Performance Evaluation of Gas Turbines: A Critical Review of Methods, Real-World Challenges, and a Proposed Unified Framework

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ABSTRACT

The gas turbine is a powerful source of electricity in many developing countries. However, it has not always performed according to OEM recommendations, especially under hot and humid conditions and during frequent cycling. This critical review includes over 50 peer-reviewed studies (2009–2024) on the performance of gas turbines under ambient conditions, fuel quality, component degradation, cycling penalties, and methodological limitations. It highlights important issues, including limited field data from tropical and sub-Saharan Africa and reliance on OEM-controlled data. Field and laboratory studies from Nigeria, Egypt, Algeria, and Indonesia show that deviations from the ISO 15°C can reduce net power output by 1.37%–2.5% per °C, and combining degradation can lead to 10%-30% power loss in ageing plants. The study suggests a Unified Performance Evaluation Framework based on thermodynamic, operational, and economic factors.

Keywords: gas turbine performance; compressor fouling; ambient conditions; degradation mechanisms; fuel variability; flexible cycling; tropical climate; performance evaluation framework

INTRODUCTION

Gas turbines have been the workhorse of thermal power generation for decades. The advantages include smaller footprint, rapid start up, flexibility in fuel mix, and integration with combined-cycle plants. But, if you have worked with a GT plant running, especially in Sub-Saharan Africa, the Middle East, or South-East Asia, you will quickly find out that the numbers printed on the nameplate do not always match the real outcomes of the plant. This lack of compliance between the design and the application is not an academic curiosity: in places like Nigeria where more than 80% of electricity is produced by gas turbines (Esan et al., 2019), such as Nigeria, the plethora of underperforming plants have direct impact on the reliability of the grid, consumption, and energy security.

The thermodynamic principles of the Brayton cycle are well known (Oyedepo et al., 2014). What is not well known, but, is how ambient conditions, fuel quality, degradation of components, and cycling behaviours contribute to the performance deficits observed in real life. Review articles by technical disciplines show a tendency to isolate them, such that papers on compressor fouling seldom address humidity or cycling effects, papers on hydrogen co-firing rarely address real world degradation, and many analyses rely on OEM data that may not accurately reflect the state of an ageing fleet (Farhat & Salvini, 2022).

In this review, it has four main objectives: (1) critically assessing the methods currently used to assess GT performance under real conditions; (2) assessing the combined effect of ambient conditions, fuel quality, and degradation on efficiency and output; (3) comparing OEM theoretical benchmarks with independent field studies and identifying inconsistencies; and (4) proposing a Universal Performance Evaluation Framework (UPEF) applicable to operators of GTs operating in different climates and operating conditions. The paper is

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structured to address these objectives as a series of papers that begin with a thermodynamic basis, then each factor affecting GT performance and ending with the proposed framework and future directions.

Gas turbine performance in practical operation is shaped by multiple interdependent factors that extend well beyond the idealised assumptions embedded in standard OEM performance specifications. Ambient conditions determine the thermodynamic quality of the working fluid, fuel quality governs combustion behaviour and firing temperature control, component degradation alters aerodynamic and thermal efficiencies, and operational cycling introduces non linear life consumption and transient penalties. These influences do not act independently; rather, they interact to define the actual performance delivered by a gas turbine at any given time. Figure 1 illustrates these primary performance drivers and their combined influence on key output and efficiency metrics under real operating conditions, providing a conceptual foundation for the critical review that follows.

