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Performance Analysis of an Energy System in the Tropical Rainforest: A Thermo-Economic Approach

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Abstract

This paper presents the thermos-economic evaluation of a simple gas turbine (SGT) within the Niger Delta, Nigeria. Steady-state monitoring and direct collection of data from the 25 MW plant were performed including logged data for a 12 months period. MATLAB software was used to model the various thermodynamic performance equations of the plants while net present value (NPV), internal rate of return (IRR), and Payback period (PBP) were used to model the economic concept of the plant performance. The thermodynamic analysis shows that for every 1˚C rise in the ambient temperature, the percentage power drop increases by 2.07%, thermal efficiency drops by 0.66%, and the specific fuel consumption increases by 0.93%. For every 1% drop in the power output, the percentage thermal efficiency drops by 0.79% for the given consideration. The economic analysis based on the performance reveals that the power shortages represent about 47.9% of the net power generated and the revenue worth of $4198741.60 is lost due to the inability of the plant to perform at its design point. The NPV value of $6434899.97 shows that the plant investment is viable for the period of twenty years of operation and the IRR on investment is determined to be 12.40% by a numerical approximation for the period, with a PBP of 8.5 years. This provides technical and economic details to plant operators and energy systems investors for decision making.

Keywords

Gas Turbine, Power Output, Overall Efficiency, Net Present Value, Internal Rate of Return, Payback Period

1. Introduction

Energy system performance is critical to any growing economy that is poised for growth and sustainability. Researchers have investigated several power plants within the tropical zone, and ways of optimizing their performance have been suggested. Although one way we can achieve energy efficiency is by systematically and effectively minimizing losses in our current energy systems. In addition the establishment of a performance rating philosophy of such systems and their evaluation in terms of technical performance parameters, their cost elements and implications to the environment are pertinent. Our industries today make use of coal, steam electrical energy, furnace, oils, diesel, chemicals, lubricating oil, etc. Although, because of their contribution to global warming, renewable energy development has been in an increasing measure in recent times. Raw materials like steel, copper, aluminum etc. are processed by energy-intensive processes. Even transportation by road, rail, ocean, and air requires high energy input [1]. Without an adequate supply of energy, the stability of the economic order, as well as the political structure of a society is in jeopardy [2]. Hence, energy both its production and its use in an environmentally safe manner is a platform for broader economic growth and improves the quality of life of people around the world [1].

The only form of energy which is easy to produce, transport, use and control is electrical energy. So, it is mostly the terminal form of energy for transmission and distribution [3]. The economic development and living standard of any society are a function of the availability and accessibility of electrical power to do her biding. Although most of the world have had chances to benefit from the merits brought by having access to electrical power, people in developing countries have not been as fortunate. In these countries, providing electricity will increase life expectancy and productivity, and will help in erasing illiteracy [4]. Therefore, the acknowledgment of the importance of increasing access to commercial electricity is fundamental to the future and sustainable development of any society.

The turbine is the most satisfactory power developing unit among various means of producing mechanical power due to its exceptional reliability [5]. Generally, turbines are any kind of spinning that uses the action of a fluid to produce work [6]. They are prime-movers used for driving rotating equipment like pumps, compressors etc., or for generating the electricity required for process industries or a community. The idea of using the axial flow compressors, combustion chamber and turbine was conceived as early as in 1872 [5]. The gas turbine plant can be either open cycle or closed cycle. The major difference between the closed cycle and open cycle is that the working fluid (product of combustion) is continuously circulated in the closed cycle as the fluid coming out from the turbine is cooled to its original temperature in a cooler using an external cooling source before passing into the compressor whereas, in the open cycle, the working fluid is continuously replaced as they are exhausted into the atmosphere [5].

