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Thermo-economic Optimization and Exergy Analysis of a Simple Cycle Gas Turbine Power Plant under High Ambient Temperature Conditions: A Case Study of Libya

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Abstract
The energy sector of Libya is dealing with an increase in demand and severe weather conditions that limit the generation of electricity. Most of the grid's electricity generation comes from gas turbines, but their thermodynamic output is diminished due to hot weather, averaging 303 K in the coastal regions. This research breaks from standard air assumptions and develops a more complex mathematical model to account for temperature-dependent specific heat changes, using the NASA 9-coefficient polynomials for more accurate predictions. A multi-objective parametric optimization was used to investigate the trade-offs between thermodynamic efficiencies and total cost rates. The primary results of the thermal simulation show efficiencies of 27.38%, 26.33% for exergy and thermic efficiencies, respectively. It also identifies the combustion chamber as the primary source of exergy destruction due to the destruction of an estimated 74.5% of the exergy. However, the economic analysis presents a financial cliff. While the efficiency is at an all-time optimum pushing toward a TIT of 1600 K], the relationship between efficiency and costs becomes exponential beyond $30 million/h. Therefore, the analysis identifies an optimal design region of r_p ≈ 16 and TIT ≈ 1350 – 1450 K where the LCOE is at 11.6 cents/kWh, given the opportunity cost of fuel $5/GJ. This analysis is of great Techno-Economic importance to the energy planners intending to modernize the power supply system of Libya.
Keywords: Gas Turbine; Exergy Analysis; Thermoeconomics; Libya; Pareto Frontier; NASA Polynomials; LCOE.

1. Introduction

1.1. Global and Local Energy Context

Gas turbines ~GT) are still core components of the global power generation industry. They are very particular because of their high power density, flexibility of operation, and relatively low initial costs compared to steam plants (1]. In the case of North Africa, specifically Libya, the General Electricity Company of Libya (GECOL) employs simple cycle gas turbines to satisfy both base and peak electrical demands. Considering the region's fossil fuel conserver, more gas makes turbines very appealing option economically (2]. However, the gas turbines average operating efficiency is very sensitive to climacteric changes. They are air breathing engines characterized by considerable drops in mass flow intake and lower density of the air as temperatures rise. Libya's climate ranges from Mediterranean to the desert and often has very warm summers where the temperature can exceed 40 C (313 K). This often results in severe derating of a power plants output where peak electrical load is required and is due to air conditioning (3]..

1.2. The Necessity of Exergy and Economic Analysis

In terms of thermodynamics, the first law of thermodynamics primarily focuses on determining the transformation of energy. Such measurement, however, does not give the exact location and the magnitude of the degradation of energy quality (or irreversibility) [4]. Thus, determining the lost potential useful work (exergy) is analyzed thermodynamically (second law of thermodynamics) [4]. Besides, thermodynamic analysis should also be optimized with respect to the economy as well. Generally, to enhance the efficiency of the given system, it should be subjected to increased pressure ratios and increased Turbine Inlet Temperature (TIT), which requires expensive superalloy and sophisticated cooling schemes. Hence, it will be appropriate to carry out a combined thermo-economic ((exergoeconomic)) analysis to find the optimum balance between fuel-saving (efficiency) and capital expenditure. [5]

1.3. Literature Review and Research Gap

A significant number of studies have analyzed the gas turbine (GT) performance. Bejan et al. [6] paved the way for thermal design optimization by creating cost correlations for GT components. In the same manner, Boyce [7] provided a great amount of engineering data of GT systems but did not put much focus on the economic optimization in the specific, high-temperature, and sub-regional climates. Most of the papers concerning Libya are heavily dependent on "Air Standard Assumptions" and consider the specific heat (cp) as a constant value. Such a simplification results in the introduction of substantial errors into the model of processes at high temperatures (T>1000 K). In addition to that, a great number of economic assessments take advantage of fuel prices with local subsidies, and as a result, the true economic feasibility of efficiency improvements is being misrepresented.

