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# Optimization, Thermodynamic, and Exergoenvironmental Analyses of Gas Turbines: A Critical Review

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## Abstract

Gas turbines (GTs) occupy a central role in global power generation, industrial processing, and aviation, yet fundamental questions persist about how rigorously and consistently they are analyzed. This critical review examines the landscape of thermodynamic, exergy, exergoeconomic, and exergoenvironmental studies published over the last three decades, with particular attention to work from 2015 onwards. The review identifies five persistent gaps: disciplinary fragmentation, idealized optimization assumptions, inconsistent environmental accounting, limited algorithmic critique, and the disconnect between exergy diagnostics and real operational decisions. In response, we introduce the Energy–Exergy–Economic–Environmental–Operational ($E^3O$) framework, a unified structure that connects component-level thermodynamic rigor to system-level economic and environmental accountability and, crucially, to practical maintenance and operational planning. We critically evaluate approximately 55 representative studies, expose recurring methodological weaknesses, and propose standardized reporting guidelines for future work. The review concludes that the field's maturity is hampered not by lack of analytical tools but by fragmented application and poor methodological transparency.

## Keywords

Gas turbine; exergy analysis; exergoeconomics; exergoenvironmental analysis; multi-objective optimisation; Brayton cycle; $E^3O$ framework

## 1. Introduction

Ask most engineers what makes a gas turbine efficient, and they will reach for thermal efficiency figures perhaps the pressure ratio, the turbine inlet temperature, or the effectiveness of a recuperator. These are reasonable starting points. But efficiency in a gas turbine is a layered concept: it can mean converting the most fuel energy to shaft work (first law), destroying the least thermodynamic potential (second law), imposing the smallest economic penalty per unit of useful output (exergoeconomics), or leaving the lightest environmental footprint per kilowatt-hour generated (exergoenvironmental analysis). The problem is that most published studies pick just one of these lenses, optimize within it, and call the job done.

Thermodynamic analysis of gas turbines has progressively evolved from first-law performance metrics toward integrated second-law-based sustainability assessments that explicitly capture environmental trade-offs. While the Brayton cycle and its advanced configurations remain well established, recent studies have reinforced the

inadequacy of energy-only indicators for resolving component-level inefficiencies and environmental burdens in modern gas-turbine and combined-cycle systems. Exergy-based approaches, long recognized for their ability to localize irreversibilities, now constitute the backbone of contemporary assessment frameworks, particularly when coupled with life-cycle-based environmental indicators. Since 2020, a growing body of literature has applied exergoenvironmental analysis to simple-cycle, combined-cycle, and regenerative gas-turbine systems, consistently identifying the combustion chamber as the dominant contributor to both exergy destruction and environmental impact rates, even in high-efficiency configurations [1-3]. Recent investigations have further expanded the scope of analysis by accounting for ambient variability, part-load operation, and waste-heat recovery integration, demonstrating that environmentally optimal operating conditions do not necessarily coincide with exergy- or cost-optimal points [4, 5].

In parallel, advanced exergoenvironmental analysis has gained increased attention as a means of distinguishing avoidable from unavoidable environmental impacts and separating endogenous component inefficiencies from system-level interactions. Post-2020 applications to combined-cycle gas-turbine plants indicate that a substantial fraction, typically on the order of 25-35% of the total environmental impact associated with exergy destruction, is theoretically avoidable through targeted improvements in combustion, cooling, and heat-recovery subsystems [6, 7]. These findings highlight the diagnostic value of advanced decomposition despite its higher modeling complexity, as it enables the prioritization of retrofit and redesign strategies consistent with decarbonization objectives. More recent studies have coupled exergoenvironmental analysis with multi-objective optimization, carbon-capture integration, and hybrid bottoming cycles, positioning the method as a critical decision-support framework for next-generation gas-turbine systems operating under increasingly stringent environmental constraints [8, 9].

Across contemporary gas-turbine research, optimization has become not merely common but almost reflexive, with evolutionary algorithms, genetic algorithms, particle swarm optimization, and hybrid metaheuristics routinely embedded within exergoeconomic and exergoenvironmental frameworks. Post-2020 studies continue to report Pareto fronts spanning efficiency, cost, and environmental impact, often giving the impression of methodological sophistication and decision-support relevance [1, 2]. However, a closer examination reveals that much of this optimization literature remains conceptually shallow. The overwhelming majority of studies still assume steady-state, design-point operation, with off-design behavior, start-up transients, and long-term degradation either ignored or treated only implicitly, despite their dominant influence on real gas-turbine environmental performance [5, 6]. As a consequence, many reported "optimal" solutions are little more than numerical artefacts of an idealized operating envelope rather than implementable design or control strategies.

Moreover, recent exergoenvironmental optimization studies continue to exhibit a troubling disconnect from operational realism. Material temperature limits, component lifetime constraints, fouling, and maintenance scheduling are rarely enforced explicitly, allowing optimization algorithms to push turbine inlet temperatures, pressure ratios, and heat-recovery effectiveness into regimes that would be unacceptable in industrial practice [4, 7, 10]. While such solutions may minimize exergoenvironmental impact indices in a mathematical sense, they offer limited guidance for practitioners tasked with balancing reliability, availability, and emissions compliance. At the same time, despite more than a decade of methodological development, post-2020 exergoenvironmental studies still lack methodological convergence: different life-cycle impact assessment methods, characterization factors, functional units, and system boundaries are routinely employed, rendering cross-study comparison highly ambiguous and, in some cases, actively misleading [9, 11]. Without stronger standardization and closer integration of operational constraints, recent optimization-driven exergoenvironmental analyses risk becoming internally consistent but externally irrelevant precisely at a time when gas-turbine technologies are expected to play a credible transitional role in low-carbon energy systems.