The open cycle gas turbines can be started and stopped so easily compared with other power plants and therefore, are used for peak load power and tertiary reserve, and operate for a limited number of hours per year, typically 2000 and 5000 hours. The gas turbines used for electric power generation can produce electric power from the range of 20 to 250 MW with efficiencies of about 40% [7]. These gas turbines typically have a single-shaft configuration, operate on Brayton cycle [8] and consist of a compressor, a combustion chamber, and a turbine. Air is drawn from the atmosphere and is compressed to a high pressure in the compressor. The high-pressure air enters the combustion chamber where fuel is sprayed (added) to the compressed air and ignited to increase the fuel-air mixture (gas) temperature at constant pressure.

However, gas turbines that operate in simple cycles have low efficiencies because the emission from the turbine exhaust comprises of hot gases and this energy is lost to the atmosphere. In order to better the performance and reduce atmospheric emissions advanced cycles that utilize the energy in the hot emitted gases in a combined cycle to generate more power are being proposed, designed and studied. Efficiencies of about 50% - 60% have been reported [9]. Although, as part of performance audit, Adumene [10] presented an exergy-based analysis of an offshore gas plant. The result of his analysis revealed that there is a drop in both the thermal efficiency and exergy efficiency by 0.17% and 0.25% respectively, for every 1% drop in the operational load. The application of the first and second law of thermodynamics provides a holistic result for the plant performance prediction.

Eti *et al.* [11] made suggestions following series of investigations to improve the performance of the Afam V power plant by improving the Reliability and Productivity of the plant, and Thamir *et al.* [12] developed design methodology for a parametric study to improve gas turbine performance. Increase in thermal efficiency depends on certain factors including changes in some engine cycle parameters, such as overall pressure ratio (OPR), and exhaust temperature of the turbine [13]. Nkoi *et al.* [14], analysis three plant configuration, such as simple gas turbine (SGT), intercooled/recuperated (ICR) engine and recuperated engine (RC) and it was observed that some modified gas turbine cycle configurations incorporating unconventional components such as engine cycle with low-pressure compressor (LPC) zero-staged, recuperated engine cycle, and intercooled/recuperated (ICR) engine cycle exhibited better performances in terms of thermal efficiency and specific fuel consumption than the traditional SGT.

Espanani *et al.* [15] noted that gas turbines are machines that work directly with ambient air, thus, anything that causes a change in the inlet air condition has an effect on turbine efficiency. Hence, relative humidity, mean sea level and environmental temperature have an effect on gas turbine efficiency. It was observed that fogging and evaporative method is most effective methods of efficiency improvement in Khoramshahr power plant. In Adumene *et al.* [16] research, it was revealed that decreasing the ambient temperature of the gas turbine plant within the tropical zone by 41.9% improved the plant performance by about 0.78%.

Wang and Chiou [17] in their study concluded that implementing both steam injection gas turbine and inlet air cooling features cause more than a 70% boost in power and 20.4% improvement in heat rate. Bouam *et al.* [18] studied combustion chamber steam injecting for gas turbine performance improvement during high ambient temperature operation. Also performed by Harlock *et al.* [19] was the effect of exergy analysis on the gas turbine inlet temperature, and steam injection level in the gas turbine, and Srinivas *et al.* [20] concluded that steam injector decreases combustion chamber and gas re-heater energetic loss from 38.5% to 37.4% compared to the case without steam injection in combustion chamber. Wadhah [21] introduced an intercooler into the plant analysis and the result shows that the implementation of intercooling increases the power plant thermal efficiency of the case study gas turbine power plant when compared to the non-intercooled gas turbine plant configurations. The above is some of the various methodologies for gas turbine performance improvement, including gas turbine combined cycle. This work seeks to carry out an economic evaluation of the plant performance for its life cycle and predict the possible breaks even point for plant investors and energy mangers.

2. Materials and Methods

The following research methodology was adopted:

1) Data were collected from the Trans-Amadi gas plant (a single-shaft gas turbine) through the human machine interface and logbooks for 12 months.

2) Assessment of the plant operating condition was carried out.

3) MATLAB software code was developed to model the various equations employed for the analysis.

4) An economic model with the Net present value as the objective function was developed to predict the economic viability of the plant and to assess the rate of return on the investment.