1.4. Research Objectives

This paper addresses these gaps by:

1. Developing a high-fidelity MATLAB model using NASA Polynomials for variable properties to ensure simulation precision.
2. Conducting a case study specifically for Libyan coastal conditions (101.3 kPa, 30°C).
3. Using international opportunity costs for fuel (5 $/GJ) to reflect the true economic value of natural gas exports [8].
4. Performing a multi-objective optimization to generate a Pareto Frontier, visualizing the cost-efficiency trade-off.

2. System Description and Assumptions

2.1. Physical Model

The system being analyzed is an open-cycle A simple gas turbine plant consisting of the three main elements:

- **Axial Flow Compressor (AC):** Raises the pressure of the ambient air to a specified pressure ratio (r_p).
- **Combustion Chamber (CC):** A place where natural gas is injected and burnt at constant pressure.
- **Gas Turbine (GT):** The one by expands the heated gas, generating mechanical power that is used to drive the compressor as well as the electrical generator.

2.2. Operating Conditions (The Libyan Case)

The purpose of these simulations was to represent a Libyan coastal city power plant, more specifically, a site like Tripoli or Benghazi. Climate conditions were held to a constant temperature of 303 K (30°C), which, like the other closed-loop systems, corresponds to a weighted average from the allocated periods of the year and is hotter than the standard ISO, 288 K. Firstly, Table 1 presents the thermodynamic properties which have been determined for the four predominant state points of the advanced Brayton cycle, which have been calculated with great accuracy for real gases using NASA polynomials.

Table 1: Initial parameters for the baseline simulation (Libyan Case Study).[3]

Parameter	Symbol	Value	Unit	Justification/Source
Thermodynamic Parameters				
Ambient Temperature	T_1	303	K	Average High Temp (Libya)
Ambient Pressure	P_1	101.3	kPa	Coastal Conditions
Pressure Ratio	r_p	10	-	Design Baseline
Turbine Inlet Temperature	TIT	1300	K	Material Limit

Air Mass Flow Rate	$\dot{m}_{air}$	50	kg/s	Unit Scale
Compressor Efficiency	η_c	87	%	Polytropic Estimate
Turbine Efficiency	η_t	89	%	Polytropic Estimate
Economic Parameters				
Specific Fuel Cost	C_f	5.0	$/GJ	Int. Opportunity Cost.**[8]**
Interest Rate	i	7.0	%	Regional Economic Data
Plant Life	n	23	Years	Standard Lifespan
Operating Hours	N	7000	h/yr	Baseload Operation

2.3. Modeling Assumptions

- The operation of the system is considered to be in a steady state for all components.
- The changes in kinetic and potential energies are considered to be negligible.
- It is assumed that there is a 2% pressure drop across the combustion chamber [1].
- Air and combustion gases are assumed to be ideal gases with temperature-dependent specific heats.
- For the calculation of chemical exergy, fuel is considered to be 100%methane.

3. Mathematical Modeling

The simulation model was created in MATLAB, using a modular programming design.

3.1. Thermodynamic Property Model (NASA Polynomials)

To ensure that results are accurate to a high degree, the thermodynamic properties of the system, i.e., specific heat capacity (Cp), enthalpy (h), and entropy (s∘), are calculated from the 9-coefficient polynomials given by NASA [9]. The formulas for any temperature T are:

$$\frac{C_p(T)}{R} = a_1T^{-2} + a_2T^{-1} + a_3 + a_4T + a_5T^2 + a_6T^3 + a_7T^4$$

$$\frac{h(T)}{RT} = -a_1T^{-2} + a_2T^{-1}\ln T + a_3 + \frac{a_4}{2}T + \frac{a_5}{3}T^2 + \frac{a_6}{4}T^3 + \frac{a_7}{5}T^4 + \frac{b_1}{T}$$

This technique lessens the errors that are characteristic of the "Cold Air Standard" assumption (C_p = 1.005 kJ/kg. K).

