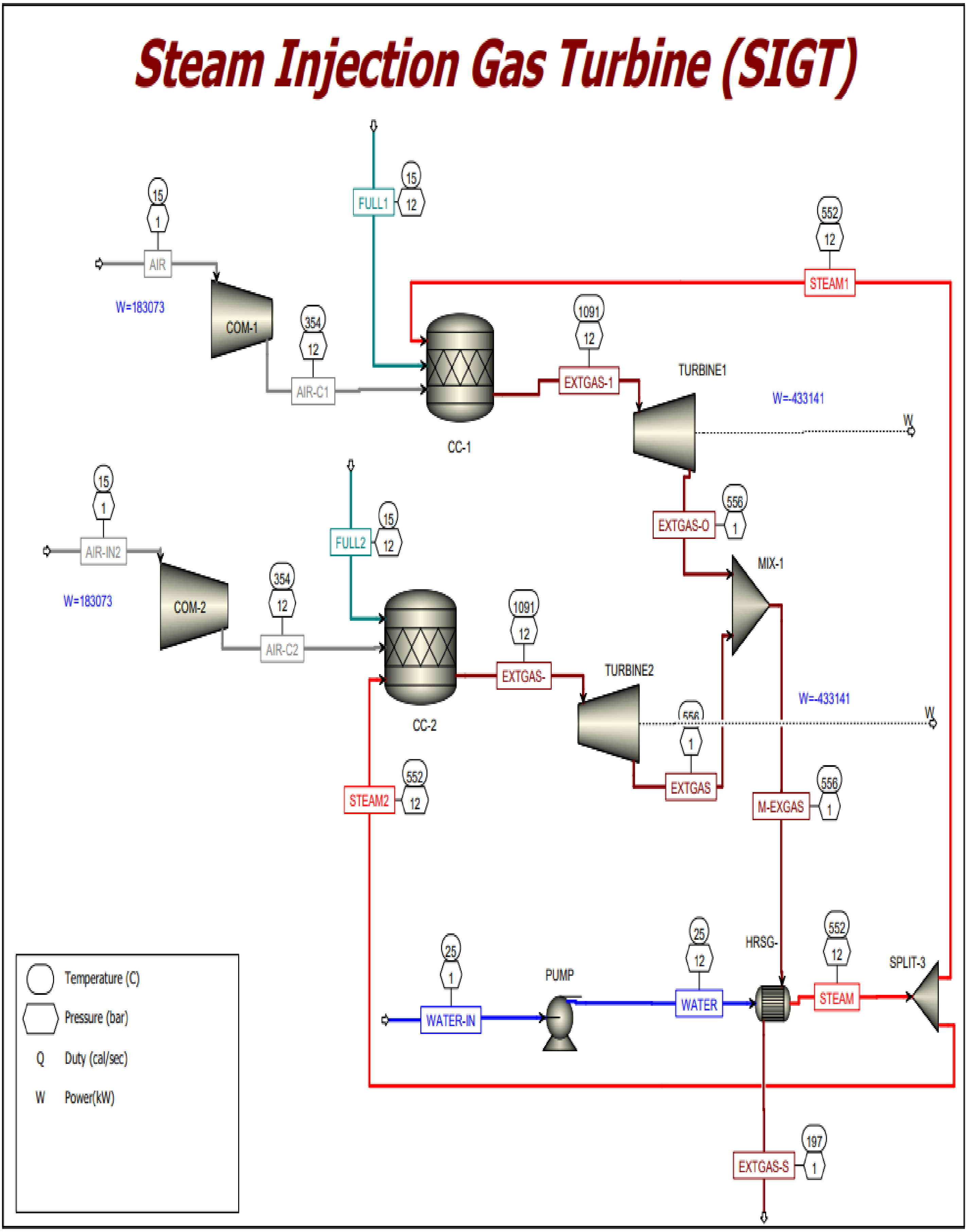


Figure (1): Simulation model of SGT5-2000E Gas Turbine power plant using Steam Injection (SIGT).

3.2. Simulation of Two Gas Turbine Units Using the Combined Cycle (CCPP)

The Combined Cycle Power Plant (CCPP) technology was applied to the two Siemens SGT5-2000E gas turbine units to investigate their economic performance. Figure (2) illustrates the simulation of the two gas turbine units integrated with the combined cycle using Aspen Plus.