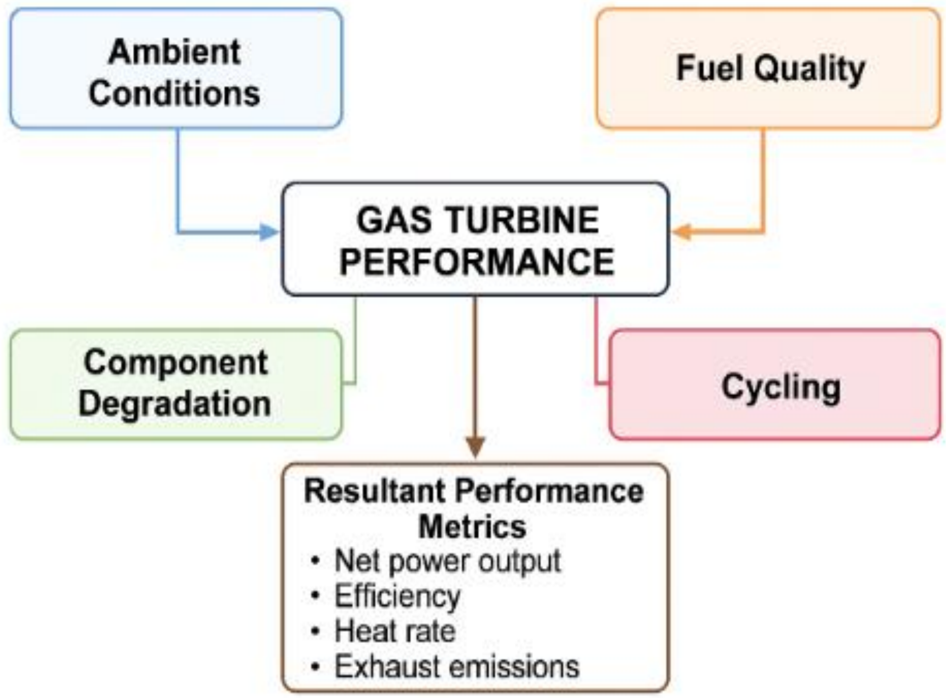

Figure 1. Schematic of Gas Turbine Performance Influences under Real Operating Conditions

Thermodynamic Foundations and Standard Performance Benchmarks

Before critiquing how performance is measured, it is worth establishing what is being measured. A gas turbine operates on the Brayton cycle, drawing in atmospheric air, compressing it, mixing it with fuel in the combustor, expanding the hot gas through the turbine, and exhausting the products. The useful output is the net work after accounting for the compressor work, which can consume 60–65% of the turbine's gross output (Kurz & Brun, 2009). This high work fraction is the reason GT performance is so sensitive to small changes in compressor efficiency or inlet conditions. A 5% reduction in compressor efficiency has a disproportionately large effect on net output compared with the same loss in the turbine section (Kurz & Brun, 2009), making compressor health one of the most critical variables in any performance evaluation exercise.

Standard performance is specified at ISO conditions: 15°C ambient temperature, 60% relative humidity, sea level pressure, and no inlet or exhaust pressure losses. These conditions rarely, if ever, occur simultaneously at a real plant site. The ISO datum exists for contractual and comparative purposes, but it has become something of a convenient fiction in the performance evaluation literature. Manufacturers present performance curves at ISO conditions; operators experience performance at 35°C and 80% relative humidity; and the difference between these two data points is where much of the practical knowledge gap lies. **Table 1** contrasts the ISO standard reference conditions commonly used in OEM performance declarations with typical operating conditions reported for gas turbine plants in hot and humid regions, highlighting the resulting performance implications documented in field studies.

Table 1. ISO Standard Performance Conditions versus Real-World Tropical Operating Conditions

Operating Parameter	ISO Standard Condition	Typical Tropical / Hot-Climate Conditions	Primary Performance Implication	Representative References
Ambient Temperature (°C)	15 °C	30–45 °C common; peaks above 45 °C in arid and coastal regions	Reduced inlet air density leads to chronic net power output loss of approximately 1.37–2.5 % per °C above ISO	Lebele-Alawa & Jo-Appah (2015); Dabwan et al. (2023); Egware & Ighodaro (2023)
Relative Humidity (%)	60 %	70–90 % common in equatorial and coastal regions	Increased moisture content reduces compressor efficiency and accelerates fouling; additional power loss beyond temperature effect	Shukla & Singh (2014); Sánchez Cabarcas et al. (2024)
Ambient Pressure / Altitude	Sea level (101.325 kPa)	Reduced pressure at inland plateaus; coastal but thermally expanded air	Lower air mass flow further reduces power output and compressor surge margin	Oyedepo et al. (2014); Kazemiani-Najafabadi & Amiri Rad (2021)
Inlet Air Quality	Clean, controlled test-cell air	High particulate loading: dust, salt aerosols, industrial pollutants	Accelerated compressor fouling, faster performance degradation between wash intervals	Kurz & Brun (2009); Emenike et al. (2025)
Fuel Composition	Stable, specification-grade natural gas	Variable gas composition; presence of heavier hydrocarbons or inerts	Variations in LHV and Wobbe Index lead to output deviation and combustion instability	Oyedepo et al. (2014); Ighodaro et al. (2020)
Operating Profile	Steady baseload operation	Frequent starts, stops, and part-load operation	Increased heat rate, reduced efficiency, accelerated component life consumption	Farhat & Salvini (2022); Bagga et al. (2023)
Machine Condition	Clean, post-overhaul baseline	Partially fouled or aged components typical of in-service units	ISO correction factors systematically overestimate achievable field performance	AYADJU & Ujevwerume (2022); Agbadede & Kainga (2025)