3.2. Energy Analysis

The first law of energy balance is applied for every component:

- **How a Compressor Works:** $\dot{W}_c = \dot{m}_{air}(h_2 - h_1)$
- **Heat Input:** $\dot{Q}_{in} = \dot{m}_{fuel} \cdot LHV = \dot{m}_{gas}(h_3 - h_2)$
- **Turbine Work:** $\dot{W}_t = \dot{m}_{gas}(h_3 - h_4)$
- **Net Power Output:** $\dot{W}_{net} = \dot{W}_t - \dot{W}_c$
- **Thermal Efficiency:** $\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{in}}$

3.3. Exergy Analysis

Exergy is a measure of the maximum possible work that can be obtained. Total specific exergy is evaluated as the addition of physical (ψ_{ph}) and chemical (ψ_{ch}) exergy parts.[4]:

$$\psi_{ph} = (h - h_0) - T_0(s - s_0)$$

The exergy efficiency is defined as:

$$\eta_{ex} = \frac{\dot{W}_{net}}{\dot{E}_{fuel}}$$

Where $\dot{E}_{fuel} \approx 1.06 \times LHV \times \dot{m}_{fuel}$ for natural gas.

3.4. Economic Model (Cost Functions)

The economic assessment estimates the cost level that goes hand in hand with plant ownership and operation. The Total Cost Rate ($\dot{C}_{total}$) is a combination of the Capital Investment Cost rate ($\dot{Z}$) and the Fuel Cost rate ($\dot{C}_f$): $\dot{C}_{total} = \dot{Z}_{tot} + \dot{C}_f$

Component purchase costs (Z_k) are figured out by using correlations from Bejan et al. [6] that are based on thermodynamic variables. One interesting thing to point out is that the turbine cost function has a term that is exponential with the inlet temperature:

$$Z_{GT} = 479.34 \cdot \dot{m}_g \cdot \frac{1}{0.93-\eta_t} \cdot \ln(r_p) \cdot [1 + \exp(0.025T_3 - 26.4)]$$

His phrase $\exp(0.025T_3)$ is essential because it represents the sudden and (TIT) going beyond metallurgical limits (typically >1400 K), which causes the need for materials that are not commonly used. The plant investments are converted into a yearly equivalent using the

$$CRF = \frac{i(1+i)^n}{(1+i)^n-1}, \quad \dot{Z} = \frac{Z_{total} \cdot CRF}{N_{hours}}$$

3.5. Model Validation

A validation study was conducted to check the trustworthiness of the MATLAB code, which was developed by comparing the simulation results with a benchmark gas turbine cycle problem from Çengel and Boles (Example 9-6) [10].

The validation case models a normal Brayton cycle with the input parameters as follows: $T_1 =$ 300 K, $P_1 =$ 100kPa, $r_p = 8$, $TIT = 1300$ K, $\eta_c = 85\%$,and $\eta_t = 90\%$:

Table 2: Validation of the present model against literature data [10].

Parameter	Present Work (Real Gas)	Reference [10] (Air Standard)	Deviation
Thermal Efficiency (η_{th})	25.84 %	32.60 %	*Due to gas properties*
Net Specific Work (w_{net})	296.8 kJ/kg	286.2 kJ/kg	3.7 %
Turbine Exit Temp (T_4)	929.9 K	780.7 K	*Due to $C_p(T)$ variation*

Note: Validation inputs: $T_1 = 300K, r_p = 8, TIT = 1300\ K, \eta_c = 85\%, \eta_t = 90\%.$

Discussion of Validation Results:

Table 2 shows that the model can correctly estimate performance trends, but changes in efficiency and exhaust temperature are noticed. These differences are explained from a scientific point of view by the difference in modeling fidelity:

1. **Working Fluid:** The reference [10] employs "Air-Standard Assumptions," treating the working fluid as air with constant properties. Conversely, the present model simulates actual combustion products (including $CO_2$and H_2O). Combustion gases possess a higher specific heat capacity (C_p) than pure air, resulting in higher turbine exit temperatures (T_4).
2. **Pressure Losses:** Unlike the reference, this model accounts for realistic pressure drops in the combustor, which naturally reduces thermal efficiency.
   Thus, the results from the developed code are considered more conservative and representative of actual power plant behavior.