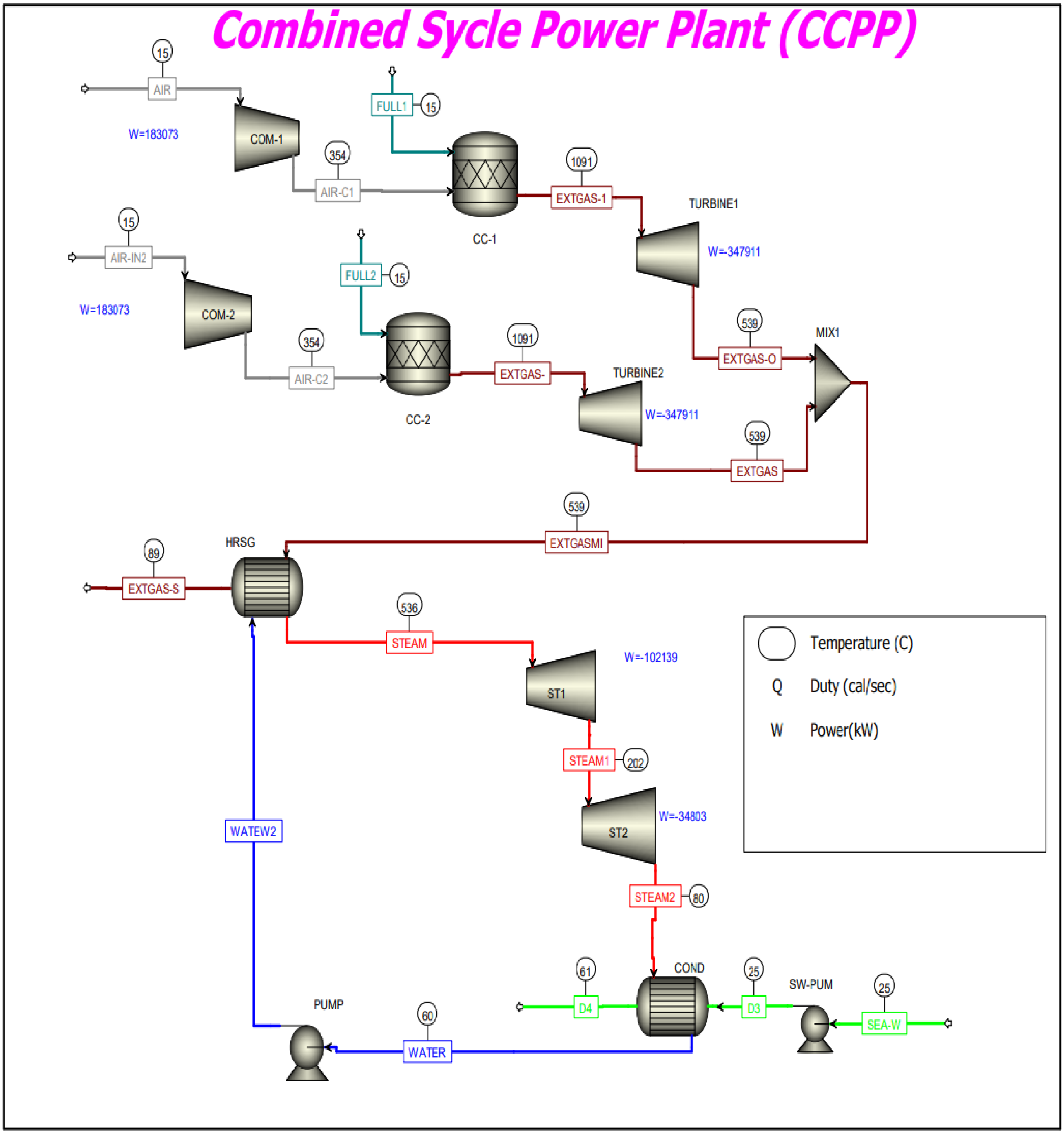


Figure (2): Simulation model of SGT5-2000E Gas Turbine power plant using the combined cycle (CCPP).

4. Results and Discussion

4.1. Economic Model Analysis of Power Generation Plants

The economic feasibility of two Siemens SGT5-2000E gas turbine units, each with a total capacity of 166 MW, was investigated for the base case, as well as for the application of Steam Injection Gas Turbine (SIGT) and Combined Cycle Power Plant (CCPP) technologies. The analysis included Capital Cost, Net Present Value (NPV), Payback Period (PBP), Annual Rate of Return (ARR), and Profitability Index (PI) for each case.