The key thermodynamic performance indicators tracked in the literature include thermal efficiency (or heat rate), net power output, specific fuel consumption (SFC), compressor pressure ratio, and turbine inlet temperature (TIT). Exergy analysis adds a second-law lens, allowing identification of the components responsible for the greatest thermodynamic irreversibilities. A comprehensive exergy analysis of a gas turbine power plant in Assiut, Egypt, found that the combustion chamber accounted for 85.22% of total exergy destruction, followed by the compressor at 8.42% and the turbine at 6.36%, with overall energy and exergy efficiencies of 28.8% and 27.17%, respectively (Elwardany et al., 2024). These figures are substantially lower than the values published in OEM performance catalogues, illustrating the systematic gap between theoretical and operational benchmarks that this review seeks to address.

To ensure clarity and consistency across the diverse body of literature reviewed in this study, the key performance indicators (KPIs) commonly used to characterise gas turbine (GT) behaviour must be explicitly defined and contextualised.

These indicators originate from a combination of first law thermodynamic analysis, OEM performance testing protocols, and, increasingly, second law (exergy based) diagnostics. However, their definitions, measurement bases, and interpretive value vary substantially between manufacturer documentation and independent field studies, particularly under non ISO operating conditions. Table 2, summarises the principal GT performance indicators referenced throughout this review, together with their physical meaning, diagnostic value, known limitations in field application, and representative literature sources.

Table 2. Key Performance Indicators Used in Gas Turbine Performance Evaluation

Performance Indicator	**Definition / Description**	**Primary Performance Insight**	**Typical Measurement Basis**	**Key Limitations in Field Application**	**Representative References**
Net Power Output (MW)	Electrical power delivered at generator terminals after accounting for internal losses	Direct indicator of plant capacity and revenue potential	Generator electrical output, sometimes ISO-corrected	Strongly affected by ambient temperature, fouling, auxiliary loads; ISO corrections may under-predict losses in tropical climates	Oyedepo et al. (2014); Lebele-Alawa & Jo-Appah (2015); AYADJU & Ujevwerume (2022)
Thermal Efficiency (%)	Ratio of net electrical output to fuel energy input (typically LHV-based)	Overall energy conversion effectiveness	Fuel flow rate, LHV, net output	Conceals component-level irreversibilities; sensitive to fuel composition variability	Kurz & Brun (2009); Elwardany et al. (2024)
Heat Rate (kJ/kWh or Btu/kWh)	Fuel energy input required per unit of electricity generated (inverse of efficiency)	Fuel cost and operational efficiency indicator	Fuel flow and net output	Averaging masks cycling and start-up penalties; affected by measurement uncertainty	Oyedepo et al. (2014); Esan et al. (2019)
Specific Fuel Consumption (SFC)	Fuel mass or volumetric flow per unit of power output	Short-term operational efficiency and dispatch metric	Fuel flow and generator load	Highly load-dependent; not directly comparable across sites or climates	Lebele-Alawa & Jo-Appah (2015); Shukla & Singh (2014)
Compressor Pressure Ratio (—)	Ratio of compressor discharge pressure to inlet pressure	Indicator of compressor aerodynamic health and operating point	Inlet and outlet pressure measurements	Fouling shifts operating line non-linearly; pressure losses may be misattributed to degradation	Kurz & Brun (2009); Meher-Homji et al. (2013)
Turbine Inlet Temperature (TIT)	Temperature of working fluid entering the turbine section	Proxy for firing temperature and thermal loading	Estimated via exhaust temperature and performance models	Rarely measured directly; OEM estimations may obscure local hot spots	Aldi et al. (2019); Salilew et al. (2022)
Exergy	Ratio of useful work output to fuel	Quantifies irreversibilities	Full thermodynamic	Data-intensive; sensitive to dead-state	Egware & Ighodaro (2023);

