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EXERGY ANALYSIS REVEALS TURBINE AS PRIMARY SOURCE OF IRREVERSIBILITY IN A 20MW GAS TURBINE POWER PLANT: A CASE STUDY FROM BAYELSA STATE, NIGERIA

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Abstract

This paper presents a comprehensive exergy analysis of a 20MW gas turbine power plant located in Imiringi, Bayelsa State, Nigeria, which chronically underperforms, with actual output of only 12MW, a 40% deficit. Using ten years of operational data from 2015 to 2024 and site-specific fuel composition, the study quantifies exergy destruction in each component. It compares First Law (energy) and Second Law (exergy) efficiencies. Contrary to established literature, in which the combustion chamber typically accounts for irreversibility of about 70% to 80%, this analysis reveals a unique observation: the turbine is the single largest source of exergy destruction at 85.77 MW, followed by the combustion chamber at 78.32 MW and the compressor at 32.86 MW. While thermal efficiency is 53.79%, exergy efficiency is 2.49%. This indicates that over 97% of the fuel's work potential is destroyed. These

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findings shift optimization focus from combustion improvements to critical turbine mechanical degradation, providing plant operators with unambiguous priorities for targeted maintenance intervention.

NOMENCLATURE

S/NO	SYMBOL	DESCRIPTION	UNIT
1	Ė	Exergy rate	MW
2	Ĺ	Irreversibility (exergy destruction) rate	MW
3	ṁ	Mass flow rate	kg/s
4	T	Temperature	K
5	P	Pressure	Bar
6	H	Efficiency	%
7	E	Specific exergy	KJ/Kg
8	H	Specific enthalpy	KJ/Kg
9	S	Specific entropy	KJ/Kg.K
10	Xi	Flow rate per mole of mixture	kmol/s

SUBSCRIPTS:

O, - Dead state
1,2,3,4 - State point.
C - Compressor.
t. - Turbine.
CC - Combustion chamber.
Ph - Physical.
Ch, - chemical

Introduction

The pursuit of efficient power generation remains a pressing global challenge, with the International Energy Agency projecting a nearly 50% increase in energy demand by 2050. (IEA, 2023). Gas turbines have gained strategic importance due to their compact design, operational flexibility, and lower emissions compared to coal-fired plants (Boyee 2012), (Saravanamuttoo 2017). In Nigeria, despite proven natural gas reserves exceeding 209 trillion cubic feet (NNPC 2022), Effective power generation capacity fluctuates between 4,000 and 5,000 MW, which is grossly inadequate for a population exceeding 200 million (Bank 2022) (NERC 2022).

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This deficit often necessitates a reliance on less efficient, smaller-scale generating units and exacerbates energy poverty across various sectors. This substantial disparity between potential and actual power output underscores an urgent need for rigorous thermodynamic assessments to identify and mitigate inefficiencies within existing power infrastructure, particularly gas turbine power plants. Exergy analysis, a robust thermodynamic methodology based on both the first and second laws of thermodynamics, offers a comprehensive approach to quantify energy degradation and pinpoint the true sources of irreversibility within complex energy systems (M. N.-M. Elwardany 2023). Unlike conventional energy analyses that focus solely on energy conservation, exergy analysis provides a crucial metric for evaluating energy quality and the magnitude of energy destruction, thereby offering a more nuanced understanding of system performance (Adumene 2016). This methodology is particularly vital for gas turbine power plants, where significant exergy losses often occur in components like combustion chambers and turbines (Edward 2023) (Abdulsitar 2026). Previous studies have consistently identified the combustion chamber as the primary contributor to exergy destruction in gas turbine systems, frequently accounting for over 50% of total exergy loss (M. N.-M. Elwardany 2023) (Ogbe 2017). However, the specific operational conditions, component design, and fuel characteristics of individual plants can significantly alter this distribution, necessitating site-specific evaluations to accurately identify dominant irreversibility sources. (Abdulsitar 2026). This is critical for optimizing system performance and ensuring the sustainability of energy infrastructure, especially in regions with burgeoning energy demands and existing operational inefficiencies (M. N.-M. Elwardany 2023) (Ogbe 2017). Therefore, applying exergy analysis enables a detailed understanding of where thermodynamic energy value is lost, guiding targeted interventions to improve the efficiency and sustainability of power generation (M. A. Elwardany 2024). The present study employs this rigorous analytical framework to investigate a 20 MW gas turbine power plant in Bayelsa State, Nigeria, to precisely identify the dominant sources of exergy destruction and propose targeted interventions to enhance its operational efficiency.