4.1.1. Capital Cost of the Two Gas Turbine Units with Steam Injection and Combined Cycle Technologies

The capital cost of the two gas turbine units was 296.76 million and increased to 309.11 million when the Steam Injection Gas Turbine (SIGT) technology was applied, representing an increase of only 4.1%. In contrast, the capital cost of the Combined Cycle Power Plant (CCPP) reached 445.20 million, representing increases of 50.0% compared with the simple-cycle case and 44.0% compared with the steam injection case, due to the additional steam turbines and equipment required. The Net Present Value (NPV) of the two gas turbine units was 1,068.30 million and increased to 1,845.71 million with steam injection, representing an increase of 72.8%. In the combined-cycle case, the NPV reached 1,571.87 million, representing an increase of 47.2% compared with the simple-cycle case, but remained 14.8% lower than that of the steam injection case, indicating the superior economic return of the latter. The Payback Period (PBP) was 2.07 years for the two gas turbine units and decreased to only 0.61 years with steam injection, making it the fastest option for capital recovery. In the combined-cycle case, the PBP increased to 2.14 years due to the higher investment cost. Similarly, the Annual Rate of Return (ARR) increased from 46.85% in the simple-cycle case to 71.00% with steam injection, while it reached 46.15% in the combined-cycle case, a value close to that of the base case, reflecting the impact of the higher capital cost on the economic return. Likewise, the Profitability Index (PI) increased from 3.60 for the two gas turbine units to 5.97 with steam injection, while it reached 3.53 in the combined-cycle case. These results confirm that the steam injection technology represents the most economically feasible option among the three systems, achieving the highest NPV and annual return and the shortest payback period, with only a limited increase in capital cost compared with the combined-cycle system.

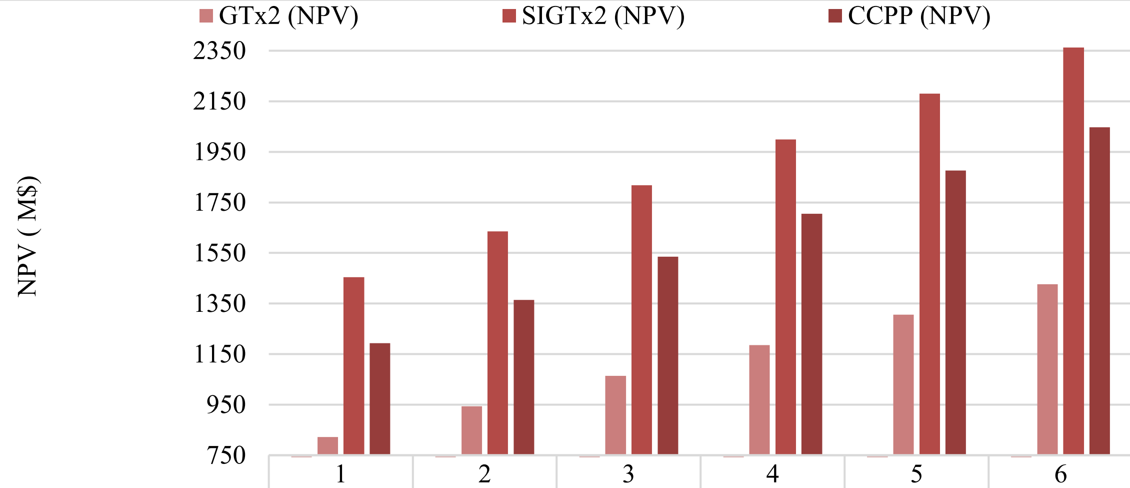
Table (3): Economic model results for two gas turbine units with and without SIGT and CCPP.

Economic Model Outcomes	(GTx2)	(SIGTx2)	(CCPP)
Capital Cost(M)	296.76	309.11	445.20
NPV(M)	1068.30	1845.71	1571.87
PBP(Years)	2.07	0.61	2.14
ARR	46.85	71.00	46.15
PI	3.60	5.97	3.53

- **Analysis of Economic Feasibility and the Effect of Electricity Selling Price and Fuel Price on Financial Performance**

Figure (3) shows that the Net Present Value (NPV) increases as the electricity selling price rises from 0.055 to 0.08 USD/kWh for all studied systems, with different rates of increase. For the gas turbine case, the NPV increased from 822.48 thousand to 1,426.91 thousand, representing an increase of 73.5%. The Steam Injection Gas Turbine (SIGT) achieved the highest NPV values at all price levels, increasing from 1,454.25 thousand to 2,362.46 thousand, with an increase of 61.5%, demonstrating its economic superiority. In comparison, the Combined Cycle Power Plant (CCPP) showed intermediate values, ranging from

1,193.42 thousand to 2,047.05 thousand, representing an increase of 71.5%. These results confirm that steam injection provides the highest economic return at different electricity prices, making it the most economically feasible option, in addition to its higher thermal efficiency. The results also highlight the sensitivity of the economic performance of the studied systems to changes in electricity prices.