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Efficiency (%)	exergy input	and true thermodynamic losses	and chemical exergy analysis	assumptions	Elwardany et al. (2024)
Equivalent Operating Hours (EOH)	Operating hours adjusted for cycling severity and load	Component life consumption and maintenance planning metric	OEM-defined weighting of starts, stops, and load levels	Vendor-specific definitions; may underestimate damage from flexible operation	Farhat & Salvini (2022); Bailera et al. (2020)

Combined-cycle configurations complicate this picture further. The exhaust energy recovery in a heat recovery steam generator (HRSG) improves overall plant efficiency to 55–60% in modern installations, compared with 30–38% for open-cycle operation, but the bottoming cycle introduces additional sensitivity to GT exhaust temperature (Adam et al., 2024). This means that performance degradation in the GT is amplified at the plant level, a factor that many single-system analyses overlook. Pattanayak et al. (2017) demonstrates through full combined cycle exergy analysis that GT performance degradation propagates directly into bottoming cycle inefficiencies and reduced overall plant efficiency.

Ambient Conditions: A Persistent And Underestimated Driver

Temperature Effects

The relationship between ambient temperature and GT power output is well documented but remains underappreciated in its practical severity. Since the compressor draws in air at ambient conditions, higher temperatures mean lower air density, reduced mass flow through the machine, and diminished net output. This is not a second-order effect.

Field data from a gas turbine plant in equatorial southern Nigeria showed that a one-degree Celsius rise in ambient temperature produced a 1.37% reduction in net power output, a 1.49% reduction in thermal efficiency, a 2.16% increase in heat rate, and a 2.17% increase in specific fuel consumption (Lebele-Alawa & Jo-Appah, 2015). These are compounding effects: a plant operating at 35°C rather than the ISO standard of 15°C faces a chronic, daily performance deficit that cannot be addressed through operational adjustments alone.

While the inverse relationship between ambient temperature and gas turbine performance is well established theoretically, its magnitude under real operating conditions varies considerably depending on machine type, site climate, and degradation state. Field measurements from hot and tropical regions consistently demonstrate that temperature induced derating is more severe than that implied by generic OEM correction curves, particularly for ageing or fouled machines.

Table 3, summarises reported ambient temperature sensitivity values from representative field and validated analytical studies, expressed as percentage change in performance per degree Celsius increase above reference conditions.

Table 3. Reported Ambient Temperature Sensitivity of Gas Turbine Performance in Field and Case-Study Literature

Study / Location	**Gas Turbine Type / Capacity**	**Ambient Temperature Range (°C)**	**Net Power Output Sensitivity**	**Efficiency / Heat Rate Impact**	**Notes on Operating Context**
Lebele-Alawa & Jo-Appah (2015), Southern Nigeria	Industrial GT, ~25–30 MW class	~25–35 °C	**−1.37 % per °C**	−1.49 % efficiency; +2.16 % heat rate per °C	Equatorial rainforest climate; high humidity; field data
Egware &	153 MW	20–40 °C	**≈−1.5 to**	Progressive	Sustainability-oriented

Ighodaro (2023), Nigeria	open-cycle GT	(simulated & field-validated)	**−2.0 % per °C**	decline in exergy efficiency	exergy analysis under hot conditions
Dabwan et al. (2023), Gulf region	Intercooled GT-CCGT	15–45 °C	**≈−1.0 to −2.2 % per °C**	Heat rate increase of ~1–2 % per °C	Extreme hot-climate case with inlet cooling comparison
Oyedepo et al. (2014), Nigeria	Grid-connected GT plant	~18–35 °C	**≈−1.5 to −2.3 % per °C**	Heat rate penalties increase nonlinearly	Longitudinal performance and economic assessment
AYADJU & Ujevwerume (2022), Nigeria	GE Frame 9E (~113 MW rated)	20–38 °C	**Observed cumulative loss ~20–30 %** (implied ≈−1.2 to −2.0 % per °C)	Significant efficiency shortfall vs OEM	Ageing units; degraded condition; field comparison
Kazemiani-Najafabadi & Amiri Rad (2021), Iran	Industrial GT (case study)	15–40 °C	**≈−1.0 to −1.8 % per °C**	Efficiency decline linked to TIT optimisation	Hot, semi-arid climate; optimisation-oriented analysis