4. Results and Discussion

4.1. Thermodynamic Cycle Representation

To confirm the simulation accuracy, thermodynamic processes under the Libyan coastal conditions ($T_1 = 303$ K) were visualized. Figure 1 shows the Temperature-Entropy (T-s) diagram of the baseline cycle. The expansion of internal irreversibilities is reflected in the deviation of the compression (1-2) and expansion (3-4) lines from the vertical isentropic path, as the model's polytropic efficiencies have been used to capture them. The area enclosed by the cycle stands for the net work output, which is considerably limited by the high ambient temperature that causes state point 1 to shift to a higher entropy level relative to standard ISO conditions.

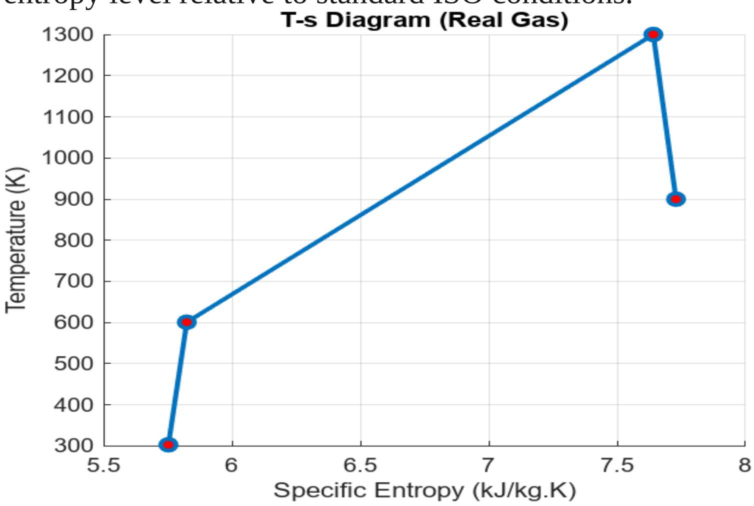

Figure 1: Temperature-entropy (T-s) diagram of the gas turbine cycle utilizing variable specific heats under Libyan operating conditions.

The detailed thermodynamic properties calculated at each main state point of the cycle are listed in Table 3.

Table 3: Calculated thermodynamic properties at the main state points for the baseline cycle.

State Point	Location	Temperature (K)	Pressure (kPa)	Specific Entropy (kJ/kg·K)
1	Compressor Inlet	303.00	101.30	5.7490
2	Combustor Inlet	600.84	1013.00	5.8205
3	Turbine Inlet (TIT)	1300.00	992.74	7.6373
4	Turbine Exit	899.87	102.31	7.7256

4.2. Baseline Performance Analysis

The very first set of simulations was performed at the baseline design point ($r_p = 10, TIT = 1300$ K). A complete 3E (Energy, Exergy, Economic) analysis of the results obtained is given in Table 4.

Table 4: Summary of energetic, exergetic, and economic analysis results (Base Case).

Metric	Symbol	Value	Unit	Description
Energy Analysis				
Net Power Output	$\dot{W}_{net}$	15.19	MW	First-Law Output
Thermal Efficiency	η_{th}	27.38	%	First-Law Efficiency
Exergy Analysis				
Exergy Efficiency	η_{ex}	26.33	%	Second-Law Efficiency
Total Exergy Destruction	$\dot{E}_{D,tot}$	42.51	MW	Total Irreversibility
Economic Analysis				
Total Cost Rate	$\dot{C}_{total}$	176,621	$/h	Capital + Fuel Costs
Levelized Cost of Electricity	$LCOE$	11.63	¢/kWh	Cost per Unit Energy

The recorded thermal efficiency of 27.38% is significantly lower than standard ISO-rated values (~30-32%). The reduction in performance is essentially the result of the high ambient temperature ($T_1 = 303$K) situation in the Libyan area. Higher inlet temperatures lower air density; thus, the mass flow rate is decreased and the specific work required by the compressor is increased [10].
Moreover, Figure 2 provides a direct comparison between First Law (Energy) and Second Law (Exergy) efficiencies. The closeness of these two figures indicates the effective energy conversion; however, the exergy efficiency is still a bit lower due to the inherent exergy destruction, most of all in the combustion process.