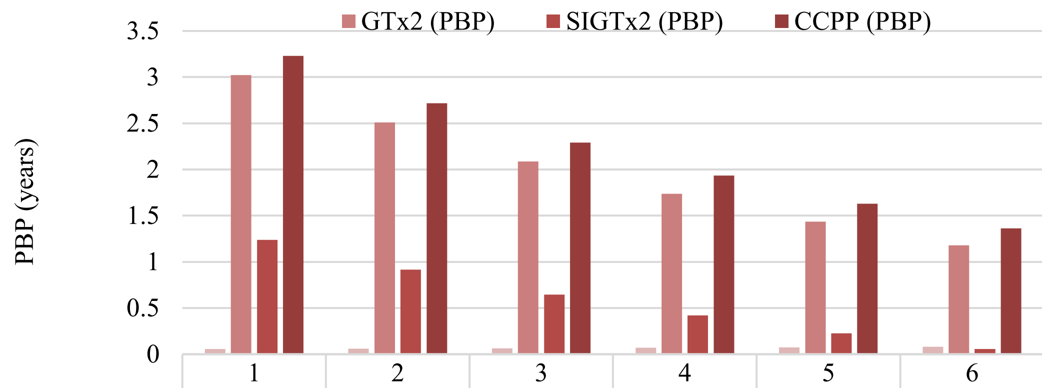


	1	2	3	4	5	6
Electricty price ($/KWh)	0.055	0.06	0.065	0.07	0.075	0.08
GTx2 (NPV)	822.48	943.37	1064.26	1185.14	1306.03	1426.91
SIGTx2 (NPV)	1454.25	1635.90	1817.54	1999.18	2180.82	2362.46
CCPP (NPV)	1193.42	1364.15	1534.88	1705.60	1876.33	2047.05

Figure (3): Results of the analysis of the effect of electricity selling price on Net Present Value (NPV)

- **Analysis of the Effect of Electricity Selling Price on Payback Period (PBP)**

Figure (4) shows that the Payback Period (PBP) decreases as the electricity selling price increases from 0.055 to 0.08 USD/kWh for all studied systems, with different rates of reduction. For the gas turbine case, the payback period decreased from 3.02 to 1.18 years, representing a reduction of 60.9%. The Steam Injection Gas Turbine (SIGT) achieved the shortest payback period at all price levels, decreasing from 1.24 to 0.06 years, representing a reduction of 95.2%, which reflects its high ability to accelerate capital recovery. In contrast, the Combined Cycle Power Plant (CCPP) showed intermediate performance, with the payback period decreasing from 3.23 to 1.36 years, representing a reduction of 57.9%. These results confirm the superiority of steam injection in reducing the investment payback period compared with the other systems, making it the most suitable option when the objective is to accelerate capital recovery and maximize financial returns. They also highlight the significant effect of changes in electricity prices on the economic feasibility of the studied systems.

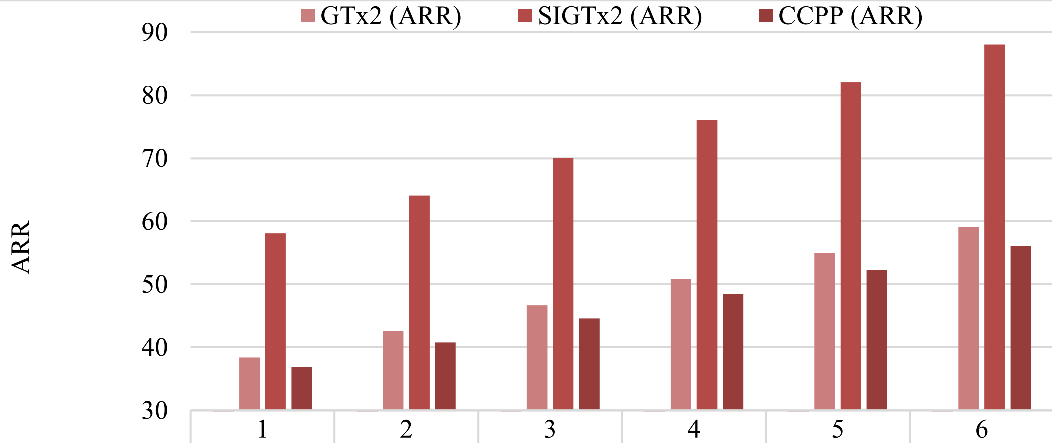


	1	2	3	4	5	6
Electricty price ($/KWh)	0.055	0.06	0.065	0.07	0.075	0.08
GTx2 (PBP)	3.02	2.51	2.09	1.74	1.44	1.18
SIGTx2 (PBP)	1.24	0.91	0.65	0.42	0.23	0.06
CCPP (PBP)	3.23	2.72	2.29	1.93	1.63	1.36

Figure (4): Results of the analysis of the effect of electricity selling price on Payback Period (PBP)

- **Analysis of the Effect of Electricity Selling Price on Annual Rate of Return (ARR)**