What is less frequently discussed is the compound effect of temperature variation within a single day. In tropical climates, diurnal temperature swings of 10–15°C are common. A plant that approximates ISO conditions at dawn may be operating 20°C above ISO at peak afternoon load, precisely when demand is highest. The performance evaluation literature tends to report annual or monthly averages, obscuring the worst-case performance conditions that often coincide with peak demand events. This methodological shortcoming needs greater attention, particularly for grid reliability assessments in countries where cooling demand peaks on the hottest days.

Humidity Effects

The effect of relative humidity on GT performance is more nuanced than temperature alone. High humidity promotes compressor fouling by creating conditions conducive to the adhesion of airborne particles to blade surfaces (Sánchez Cabarcas et al., 2024). Furthermore, humid air has a lower specific heat ratio, which subtly alters the thermodynamic characteristics of both compression and expansion. Shukla and Singh (2014) demonstrated that tropical countries experience relative humidity variations from below 24% to above 81%, with significant effects on the performance of naturally aspirated compressors. Sánchez Cabarcas et al. (2024) demonstrated that inlet air cooling combining desiccant dehumidification, evaporative cooling, and a Maisotsenko cooler can reduce gas turbine compressor inlet temperature by an average of 11.5 °C under tropical climate conditions, substantially mitigating humidity-and temperature-related performance penalties. However, the proposed configuration entails additional system integration and auxiliary power requirements, and the open literature still lacks comparative, long-term field assessments of such hybrid inlet-air-cooling systems operating continuously in tropical environments.

Humidity influences gas turbine operation through both thermodynamic mechanisms by altering the properties of the inlet working fluid and mechanical mechanisms, particularly by accelerating compressor fouling in polluted or coastal environments. The literature reports a wide range of humidity related performance impacts, depending on climate, inlet filtration quality, and machine condition. Table 4, summarises reported effects of relative humidity on gas turbine performance and degradation, based on experimental, field, and validated analytical studies conducted primarily in hot and humid regions.

Table 4. Reported Effects of Relative Humidity on Gas Turbine Performance and Fouling

Study / Location	Climate Type	Relative Humidity Range (%)	Observed Performance Impact	Primary Mechanism Identified	Key Remarks
Shukla & Singh (2014), tropical-country analysis	Hot–humid tropical	~24–81 %	Net power output reduction of **~0.1–0.3 % per %RH increase** at constant temperature	Reduced specific heat ratio; altered compression and expansion work	Effect smaller than temperature, but non-negligible at high RH
Lebele-Alawa & Jo-Appah (2015), Southern Nigeria	Equatorial rainforest	Typically >70 %	Additional efficiency loss beyond temperature penalty; increased SFC	Combined thermodynamic penalty and fouling promotion	Field measurements; humidity effect embedded in overall performance loss
Sánchez Cabarcas et al. (2024), tropical climates	Hot–humid coastal	60–90 %	Inlet air cooling with dehumidification recovered **~5–10 % power loss**	Humidity reduction increased air density and slowed fouling	Demonstrates mitigation potential but with capital/operational costs
Dabwan et al. (2023), hot regions	Hot desert / humid summer	40–75 % (seasonal)	Humidity amplified temperature-related derating by **~5–15 %**	Increased inlet air moisture content	Secondary effect relative to temperature but significant in combined cycles
Kurz & Brun (2009), multi-site review	Mixed, incl. coastal	Not explicitly quantified	Increased fouling rates in humid, contaminated air	Enhanced particle adhesion to compressor blades	Humidity accelerates degradation rather than instant power loss
Emenike et al. (2025), Niger Delta, Nigeria	Coastal tropical, polluted	Frequently >80 %	Rapid performance degradation between washing intervals	Interaction of humidity with salt and particulate aerosols	Highlights site-specific fouling severity
Sánchez Cabarcas et al. (2024), experimental validation	Tropical test conditions	65–85 %	Compressor inlet temperature reduced by **~11.5 °C** via dehumidification	Latent heat removal and density recovery	Indicates humidity control as a performance lever