Analytical Model for Plant Performance Evaluation

Trans-Amadi Gas Turbine Power Plant Operating Data

The operating conditions and data of the simple gas turbine, the Trans-Amadi gas turbine power plant is shown in **Figure 1**. The operating exit temperature of the compressor as shown in **Figure 1** is 367˚C and that of the turbine exit temperature is 487˚C. This illustrate the prevailing conditions where the plant operates, as well as the indication of some limiting factors against which the plant could not delivered at design capacity.

Applying steady flow energy equation and using the notations on the T-S diagram of **Figure 1** gives

$$\text{Heat Supplied, } \dot{Q}_1 = \dot{m}c_p\left(T_3 - T_2\right) \tag{1}$$

$$\text{Heat Rejected, } \dot{Q}_2 = \dot{m}c_p\left(T_4 - T_1\right) \tag{2}$$

$$\text{Compressor work rate, } \dot{W}_c = \dot{m}c_p\left(T_2 - T_1\right) \tag{3}$$

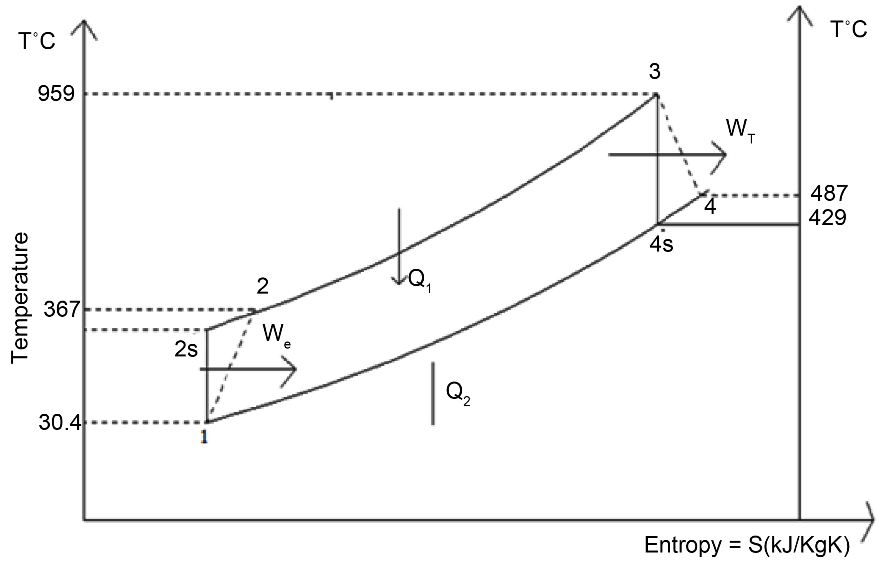

Figure 1. T-S diagram of the trans-amadi gas turbine power plant.

$$\text{Turbine work rate, } \dot{W}_t = \dot{m}c_p\left(T_3 - T_4\right) \tag{4}$$

$$\text{Turbine Inlet Temperature } T_3 = \frac{m_f \times CV}{\left(m_a + m_f\right) \times C_{pa}} + T_2 \tag{5}$$

$$\text{Specific Fuel Consumption sfc} = \frac{3600 \times m_f}{W_{net}} \tag{6}$$

(Lebele-Alawa and Anthony, [22]; De and Nag, [23]).

$$\text{Thermal efficiency} = \frac{\text{Net work Output}}{\text{Heat Supplied}} \tag{7}$$

$$\eta_{thGT} = \frac{\left(T_3 - T_4\right) - \left(T_2 - T_1\right)}{T_3 - T_2} = \frac{W_{net}}{\dot{Q}_1} \tag{8}$$

$$\text{Isentropic Efficiency of the turbine } \eta_{is} = \frac{\left(T_3 - T_4\right)}{T_3 - T_{4s}} \tag{9}$$

Nag, [3].