The Gas Turbine Power Plant in Imiringi, Bayelsa State, exemplifies this crisis. With an installed capacity of 20MW from one unit, with a second unit on standby. Actual daily output rarely exceeds 12MW, a 40% deficit attributed to blade erosion, fouling, seal wear, and mechanical degradation. Traditional performance evaluation relies on First Law (Energy) analysis, which quantifies energy conservation but ignores quality, treating 1 MJ of exhaust heat as equivalent to 1 MJ of electrical work (Cengel 2015); (Dincer 2020).

Exergy analysis, grounded in the Second Law, overcomes this limitation by measuring maximum useful work obtainable as a system reaches equilibrium with its environment (Kotas 2013). Exergy is destroyed in real processes due to irreversibility, combustion,

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Prof. Saeid Eslamian [IRAN]

friction, and finite temperature differences, providing a true measure of inefficiency (Bejan 2016), (Moran 2014).

Literature consistently identifies the combustion chamber as the dominant source of irreversibility in gas turbines. 81.1% of total exergy destruction in the combustion of a Jordanian plant. Ibrahim et al. (2017) confirmed similar patterns in regenerative cycles. (Ojijiagwo 2016) found comparable results, with over 70% at Afam Power Station in Nigeria. However, these studies were one-off evaluations, leaving a knowledge gap regarding plant-specific degradation patterns.

This study addresses that gap through a longitudinal exergy analysis of the Gas Turbine Plant using ten years of operational data from 2015 to 2024. The objectives are as stated below: (1) quantify exergy destruction in each component. (2) compare energy and exergy efficiencies and (3) provide actionable recommendations based on component-level irreversibility ranking.

THEORETICAL FRAMEWORK

Energy (First Law) Analysis

For a steady flow system, the energy balance is:

$\dot{Q} - \dot{W} = \dot{m}(h_2 - h_1)$ (1)

Thermal efficiency is defined as:

$$\text{Ideal thermal efficiency} = 1 - \frac{c_p(T_4 - T_1)}{c_p(T_3 - T_2)} = 1 - \frac{T_1\left(\frac{T_4}{T_1} - 1\right)}{T_2\left(\frac{T_3}{T_2} - 1\right)} \quad (2)$$

While essential, First Law analysis treats all energy as equivalent, masking internal irreversibility. (Dincer 2020).

2.2 Exergy (Second Law) Analysis

Exergy represents the maximum useful work obtainable in a system that interacts with its environment. Total exergy comprises physical and chemical components:

$$E = E_k + E_p + E_p h + Ech \quad (3)$$

For an ideal gas, specific physical exergy is (Bejan 2016):

$$\text{Exph} = T_o(S_o - S_1) - (h_o - h_1) = (h_1 - T_o S_1) - (h_o - T_o S_o) \quad (4)$$

From, Eph = Ext = Exp

$$\text{Exph} = C_p(T - T_o) - T_o\left[C_p \, In\frac{T}{T_o} - R \, In\frac{P}{P_o}\right] \quad (5)$$

Chemical exergy for a fuel mixture, (Moran 2014):

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Prof. Saeid Eslamian [IRAN]

$$Ex_{chm} = \sum_i xiEx_{chi} + RT_o \sum_i xi\ In\, xi \quad (6)$$

The exergy balance for a control volume is:

$$E_{in} - E_{out} - E_{destroyed} = 0 \quad (7)$$

Exergy efficiency (Second Law efficiency) is:

$$\eta = \frac{E_{useful,out}}{E_{total,in}} \times 100 \quad (8)$$

METHODOLOGY

Plant Description and Data Collection

The gas turbine plant in Imiringi operates on a simple open cycle configuration. Table 1 presents the mean operating parameters from 2015-2024 log sheets.