Component Degradation: Mechanisms, Progression, And Performance Impact

Gas turbine performance degradation arises from multiple interacting physical mechanisms that act on different engine components and evolve over operating time. These mechanisms vary widely in their reversibility, rate of progression, diagnostic observability, and economic significance. While the literature often treats individual degradation modes in isolation, practical performance evaluation requires a structured classification that distinguishes between recoverable and non recoverable losses and explicitly links physical damage mechanisms to performance indicators. Table 5, presents a consolidated classification of the principal gas turbine degradation mechanisms reported in the literature, together with their dominant performance impacts and typical diagnostic approaches.

Table 5. Classification of Gas Turbine Degradation Mechanisms and Performance Impacts

Component	Degradation Mechanism	Recoverable	Primary Performance Impact	Dominant Physical Cause	Typical Diagnostic Indicator	Representative References
Compressor (front & mid stages)	Fouling	Yes (washing)	Reduced mass flow, decreased pressure ratio, loss of net power and efficiency	Adhesion of dust, oil mist, salt, and industrial pollutants to blade surfaces	Drop in compressor efficiency, deviation in pressure ratio and exhaust temperature	Kurz & Brun (2009); Meher-Homji et al. (2013); Emenike et al. (2025)
Compressor (all stages)	Erosion	No	Permanent efficiency loss and increased surge risk	Particle impact from dust and sand ingestion	Gradual efficiency decline not recoverable by washing	Kurz & Brun (2009); Tahan et al. (2017)
Compressor casing / rotor	Tip clearance growth	No	Progressive loss of pressure ratio and efficiency	Thermal cycling, wear, rotor–stator interaction	Long-term efficiency degradation tracked via gas path analysis	Rath et al. (2024); ASME (2025)
Combustion chamber	Liner and transition piece degradation	No	Combustion instability, reduced efficiency, higher emissions	Thermal fatigue from start–stop cycles and high firing temperatures	Increased exhaust temperature spread, instability at low load	Farhat & Salvini (2022); Chowdhury et al. (2023)
Turbine blades (hot gas path)	Oxidation and corrosion	No	Reduced turbine efficiency, increased heat rate	High-temperature oxidation, fuel contaminants	Persistent exhaust temperature rise	Aldi et al. (2019); Chowdhury et al. (2023)
Turbine blades and vanes	Particle deposition and cooling-hole blockage	Partially	Elevated metal temperatures, accelerated creep and fatigue	Synfuel or hydrogen-related contaminants	Local hot spots inferred from TIT/exhaust patterns	Aldi et al. (2019); Wang et al. (2023)
Turbine hot section	Creep and thermal	No	Loss of component	High TIT and repeated	Equivalent operating	Farhat & Salvini (2022);

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	fatigue cracking		life, forced outages	cycling	hours accumulation, inspection findings	Bailera et al. (2020)
Whole engine (system-level)	Combined recoverable and non-recoverable degradation	Mixed	Compound power and efficiency losses of 10–30 % in ageing plants	Interaction of fouling, wear, cycling, and ambient stress	Integrated gas path analysis trends	Meher-Homji et al. (2013); AYADJU & Ujevwerume (2022)

Compressor Fouling

Compressor fouling is the most economically significant and best-documented form of GT degradation. Airborne contaminants, including dust, pollen, oil mist, salt, and industrial pollutants, adhere to compressor blade surfaces, increasing surface roughness, altering blade profile geometry, and reducing mass flow and isentropic efficiency. The progression of fouling follows a well-established pattern. Initial deposits in early compressor stages reduce mass flow, shifting the operating point leftward on the compressor map, increasing first-stage pressure ratio, and progressively loading downstream stages towards stall and surge (Meher-Homji et al., 2013). An analysis across 92 different gas turbines confirmed that power reduction due to fouling was a function of the net work ratio and was more severe at 40°C than at 15°C ambient temperature, meaning that tropical-climate operators face a compounded penalty from simultaneously elevated temperature and fouling rates (Meher-Homji et al., 2013). The economic cost of unmanaged fouling has been estimated to be substantial across all GT configurations, with optimal washing intervals representing a significant operational optimisation opportunity.