Economic Model for the Plant Investment Viability

The need for a terminal form of power or energy is on the increase and more potential investments can maximize this opportunity. It is therefore necessary to rank the possible power production investment based on financial return. The financial analysis requires evaluation models that compare the time-based income stream generated from the investment with the cost of investment. The techno-economic viability of power plant projects can be forecasted using various criteria that can be adopted to carry out such a comparison; such as the net present value (NPV), payback-period (PBP) and internal rate of return (IRR) [24].

The Net Present Value (NPV) is used to assess the future series of after-tax cash flow (ATCF) generated for the power generation and utilization. The NPV of the financial benefits is compared with the NPV of the investment to determine whether the investment has a positive return [25]. Mathematically, NPV is expressed as

$$\text{NPV} = -F_o + \sum_{t=1}^{N} \frac{F_t}{\left(1+d_t\right)^t} \tag{10}$$

(Nkoi *et al.*, [24]).

The NPV of the cash flows calculated is then compared with the NPV of the investment sequence, which is determined by:

$$\text{NPV}_{\text{IC}} = \sum_{i=0}^{i\,m\,n} \frac{IC_i}{\left(1+r_c\right)^i} \tag{11}$$

where i, m and n are investment period index, maintenance costs and number of financial year respectively.

If NPV_{ATCF} is greater than NPV_{IC}, the investment provides a positive return. Profitability index is defined as the ratio of the financial return to the investment. Appendix A shows a flowchart for NPV calculation. A negative NPV denotes that an investment is not economically viable, whereas an NPV equal to or greater than zero denotes an economically viable power investment.

The payback-period (SPBP) is the length of time usually in years taken to recover the initial cost of investment of the implementing plant based on the annual savings realized. That is,

$$\text{PBP}\left(\text{years}\right) = \frac{\text{Capital investment cost of the plant}}{\text{Annual saving from the Energy Generated by the plant}} \tag{12}$$

3. Results and Discussions

Results

Thermodynamic Performance of the Plant

Data recorded from the HMI in the control room of the plant is presented in **Table 1**. MATLAB software was employed to evaluate the performance of Trans-Amadi 25 MW gas turbine by calculating the percentage drops in power and thermal efficiency as the ambient temperature increases.

From the performance and economic analyses of Trans-Amadi gas turbine, **Figures 2-4** were generated.

Figure 2 shows the effect of ambient temperature on the net power. It was observed that percentage power drop increases with increase in ambient temperature. It indicated that for every 1˚C rise in the ambient temperature, the percentage power drop increases by 2.07% for the period under consideration. This further revealed that as the deviation between the design and operating ambient temperature increases, the plant performance decreases proportionally.

In **Figure 3**, as the ambient temperature (compressor inlet) increases, the

Table 1. Trans-Amadi 25 MW gas turbine performance.

Ambient Temp. (˚C)	Compressor Exit Temp. (˚C)	Air Mass Flow (kg/s)	Exhaust Temp. (˚C)	Fuel Flow (kg/s)	Actual Power Output (MW)	Thermal Efficiency (%)	Sfc (kg/MW-s)	Power Drop (%)	Thermal Efficiency Drop (%)
24	319.22	126.27	547.23	2.64	20.44	21.55	0.099	18.44	18.98
25	332.51	122.90	554.09	2.55	19.92	20.78	0.102	20.42	21.87
26	345.84	120.10	561.12	2.47	19.22	21.01	0.105	23.21	21.02
27	359.12	117.39	568.37	2.39	19.12	20.24	0.108	23.62	23.91
28	372.41	114.77	575.18	2.32	17.92	19.51	0.112	28.43	26.65
29	385.71	112.24	582.04	2.25	17.01	19.07	0.116	31.96	28.31
30	399.00	109.79	589.13	2.18	16.91	18.93	0.119	32.36	28.83
31	412.31	107.42	596.42	2.11	15.51	18.16	0.124	38.13	31.73
32	425.62	105.13	603.33	2.05	15.51	18.01	0.129	38.20	32.29