Figure (5) shows that the Annual Rate of Return (ARR) increases as the electricity selling price rises from 0.055 to 0.08 USD/kWh for all studied systems, with different rates of increase. For the gas turbine case, the ARR increased from 38.40% to 59.13%, representing an increase of 54%. The Steam Injection Gas Turbine (SIGT) achieved the highest rates of return at all price levels, increasing from 58.10% to 88.03%, with an increase of 51.5%, demonstrating its economic superiority. In contrast, the Combined Cycle Power Plant (CCPP) showed intermediate results, with the ARR increasing from 36.95% to 56.09%, representing an increase of 51.9%. These results confirm the economic superiority of steam injection at different electricity prices, supporting its adoption when the objective is to maximize the return on investment. They also demonstrate that this technology not only provides better thermal performance but also offers the highest economic feasibility compared with the other systems.

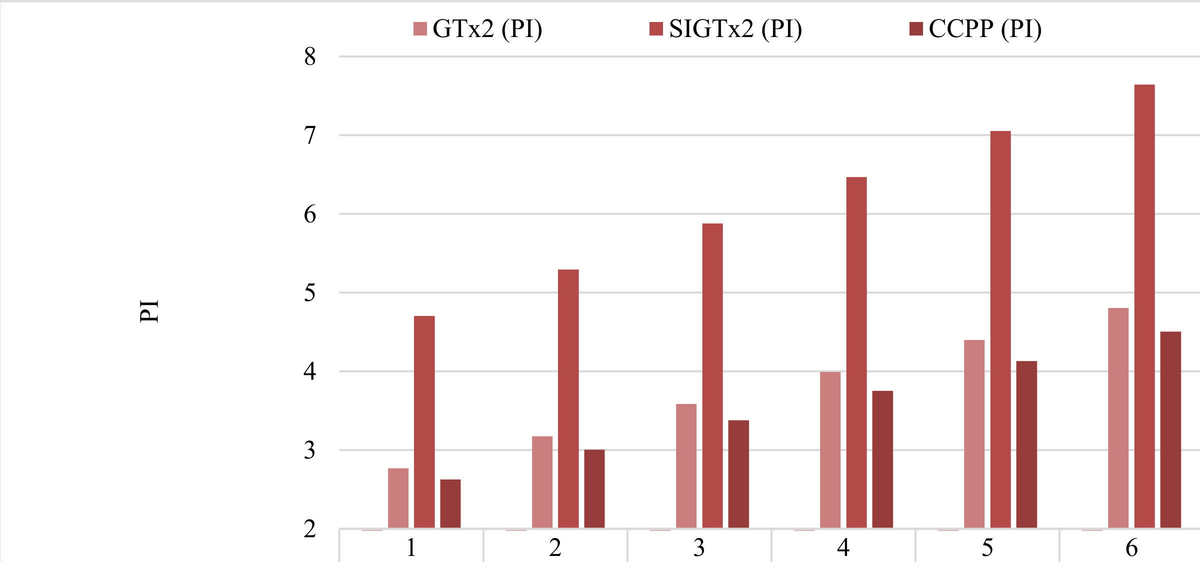


	1	2	3	4	5	6
Electricty price ($/KWh)	0.055	0.06	0.065	0.07	0.075	0.08
GTx2 (ARR)	38.40	42.55	46.69	50.84	54.99	59.13
SIGTx2 (ARR)	58.10	64.09	70.07	76.06	82.04	88.03
CCPP (ARR)	36.95	40.77	44.60	48.43	52.26	56.09

Figure (5): Results of the analysis of the effect of electricity selling price on Annual Rate of Return (ARR)

- **Analysis of the Effect of Electricity Selling Price on Profitability Index (PI)**

Figure (6) shows that the Profitability Index (PI) increases as the electricity selling price rises from 0.055 to 0.08 USD/kWh for all studied systems, with different rates of increase. For the gas turbine case, the PI increased from 2.77 to 4.81, representing an increase of 73.6%. The Steam Injection Gas Turbine (SIGT) achieved the highest PI values at all price levels, increasing from 4.70 to 7.64, with an increase of 62.3%, demonstrating its economic superiority. In contrast, the Combined Cycle Power Plant (CCPP) showed intermediate results, with the PI increasing from 2.63 to 4.51, representing an increase of 71.4%. These results confirm the economic superiority of steam injection at different electricity prices, supporting its adoption when the objective is to maximize the return on investment. They also demonstrate that steam injection provides the highest economic feasibility in addition to its higher thermal efficiency compared with the other systems.