Compressor fouling alters gas turbine performance not only by reducing isentropic efficiency but also by shifting the compressor operating point away from its design condition. As deposits accumulate on blade surfaces, effective flow area decreases, surface roughness increases, and aerodynamic loading of the front stages rises. These effects reduce corrected mass flow and force the compressor to operate at a lower pressure ratio for a given shaft speed, progressively eroding surge margin and overall performance. Importantly, this operating point shift amplifies performance losses under high ambient temperatures, where mass-flow-limited operation already prevails. Figure 2, illustrates the conceptual progression of compressor fouling on a compressor performance map, highlighting how fouling drives the operating point from a clean, design-intent condition toward a degraded, lower-flow regime.

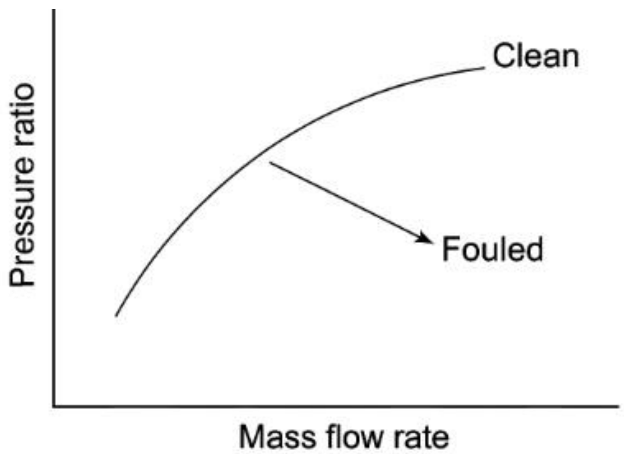

Figure 2. Compressor Fouling Progression and Operating Point Shift

Compressor washing can recover much of the fouling-related degradation, and optimising wash intervals is therefore economically significant. For tropical and hot-climate operators, who face simultaneously higher temperatures and higher humidity-induced fouling, generic OEM guidance on washing intervals is inadequate and requires local calibration.

Compressor fouling represents the most economically significant and operationally frequent degradation mechanism affecting industrial gas turbines. Its impact on performance manifests primarily through reductions in mass flow rate and isentropic efficiency, with disproportionately large consequences for net power output due to the high fraction of turbine work consumed by the compressor. Importantly, the severity of fouling related performance loss is not constant but depends strongly on fouling intensity, ambient temperature, and operating profile. Field and validated analytical studies consistently show that fouling penalties are amplified under hot climate conditions, making generic OEM guidance on fouling impact and washing intervals inadequate for tropical and arid environments. Table 6, summarises reported relationships between compressor fouling severity and gas turbine performance loss under representative operating conditions.

Table 6. Compressor Fouling Severity and Associated Gas Turbine Performance Losses

Fouling Severity Level	Typical Fouling Indicator	Ambient Temperature Context	Net Power Output Loss (%)	Thermal Efficiency Loss (%)	Fouling Recoverability	Representative References
Very mild (early fouling)	Slight increase in surface roughness; minor mass flow reduction (<1 %)	~15–20 °C	1–2 %	<1 %	Fully recoverable with online washing	Kurz & Brun (2009); Meher-Homji et al. (2013)
Mild fouling	Noticeable compressor efficiency drop (1–2 %)	~25–30 °C	3–5 %	2–3 %	Recoverable with offline washing	Meher-Homji et al. (2013); Lebele-Alawa & Jo-Appah (2015)
Moderate fouling	Mass flow reduction of ~3–5 %; operating point shift	~30–40 °C	6–10 %	4–6 %	Largely recoverable, partial residual loss	Meher-Homji et al. (2013); Emenike et al. (2025)
Severe fouling	Substantial deposit buildup; surge margin erosion	≥40 °C	10–15 %	6–9 %	Partially recoverable; permanent loss emerging	Meher-Homji et al. (2013); Aldi et al. (2019)
Compound fouling + ageing	Fouling combined with erosion or clearance growth	≥35 °C, ageing units	15–25 % (or higher cumulatively)	8–12 %	Only partially recoverable; overhaul required	AYADJU & Ujevwerume (2022); Kurz & Brun (2009)