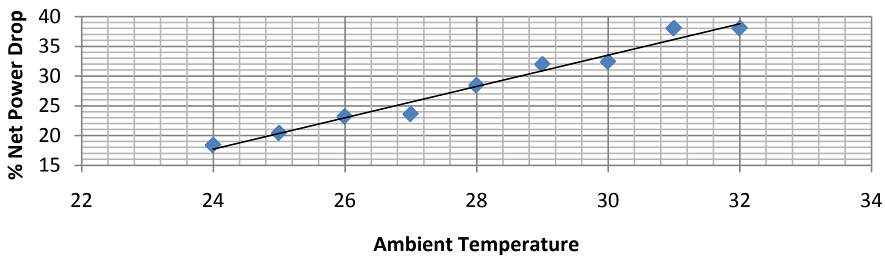

Figure 2. Variations in percentage net power drop with ambient temperature.

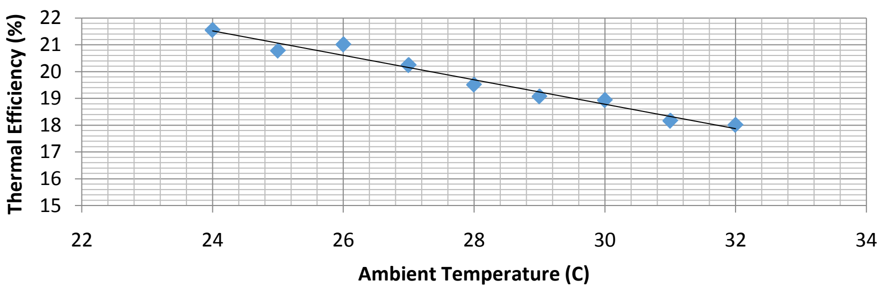

Figure 3. Variation of thermal efficiency with ambient temperature.

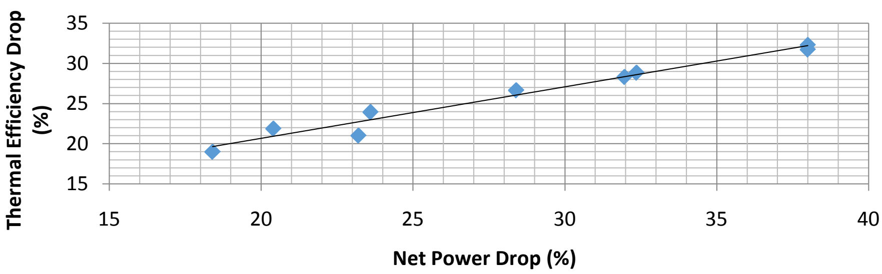

Figure 4. Variation of thermal efficiency with percentage power drop.

compressor work required for compressing the hot air increases resulting to decrease in thermal efficiency of the plant. For every 1˚C rise in the ambient temperature, the thermal efficiency drops by 0.66% for the period of analysis.

Figure 4 shows that as the net power drop increases there is a progressive increase in the thermal efficiency drop for the given range of ambient temperatures. Since the efficiency is a function of the output, increase in output will bring about a corresponding increase in efficiency. This is because both parameters are relatively proportional. For every 1% drop in the power output, the percentage thermal efficiency drops by 0.79% for the given consideration.

Figure 5 shows that specific fuel consumption (SFC) of the engine increases with increase in ambient temperature even though there is a decrease in fuel flow as shown above. This is because as the temperature increases, just any little available fuel will cause ignition whereas, any available fuel will be swept up (consumed) by the increased temperature. For every 1˚C rise in the ambient temperature, the specific fuel consumption increases by 0.93% for the given period.

Energy-Cost Analysis of the Gas Turbine Plant Performance

The analysis of the plant performance was evaluated on monthly basis. This was statistically evaluated and the average tabulated. Further analysis revealed the power available and power shortages due to the difference between the installed capacity and the generated power as shown in Table 2.

The log sheet data were evaluated and the mean net electrical power generated was 18.3 MW for a period of one year and the plant operating hours was 663 hours.