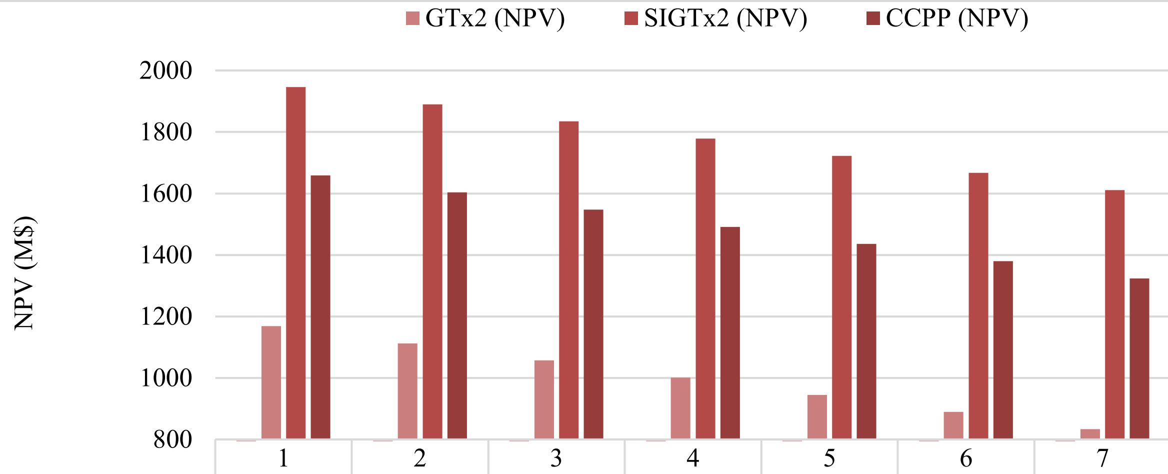


	1	2	3	4	5	6
Electricty price (\$/KWh)	0.055	0.06	0.065	0.07	0.075	0.08
GTx2 (PI)	2.77	3.18	3.58	3.99	4.40	4.81
SIGTx2 (PI)	4.70	5.29	5.88	6.47	7.06	7.64
CCPP (PI)	2.63	3.00	3.38	3.75	4.13	4.51

Figure (6): Results of the analysis of the effect of electricity selling price on Profitability Index (PI)

- **Analysis of the Effect of Fuel Price on Net Present Value (NPV)**

Figure (7) shows that the Net Present Value (NPV) decreases as the fuel price increases from 0.019 to 0.079 USD/kg for all studied systems, with different rates of decrease. For the gas turbine case, the NPV decreased from 1,168.4 thousand to 833.5 thousand, representing a reduction of 28.7%. The Steam Injection Gas Turbine (SIGT) achieved the highest NPV values at all fuel price levels, decreasing from 1,946.0 thousand to 1,611.1 thousand, representing a reduction of only 17.2%. This reflects its ability to maintain economic feasibility despite increasing fuel costs. In comparison, the Combined Cycle Power Plant (CCPP) showed intermediate results, with the NPV decreasing from 1,658.99 thousand to 1,324.04 thousand, representing a reduction of 20.2%. The results confirm that steam injection provides the highest economic return and more stable performance in response to fuel price fluctuations, making it the most economically feasible option under conditions of increasing fuel costs.

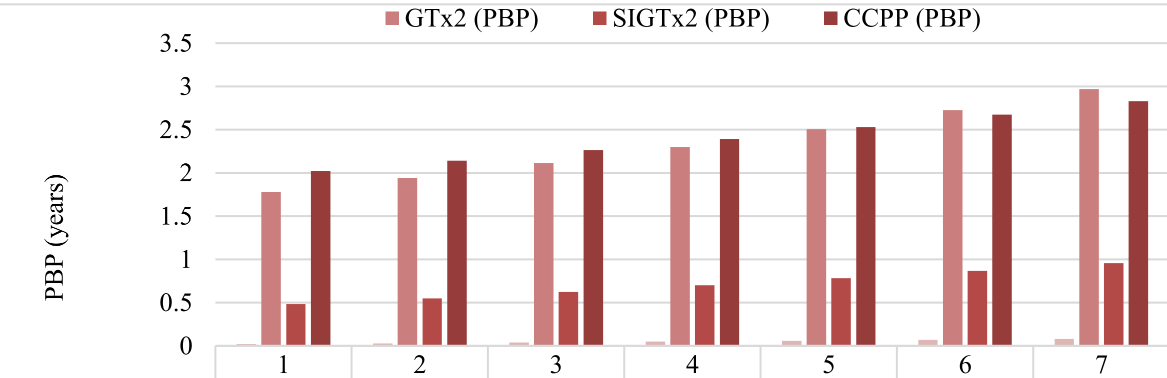


	1	2	3	4	5	6	7
Fuel Price ($/kg)	0.019	0.029	0.039	0.049	0.059	0.069	0.079
GTx2 (NPV)	1168.4	1112.6	1056.8	1001.0	945.1	889.3	833.5
SIGTx2 (NPV)	1946.0	1890.2	1834.4	1778.5	1722.7	1666.9	1611.1
CCPP (NPV)	1658.99	1603.17	1547.34	1491.51	1435.69	1379.86	1324.04