Turbine Section Degradation

For example, hot gas path degradation includes deterioration of turbine blades, oxidation of blades, and thermal barrier coating (TBC) deterioration of nozzle guide vanes due to high-temperature inlet temperatures and fuel quality. As synfuel and hydrogen blends are used more, particulates are introduced on the nozzle vanes and can clog cooling ports when TIT is between 1,400 and 1,500°C (Aldi et al., 2019). Particle deposition increases surface roughness, changes aerodynamics of blades, and hot spots that accelerate creep and fatigue crack formation.

Recoverable degradation, primarily compressor fouling, can be addressed through washing, filter replacement, and VIGV adjustment. Non-recoverable degradation, including erosion, oxidation, and clearance growth, accumulates over operating hours and can only be addressed through component overhaul or replacement. When published efficiency values conflate these two categories, comparisons between studies conducted at different points in a plant's maintenance cycle become misleading, as a freshly washed plant will appear to have recovered from degradation that is in fact still present in its non-recoverable components.

Gas turbine performance degradation evolves over time through a combination of recoverable and non-recoverable mechanisms. Figure 3 conceptually illustrates the relative contributions of recoverable and non-recoverable degradation to overall gas turbine performance decline over time.

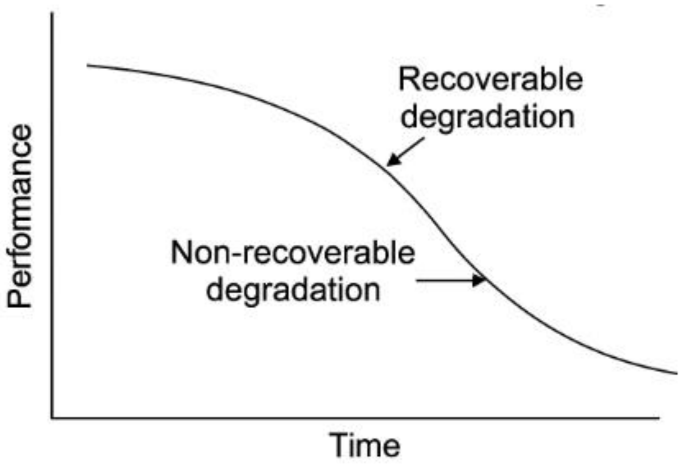

Figure 3. Recoverable vs Non-Recoverable Degradation over Operating Life.

CONCLUSIONS

Gas turbine performance evaluation has matured in theory, but there are still some serious shortcomings for users in hot, humid, and high-cycling environments. This review found that the literature focuses solely on performance factors, relies heavily upon OEM data, or lacks a robust and systematic way to tie thermodynamic performance to operation and maintenance costs.

This is at least true in the cases of Nigeria, Egypt, Algeria and Indonesia, where real-world GT performance is much lower than that provided by OEMs due to ambient temperature, compressor fouling, and fuel availability. The differences in what a one-degree Celsius increase in ambient temperature would mean in terms of a 1.37 to 2.5% net decrease in output multiplied by the 15 to 25°C difference between ISO and standard tropical operating conditions illustrates a performance gap that generic performance testing tools cannot fully capture.

The UPEF proposed in this review addresses those shortcomings through its combination of multiple performance indicators, correction methods, degradation states classification and maintenance economics into a single assessment method that can be applied to any setting and for any level of data availability. As the energy transition accelerates and gas turbines become more demanding as flexible backup generation sources, evaluation methodologies based on realistic performance under real-world conditions become desirable and necessary. Researchers, OEMs, and operators share the common goal of closing the gap between the idealized performance figures prevailing in the literature and the actual conditions under which a gas turbine plant delivers on its economic and grid stability objectives.

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