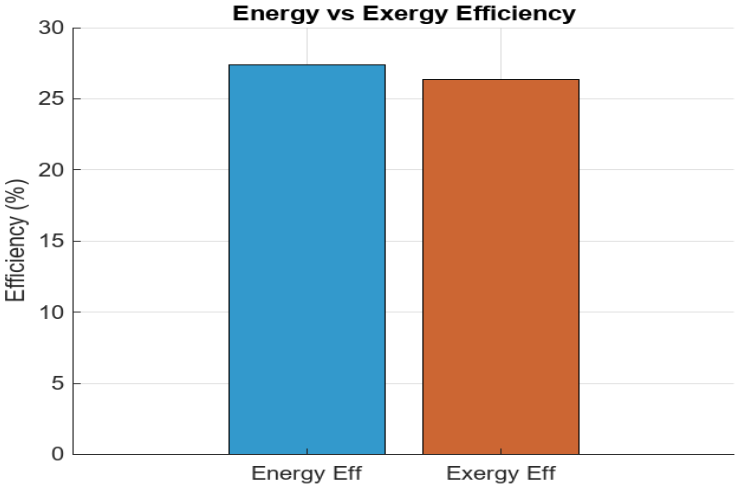

Figure 2: Comparison between Energy (Thermal) efficiency and Exergy efficiency at the baseline design point.

4.3. Exergy Destruction and Cost Distribution

In order to find out the main causes of inefficiency and economic loss, a component-level breakdown was done.

4.3.1. Exergy Destruction

Figure 3 shows the distribution of exergy destruction that is spread in the different parts of the plant.

- **Combustion Chamber:** The studied equipment is pinpointed by the analysis as the main source of the irreversibility, where the absolute destruction is 31.6 MW (close to 74.5 percent) of the destruction. This one huge value is due to the unrestrained chemical reaction and the big temperature differences between the reactants and the flame [11].

- **Turbine & Compressor:** These parts of the system are only responsible for very small portions of the destruction, thus indicating that purely aerodynamic improvements in these parts will have very little impact on the overall second-law efficiency.
- **Exhaust Losses:** Quite a significant volume of exergy is just thrown out to nature without being utilized. This fact points to the great potential that waste heat recovery technologies (e.g., Combined Cycle or Organic Rankine Cycle) have for the improvement of the sustainability of power generation in Libya.

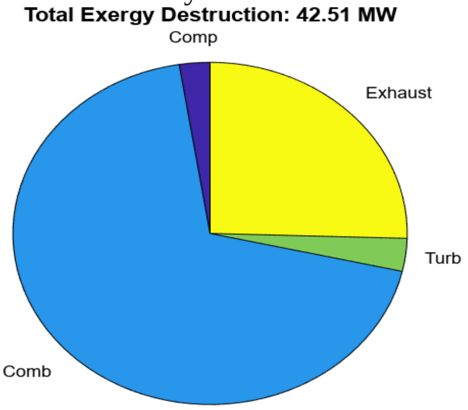

Figure 3: Percentage breakdown of total exergy destruction among power plant components.

4.3.2. Capital Cost Distribution

Moreover, Figure 4 shows the dissection of the capital cost rate ($\dot{Z}$) of the main components of the exergy analysis. The compressor is the component with the biggest capital cost rate. The turbine is the second most expensive component, while the combustor has a negligible financial impact. The difference results from the cost correlations that place a great emphasis on the air mass flow rate and pressure ratio in the compressor's cost function, thus reflecting the mechanical complexity of multi-stage axial compressors versus stationary combustion cans.