Figure (7): Results of the analysis of the effect of fuel price on Net Present Value (NPV)

- **Analysis of the Effect of Fuel Price on Payback Period (PBP)**

Figure (8) shows that the Payback Period (PBP) increases as the fuel price rises from 0.019 to 0.079 USD/kg for all studied systems, with different rates of increase. For the gas turbine case, the payback period increased from 1.8 to 3.0 years, representing an increase of 66.7%. The Steam Injection Gas Turbine (SIGT) recorded the shortest payback period at all fuel price levels, increasing from 0.5 to 1.0 year, representing an increase of 100%, while remaining the lowest compared with the other systems. This reflects its ability to accelerate investment recovery. In contrast, the Combined Cycle Power Plant (CCPP) showed intermediate results, with the payback period increasing from 2.0 to 2.8 years, representing an increase of 40%. These results confirm that steam injection provides the best economic performance in terms of capital recovery speed and maintains its economic feasibility despite fuel price fluctuations, making it the most suitable option when minimizing the investment payback period is the primary objective.

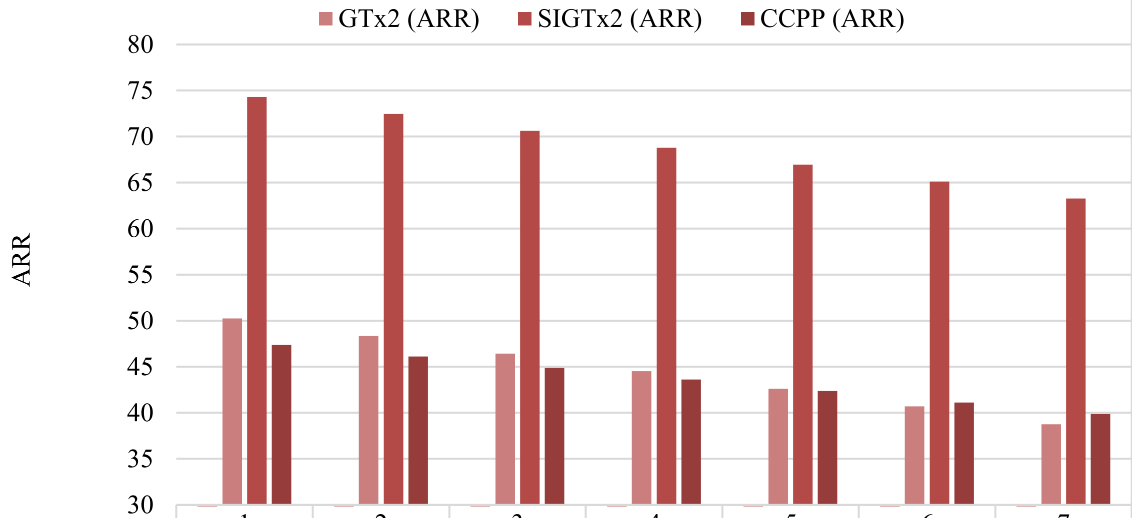


	1	2	3	4	5	6	7
Fuel Price ($/kg)	0.019	0.029	0.039	0.049	0.059	0.069	0.079
GTx2 (PBP)	1.8	1.9	2.1	2.3	2.5	2.7	3.0
SIGTx2 (PBP)	0.5	0.6	0.6	0.7	0.8	0.9	1.0
CCPP (PBP)	2.0	2.1	2.3	2.4	2.5	2.7	2.8

Figure (8): Results of the analysis of the effect of fuel price on Payback Period (PBP)

- **Analysis of the Effect of Fuel Price on Annual Rate of Return (ARR)**

Figure (9) shows that the Annual Rate of Return (ARR) decreases as the fuel price increases from 0.019 to 0.079 USD/kg for all studied systems, with different rates of decrease. For the gas turbine case, the ARR decreased from 50.3% to 38.8%, representing a reduction of 22.8%. The Steam Injection Gas Turbine (SIGT) achieved the highest rates of return at all fuel price levels, with the ARR decreasing from 74.3% to 63.3%, representing a reduction of only 14.8%. This reflects its ability to maintain a high investment return despite increasing fuel costs. In comparison, the Combined Cycle Power Plant (CCPP) showed intermediate performance, with the ARR decreasing from 47.4% to 39.9%, representing a reduction of 15.7%. The results confirm the superiority of steam injection in achieving the highest financial return on investment and the best economic stability in response to fuel price fluctuations, making it the most economically feasible option compared with the combined-cycle and conventional gas turbine systems.