Power Available for the period (KWhe) = Net Electrical Power Generated × Operating Hours.

Power Available for the period (KWhe) = 18.3 × 663 × 1000 = 12,132,900 kWhe.

Power Shortages (MW) = Installed capacity − Net power generated = 25 MW − 18.3 MW = 6.7 MW.

Revenue Generated = Power available (KWhe) × Electricity tariff (₦/kWh or $/kWh).

Where the electricity tariff = 24.91 ₦/KWh (NERC, 2015) (0.076 $/KWh, approx 0.08 $/KWh).

Revenue Generated = 12,132,900 KWhe × 24.91 ₦/KWh = ₦302,230,539 ($970,632).

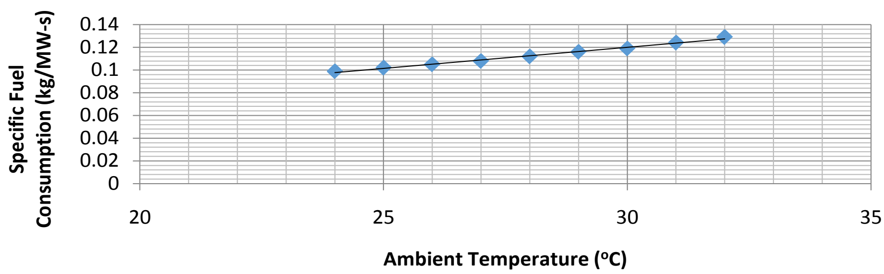

Figure 5. Variation of specific fuel consumption with ambient temperature for trans-amadi gas turbine.

Table 2. Summary of trans-amadi gas turbine annual operating performance.

Month of Operation	Net Electrical Power Generated (Avrg) (MW)	Hour of Plant Operation (hr)	Power Available (kWhe)	Power Shortages (MW)	Available Power Revenue $/kWhe	Cost of Shortages $/kWhe	Cost of outages $/kWhe
January	18.3	663	12,132,900	6.7	970,632	337599.6	79275.6
February	18.9	606	11,453,400	6.1	916,272	280941.6	163749.6
March	19.3	500	9,650,000	5.7	772,000	216,600	322,696
April	19.6	460	9,016,000	5.4	721,280	188,784	387,296
May	18.2	566	10,301,200	6.8	824,096	292508.8	213012.8
June	15.7	540	8,478,000	9.3	678,240	381,672	214,776
July	15.9	580	9,222,000	9.1	737,760	401,128	169,176
August	20.1	605	12,160,500	4.9	972,840	225,302	175,674
September	11.4	580	6,612,000	13.6	528,960	599,488	121,296
October	15.2	667	10,138,400	9.8	811,072	496781.6	61225.6
November	14.6	460	6,716,000	10.4	537,280	363,584	288,496
December	15.6	580	9,048,000	9.4	723,840	414,352	165,984
Total			**114,928,400**		**9,194,272**	**4198,741.6**	**2362657.6**

Cost of Shortages = (Installed capacity − Net power generated) × Operating hour × Electricity Tariff.

Cost of shortages = (25 MW − 18.3 MW) × 663 hours × ₦24.91/KWh = ₦110,652,711 ($337599.6).

Cost of Outages = (Total hours in the Month − Plant operating hours) × Net electrical power generated × Electricity Tariff = (720 − 663 hours) × 18.3 × 10^3 kW × 24.91 ₦/kWh = ₦ 25,983,621 ($79275.6).

The economic analysis based on the performance revealed that the power shortages represent about 47.9% of the net power generated for the period of consideration. This represents revenue loss of about $4198741.60 for the period. It further shows that the cost of outages represents 35.7% of the revenue generated per annum for the operating hours of the plant.

Investment Analysis of the Gas Turbine Plant

Reference to [24] [26] [27], the estimated gas turbine capital cost ($/kW) is 1167.95, gas turbine operation and maintenance (O & M) cost ($/kW) is 0.00939, gas turbine fuel cost ($/kWh) is 0.0469.