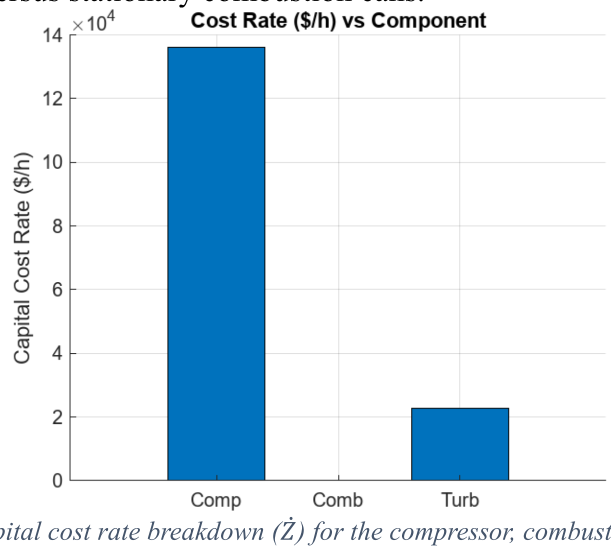

Figure 4: Capital cost rate breakdown ($\dot{Z}$) for the compressor, combustor, and turbine

4.4. Parametric Optimization

A thorough parametric study was implemented to analyze the effects of changing the Pressure Ratio (r_p: 5 to 25) and Turbine Inlet Temperature (TIT: 1100 K to 1600 K) on efficiency and cost.

4.4.1. Efficiency Trends

The results show that raising the Turbine Inlet Temperature (TIT) is always beneficial for the thermodynamic efficiency. As a matter of fact, increasing the TIT from 1100 K to 1600 K at a constant pressure ratio result in the thermodynamic efficiency going up from ~20% to more than 30%, which is a clear indication that high-temperature operation is beneficial from the thermodynamic point of view.

4.4.2. Cost Analysis and the "Cost Explosion"

Nevertheless, the economic analysis exposes a major limitation. Figure 5 (Optimization Landscape) illustrates the relationship between Total Cost Rate and Exergy Efficiency.

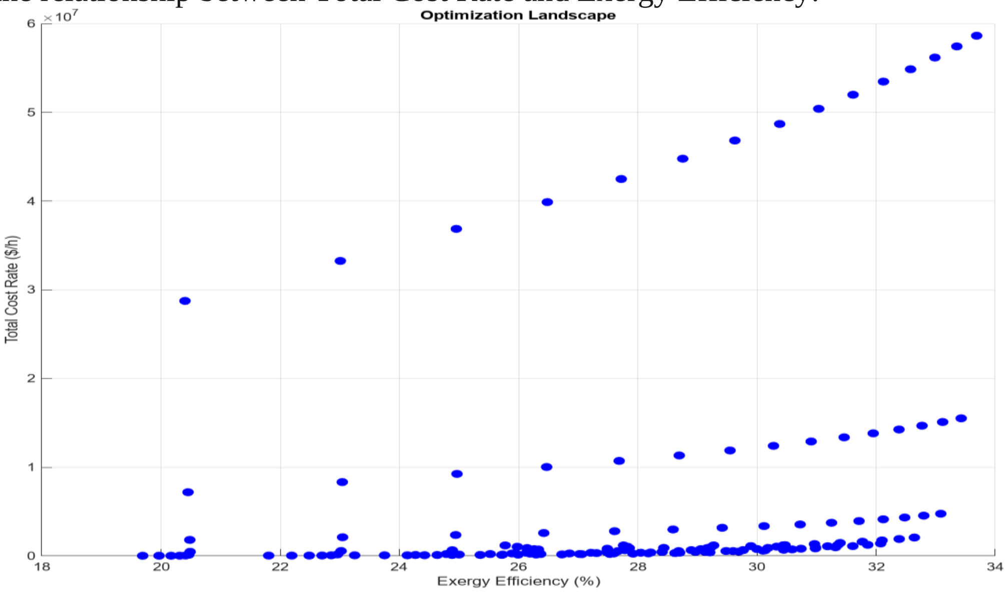

Figure 5: Thermo-economic optimization landscape illustrating the trade-off between exergy efficiency and total cost rate for varying pressure ratios and turbine inlet temperatures.