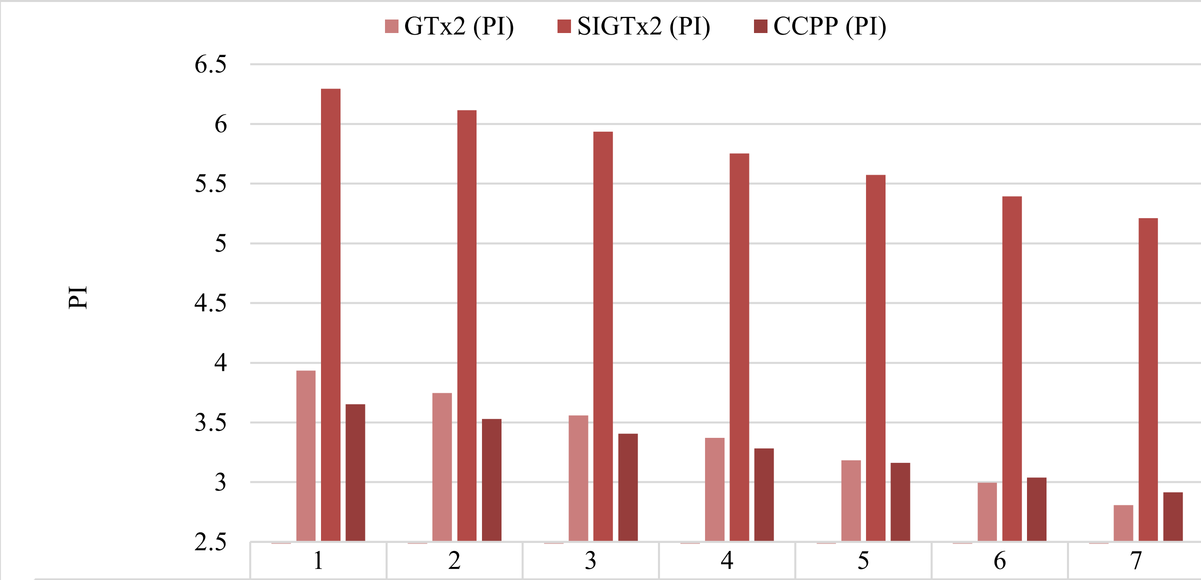


	1	2	3	4	5	6	7
Fuel Price ($/kg)	0.019	0.029	0.039	0.049	0.059	0.069	0.079
GTx2 (ARR)	50.3	48.4	46.4	44.5	42.6	40.7	38.8
SIGTx2 (ARR)	74.3	72.5	70.6	68.8	66.9	65.1	63.3
CCPP (ARR)	47.4	46.1	44.9	43.6	42.4	41.1	39.9

Figure (9): Results of the analysis of the effect of fuel price on Annual Rate of Return (ARR)

- **Analysis of the Effect of Fuel Price on Profitability Index (PI)**

For fuel prices ranging from 0.019 to 0.079 USD/kg, the Profitability Index (PI) decreases for all studied systems, with different rates of decrease, as shown in Figure (10). For the gas turbine case, the PI decreased from 3.9 to 2.8, representing a reduction of 28.2%. The Steam Injection Gas Turbine (SIGT) achieved the highest PI values at all fuel price levels, with the PI decreasing from 6.3 to 5.2, representing a reduction of only 17.5%. This reflects improved fuel consumption efficiency compared with conventional gas turbine operation. In contrast, the PI of the Combined Cycle Power Plant (CCPP) decreased from 3.7 to 2.9, representing a reduction of 21.6%. The results confirm that steam injection provides the highest profitability and better fuel consumption efficiency despite fluctuations in fuel prices, making it the most economically feasible option compared with the combined-cycle and conventional gas turbine systems.



	1	2	3	4	5	6	7
Fuel Price ($/kg)	0.019	0.029	0.039	0.049	0.059	0.069	0.079
GTx2 (PI)	3.9	3.7	3.6	3.4	3.2	3.0	2.8
SIGTx2 (PI)	6.3	6.1	5.9	5.8	5.6	5.4	5.2
CCPP (PI)	3.7	3.5	3.4	3.3	3.2	3.0	2.9

Figure (10): Results of the analysis of the effect of fuel price on Profitability Index (PI)

5. Nomenclature

Symbols	Description
TCA	Total Capital Invested
PBP	Payback Period
CFN	Recurring Net Cash Flow
NPV	Net Present Value
ARR	Average Rate of Return
NP	Average Annual Net Profi
PI	Profitability Index
SIGT	Combined Cycle Power Plant
CCPP	Steam Injection Gas Turbine
(GTx2)	Two Gas Turbine Units
(SIGTx2)	Two Gas Turbine Units with Steam Injection Technology
Model_Eror	Model Error Percentage

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