The Annual Operational and Maintenance cost for year 1 = Total annual power generated × O & M cost per kWh = 114,928,400 × 0.00939 = $1,079,178.

The Annual GT Fuel cost for year 1 = Total annual power generated × Fuel Price per kWh = 114,928,400 × 0.0469 = $5,390,142.

The Annual Net Cash Flow = Annual Electricity Revenue − (Annual O & M cost + Annual Fuel cost) = $9194272 − ($1,079,178 + $5,390,142) = $2,724,952.

$$\text{Present Value}(10\%\ \text{discount rate})\ \text{for year 1}$$

$$= \frac{\text{Annual net cash flow}\left(F_t\right)}{\left(1+\text{discount rate}\right)^t} = \frac{2724952}{\left(1+0.1\right)^1} = \$2477229.09$$

Initial Cash Flow $F_0 = (1 \times 25\ \text{MWGT}) \times$ Capital Cost per kW.

Initial Cash Flow $F_0 = (1 \times 25{,}000\ \text{kW}) \times 1167.95\ \$/\text{kW} = \$29{,}198{,}750$.

Table 3 shows the result of the economic viability of the plant based on performance. The analysis takes into consideration the investment cost, operation and maintenance (O&M) cost and fuel cost. This gives the financial details on the project investment, cost of running the plant and possible profitability on investment. Although, the depreciation cost was not considered in the maintenance cost evaluation.

$$\begin{aligned} &\text{The Net Present Value NPV}_{\text{SGT}} \\ &= \text{Total life cycle present value} - \text{Initial cash flow} \\ &= \$35633649.97 - \$29198750 = \$6434899.97 \end{aligned}$$

The NPV value shows that the plant investment is viable for the period of twenty years in operation. Although the estimate was done at the performance rating of approximately 70% based on the drop-in power output and efficiency. Also, the internal rate of return on investment was determined to be 12.40% by a numerical approximation technique.

Table 3. Result of the investment analysis of the gas turbine plant.

End of year	GT O & M Cost GTO & M (3% escalation rate) ($)	GT Fuel Cost GT_F (3% escalation) ($)	GT Annual Electricity Revenue GT_{RE} ($) (4% escalation due to tariff inc)	GT Annual net cash flow F_t ($)	Present value ($) $F_t/(1+d)^t$
1	1,079,178	5,390,142	9,194,272	2,724,952	2,477,229.090
2	1,112,275.37	5,561,376.85	9,562,042.88	2,888,390.66	2,387,099.719
3	1,145,643.631	5,728,218.156	9,944,524.595	3,070,662.809	2,308,769.029
4	1,180,012.94	5,900,064.7	10,342,305.58	3,262,227.939	2,234,402.698
5	1,215,413.328	6,077,066.641	10,755,997.8	3,463,517.833	2,151,253.312
6	1,251,875.728	6,259,378.64	11,186,237.71	3,674,983.346	2,076,261.777
7	1,289,432	6,447,160	11,633,687.22	3,897,095.223	1,998,510.371
8	1,328,114.96	6,640,574.8	12,099,034.71	4,130,344.952	1,930,067.735
9	1,367,958.409	6,839,792.044	12,582,996.1	4,375,245.648	1,853,917.647
10	1,408,997.161	7,044,985.805	13,086,315.94	4,632,332.978	1,788,545.551
11	1,451,267.076	7,256,335.379	13,609,768.58	4,902,166.127	1,720,058.29
12	1,494,805.088	7,474,025.44	14,154,159.33	5,185,328.797	1,651,378.598
13	1,539,649.241	7,698,246.204	14,720,325.7	5,482,430.254	1,589,110.219
14	1,585,838.718	7,929,193.59	15,309,138.73	5,794,106.419	1,528,787.973
15	1,633,413.879	8,167,069.397	15,921,504.28	6,121,020.998	1,464,359.091
16	1,682,416.296	8,412,081.479	16,558,364.45	6,463,866.671	1,408,249.819
17	1,732,888.785	8,664,443.924	17,220,699.02	6,823,366.316	1,348,491.367
18	1,784,875.448	8,924,377.241	17,909,526.99	7,200,274.295	1,295,013.362
19	1,838,421.712	9,192,108.559	18,625,908.06	7,595,377.794	1,241,074.803
20	1,893,574.363	9,467,871.815	19,370,944.39	8,009,498.209	1,190,118.605
Total	**29,016,753.13**	**145,083,765.70**	**273,787,754.10**	**99,687,235.27**	**35,633,649.97**