Table 1: Mean Plant Operating Parameters (2015-2024)

S/NO	COMPONENT	PARAMETER	VALUE
1	Compressor	Inlet temp. T_1	295.3k
		Outlet temp. T_2	391.3k
		Inlet pressure P_1	1.013bar
		Outlet pressure P_2	6.1bar
		Air mass flow	260kg/s
2	Combustor	Outlet temp. T_3	782.3K
		Fuel flow rate	1.5kg/s
3	Turbine	Outlet temp. T_4	476k

FUEL COMPOSITION

Natural gas composition (Table 2) was obtained and used for chemical exergy calculations. based on standard chemical exergy values from (Kotas 2013).

Table 2: Natural Gas Composition

S/NO	COMPONENT	FORMULAR	MOLE (%)	STANDERED CHEMICAL EXERGY (KJ/mol)
1	Methane	CH_4	88.0	836,510
2	Ethane	C_2H_6	4.9	1,504,360
3	Propane	C_3H_8	2.0	2,163,190
4	Butane	C_4H_{10}	0.6	2,818,930
5	Carbondioxide	CO_2	4.4	20,140
6	Nitrogen	N_2	Nil	720

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COMPONENT EXERGY ANALYSIS

3.3.1 Compressor Chamber.

$$\therefore E_{xc} = m_{air}(h_2 - h_1) - T_1 m_{air}(S_2 - S_1) \quad (9)$$

$$I_{c,irr} = W_c - \left[E_{xc} + I_{mc}\right] \quad (10)$$

3.3.2 Combustion Chamber

$$\therefore E_{x_c} + E_{x_f} = E_{x_{cc}} + E_{x_{loss}} \quad (11)$$

$$E_{x_{cc}} = E_{xc} + E_{x_f} - E_{x\,loss} \quad (12)$$

3.3.3 Turbine Chamber

$$E_{x_{cc}} = E_{x_T} + W_T + E_{x\,loss} \quad (13)$$

$$\therefore E_{x_{loss}} = E_{x_{cc}} - E_{xT} - W_T \quad (14)$$

ASSUMPTIONS

Steady-state operation (Troff 2021)
Negligible kinetic and potential exergy
Air inlet exergy = 0 (reference state)
Adiabatic components
Ideal gas behavior with temperature-dependent specific heats (Boyee 2012).

Component-Level Exergy Destruction

Table 3 presents the detailed exergy analysis results.

Table 3: Component Exergy Destruction

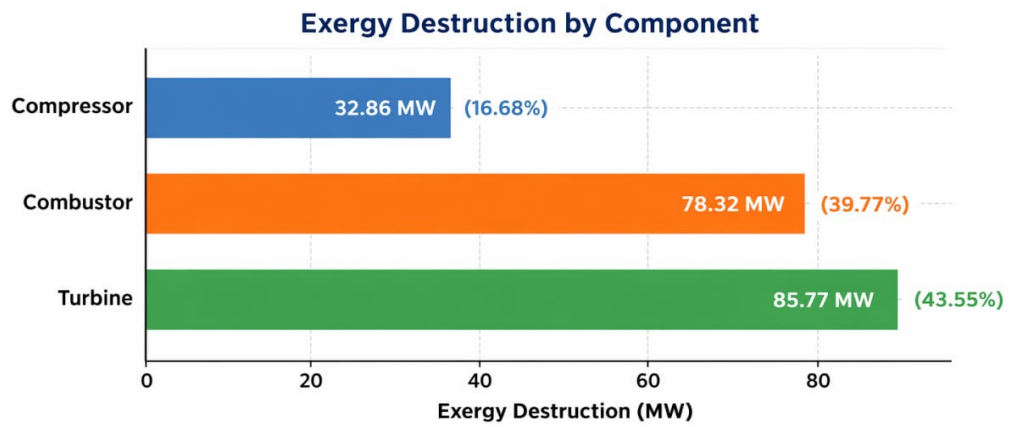
S/NO	COMPONENT	PARAMETER	VALUE(MW)
1	Compressor	Inflow Exergy	0
		Outflow Exergy	101.827
		Mechanical Irreversibility	1.700
		Process Irreversibility	6.456
		Total Irreversibility	8.154
2	Combustor	Input Exergy (air)	101.827
		Input Exergy (fuel)	126.420
		Total Input	228.247
		Output Exergy	153.977
		Exergy Loss	74.270
3	Turbine	Inflow Exergy	153.977
		Internal Power Generated	84.050

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Prof. Saeid Eslamian [IRAN]