The scatter plot reveals two different regimes:

1. **The Linear Regime ($TIT < 1450$ K):** In this lower cluster, efficiency gains are accompanied by a moderate, linear increase in cost, representing the standard operating range for industrial gas turbines.
2. **The Exponential Regime ($TIT > 1500$ K):** As TIT approaches 1600 K, the cost rate increases rapidly, reaching values of more than $30 to $60 million/hour. This is a mathematical phenomenon driven by the term $\exp(0.025T_3)$ in the cost function, which physically represents the need for advanced single-crystal superalloys, thermal barrier coatings (TBC), and complicated cooling geometries necessary to be able to withstand such extreme environments [12].

4.5. Pareto Optimization and Selection of Optimal Design

The multi-objective optimization's primary aim is to reduce the total cost rate while increasing the exergy efficiency to a maximum. The Pareto Frontier, which is essentially the lower-right border of the cluster of the data in Figure 5, gives an understanding of the optimal trade-off solutions available to system designers. By looking at the precise simulation points on this frontier, three important conclusions are drawn:

- **Baseline Limit:** The baseline design ($r_p = 10, TIT = 1300$K) offers the least risky capital investment, but at the same time confines the exergy efficiency to around 26.3%.
- **Economic Infeasibility:** The maximum theoretical efficiency (η_{ex}33.7%) can only be achieved if the system is operated at $r_p = 25$ and $TIT = 1600$K, respectively. Nevertheless, this point is economically rejected, as a total cost rate of more than $58 million/h makes it impractical, mainly due to the exponential penalty in the material cost functions that drive the increase in cost.
- **Techno-Economic Optimum:** The "knee point" of the Pareto curve is the point where the ideal balance is most clearly represented, and one can find significant efficiency gains before the cost increases dramatically. The optimization results highlight a certain set-up with a Pressure Ratio (r_p) of 16.4 and a Turbine Inlet Temperature (TIT) of 1377 K as the best design for the Libyan case. At this moment, the plant is capable of an exergy efficiency of 30.13% with a total cost rate that is quite manageable ($\approx 6.4 \times 10^5$). This configuration achieves the baseline efficiency level with a 3.8%-point increase without going beyond the capital expenditure level that is considered prohibitive.

5. Conclusion

A detailed thermo-economic analysis was developed to achieve the optimal performance of a gas turbine under the difficult climatic and particular economic situation in Libya. Conventional air-standard models were replaced with variable specific heat capacity models (NASA polynomials), and a special fuel opportunity cost exergoeconomic analysis was also employed to achieve an improved level of fidelity. The key conclusions are:

1. **Penalty due to climate quantification:** he high T_amb $(303K)$ has a significant negative effect, restricting the peak values of the First-Law and Second-Law efficiencies, which are 27.38% and 26.33%, respectively. The capacity loss under the peak summer demand indicates an immediate demand for inlet air cooling techniques on future Libyan power plants.
2. **Exergy Bottlenecks:** Component-wise exergy analysis indicates that about 74.5% of the total exergy destruction occurs in the combustion chamber. Thus, transitioning from simple-cycle development to waste heat recovery (combined cycle) is the best thermodynamic approach for Libyan energy industries.
3. **Asymptotic Cost Performance:** The optimization study revealed that the benefit of increasing TIT above 1500K results in diminishing returns to efficiency (<2%) but an exponential spike in capital costs ($30M/hr rate) from a superimposed escalating cost of superalloys and infinitesimally small improvements on mission fuel burnt reciprocated.
4. **Strategic Recommendations:** Due to cost, adopting a cheap engine (low efficiency) diesel is an unconditional decision for the policy maker and the planner in Libya. The Pareto optimal design point is at r p 16 and TIT 1400 K, and it could reduce the LCOE to bring us 11.6 cents/kWh, guaranteeing a sustainable trade-off between OPEX (fuel) and CAPEX (equipment) in today’s market conditions.

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