4. Conclusions

The thermo-economic assessments of this plant type provide a significant detail on the plants performances. The various performance indicators reveal that the SGT shows a good performance in terms of thermal efficiency, fuel consumption, power output, return on investment at lower ambient temperature with positive NPV and payback period. The analysis further indicates that the higher IRR and cash flow exceed the cost of investment, the higher the net cash flow to the investor.

Strategically, the analysis shows that the plant performs better at lower ambient temperature with greater air mass inflow. This is reflected in the net power generated and the net cash flow. The payback period was used to analyze investment risk and identify the breakeven point on investment. The payback decreases as the NPV increases as analyzed. Although there may be associated uncertainty with respect to the assumptions, this result provides a great insight on technical and economic perspective for energy system operators and investor in decision making and planning. It also provides critical information for power plants types and operational costs.

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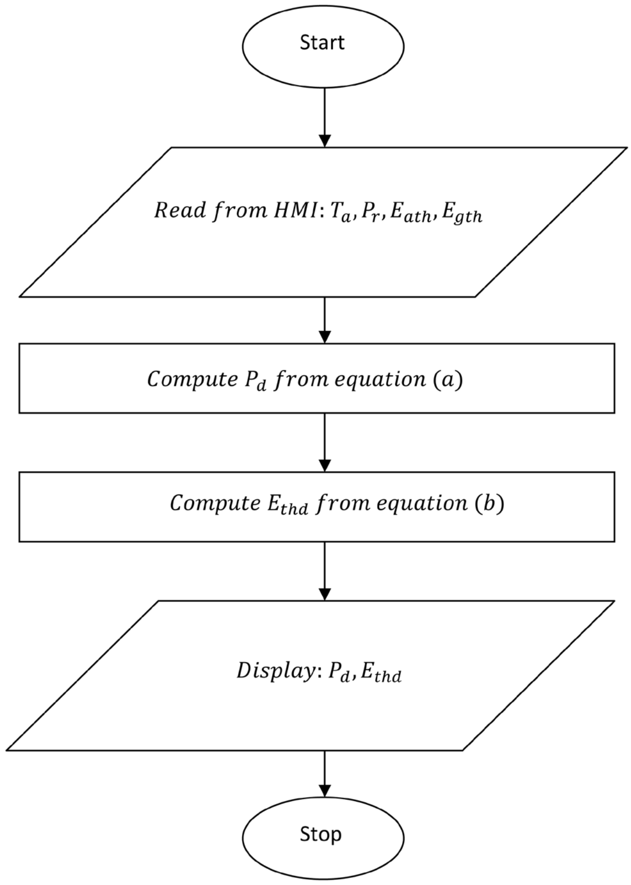
Appendix A. Flow Chart for Gas Turbine Performance Calculations



Nomenclature

C_p Specific heat constant pressure, kJ/kg·K
$\dot{m}$ Mass flaw rate, kg/s
T_3 Turbine inlet temperature, ˚C
T_2 Compressor exit temperature, ˚C
T_1 Compressor inlet temperature, ˚C
T_4 Turbine exit temperature, ˚C
m_a Air mass flow rate, kg/s
m_f Fuel mass flow rate, kg/s
C_{pa} Specific heat capacity of air, KJ/kg-K
CV Calorific value
W_{net} Net work, MW
η_{thGT} Thermal efficiency
NPV Net present value
F_0 Initial cash flow
F_t Annual net cash flow
d_t Discount rate