S/NO	COMPONENT	PARAMETER	VALUE(MW)
		Mechanical Irreversibility	0.841
		Effective Power Output	83.209
		Outflow Exergy (exhaust)	78.083
		Total Irreversibility	7.314
		Net Power Output	75.894

The turbine emerges as the largest source of exergy destruction at 85.77 MW (combining internal and mechanical irreversibility), followed by the combustion chamber at 78.32 MW and the compressor at 32.86 MW. This finding contradicts established literature, where the combustor typically accounts for 70-80% of total irreversibility (Cengel 2015), (Aljundi 2009)

Figure 1: Exergy Destruction Distribution by Component



This figure illustrates the distribution of exergy destruction among major components. Turbine: 85.77 MW (43.55%), Combustor: 78.32 MW (39.77%), Compressor: 32.86 MW (16.68%).

Table 4: Overall Performance Indicators

S/NO	PARAMETER	VALUE
1	Thermal Efficiency (First Law)	53.79%
2	Exergy Efficiency (Second Law)	2.49%
3	Fuel Utilization Efficiency	13.55%
4	Heat Rate	6.343 MJ/kWh
5	Work Ratio	1.04

The dramatic disparity between thermal efficiency (53.79%) and exergy efficiency (2.49%) reveals the true thermodynamic state of the plant. over 97% of the fuel's work potential

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is destroyed before conversion to electricity. This explains precisely why a 20MW unit struggles to deliver only 12MW.

DISCUSSION OF FINDINGS

The identification of the turbine as the primary loss source represents a critical departure from conventional perception. In typical gas turbine systems, combustion irreversibility dominates due to the highly non-equilibrium chemical reaction and heat transfer across large temperature differences (Bejan 2016). However, this plant presents a unique perception that Turbine chamber losses (85.77 MW) are greater than Combustor chamber losses (78.32 MW) while the compressor chamber produces the least losses (32.86MW). However, these losses indicate severe mechanical degradation in the expander section, which is likely attributable to the Blade erosion and fouling in the Niger Delta's humid, dusty environment, accelerating degradation, Increased tip clearances, and Age-related wear, which increases leakage losses, Seal wear, which compromises sealing, and foreign object damage, which includes Historical damage from ingested debris. The compressor, at 32.86 MW losses, appears comparatively healthier, though still significant.

Table 5: Comparison with Literature

S/NO	Study	PLANT LOCATION	COMPRESSOR LOSS	COMBUSTION LOSS	TURBINE LOSS
1	Aljundi (2009)	Jordan	8.8%	81.1%	10.1%
2	Ojijiagwo and others. (2016)	Afam, Nigeria	10%	73%	15%
3	This study	Bayelsa, Nigeria	32.86MW (19.1%)	78.32MW (38.6%)	85.77MW (42.3%)

The unique distribution in this study underscores the importance of plant-specific analysis rather than relying on generalized literature values (Adumene 2016).

IMPLICATIONS FOR PLANT OPERATION

This analysis transforms abstract thermodynamic theory into a quantified roadmap for intervention. Plant operators now have unambiguous priorities:

Immediate turbine inspection and overhaul – Address the 85.77 MW loss source

Combustion optimization – Reduce 78.32 MW losses through air-fuel ratio tuning

Compressor maintenance – Address fouling and blade cleaning

Without exergy analysis, a First Law approach would flag exhaust heat as the primary loss, potentially leading to misplaced investment in waste-heat recovery while ignoring the more critical turbine degradation.

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CONCLUSIONS

The exergy analysis of a 20MW gas turbine plant in Bayelsa State, Nigeria, reveals that the turbine is the largest source of exergy destruction at 85.77 MW, which is contrary to established literature where combustor dominates. Exergy efficiency is a stark 2.49% versus thermal efficiency of 53.79%, indicating over 97% of fuel work potential is destroyed. Combustion chamber losses total 78.32 MW; compressor losses 32.86 MW. The 40% output deficit from the 20MW installed to the 12MW actual is directly attributable to these irreversibilities, noting that Exergy analysis provides superior diagnostic capability over traditional First Law methods. The study successfully demonstrates that plant-specific component-level exergy destruction ranking is essential for a targeted maintenance optimization approach, as the literature would have missed the critical turbine degradation.

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