This review sets out to do several things at once. First, it critically synthesises the current state of thermodynamic, exergy, exergoeconomic, and exergoenvironmental analyses as applied to gas turbines. Second, it evaluates the optimization algorithms in widespread use and honestly assesses their suitability and limitations for gas-turbine (GT) applications. Third, it catalogues the inconsistencies in environmental impact assessment. Fourth, and most importantly, it proposes the $E^3O$ framework as a unifying methodological structure, and recommends reporting standards that the field badly needs.

## 2. Thermodynamic Analysis of Gas Turbine Systems

Figure 1 provides a simplified schematic of a generic gas turbine system annotated with exergy flow paths. This representation is used throughout this review to anchor discussions of energy and exergy analyses at the component

level. By explicitly distinguishing exergy inputs, useful outputs, and exergy destruction within the combustor, turbine, and heat recovery sections, the figure illustrates why second-law analysis offers substantially greater diagnostic resolution than first-law energy balances alone. The schematic also serves as a reference structure for subsequent sections on exergoeconomic and exergoenvironmental burden allocation.

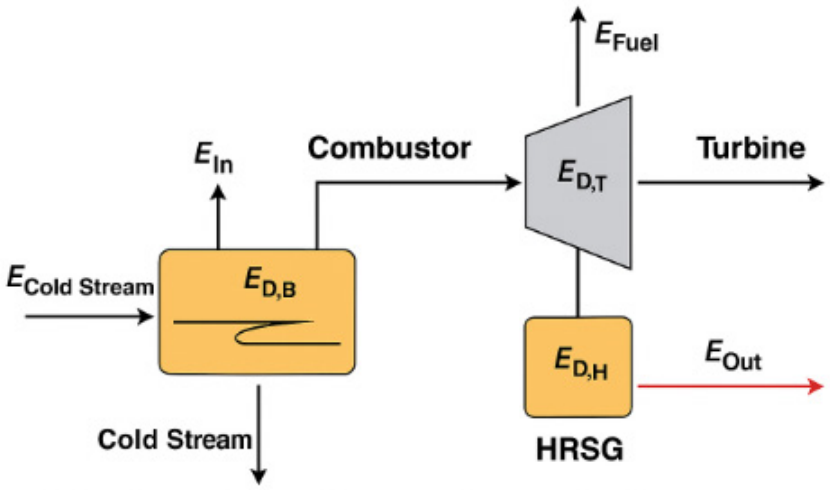


**Figure 1. Schematic of a Generic Gas Turbine System with Exergy Flow Paths.**

## 2.1 First-law Perspectives: What We Measure and What We Miss

Conventional energy-based analyses of gas turbines continue to frame performance largely in terms of Brayton-cycle thermal efficiency and its dependence on pressure ratio, obscuring the deeper physical and environmental mechanisms that govern real system behavior. Recent exergoenvironmental studies have demonstrated that this textbook perspective is increasingly inadequate, particularly for advanced configurations involving intercooling, reheating, regeneration, and combined-cycle integration. Post-2020 analyses of gas-turbine and combined-cycle systems consistently show that modifications which appear beneficial from an energy standpoint, such as intercooling to reduce compressor work or reheating to increase specific power, often shift, rather than reduce, the environmental burden by increasing fuel demand, upstream emissions, or irreversibilities in the combustion system when judged on an exergy basis [1, 2]. These studies confirm that the apparent efficiency gains predicted by simple energy balances frequently mask substantial increases in exergy destruction and associated environmental impact rates, particularly in high-temperature components.

Moreover, recent exergoenvironmental assessments have shown that the concept of an “optimal” pressure ratio becomes fundamentally configuration- and objective-dependent once environmental impact is introduced as an explicit optimization criterion. Advanced combined-cycle gas-turbine studies performed after 2020 demonstrate that pressure ratios maximizing thermal efficiency or net work output rarely coincide with those minimizing exergoenvironmental indicators, especially when waste-heat recovery and bottoming cycles are included [5, 6]. This divergence becomes more pronounced when life-cycle-based impact factors are applied, revealing that energy-optimal designs can perform poorly in terms of cumulative environmental burden. Despite these insights, much of the recent literature still evaluates cycle modifications in isolation and under steady-state assumptions, offering configuration-specific conclusions rather than transferable design guidance. As a result, exergoenvironmental analysis has effectively exposed the limitations of energy-based reasoning: by demonstrating that improvements in thermal efficiency alone provide, at best, an incomplete and at worst, misleading basis for gas-turbine design decisions in a decarbonization-constrained energy system [4, 9].

To provide a structural overview of the systems surveyed in this review, Table 1 summarizes the principal gas turbine cycle configurations addressed in the literature. These configurations span simple Brayton cycles through increasingly complex arrangements incorporating intercooling, recuperation, reheat, combined cycles, and hybrid or renewable integrated systems. The diversity of configurations reflects both the thermodynamic maturity of gas turbine technology and the expanding range of economic, environmental, and operational objectives imposed on modern systems. This classification framework is used throughout the subsequent sections to contextualize reported exergy destruction patterns, optimization results, and methodological limitations.

**Table 1. Representative Gas Turbine Cycle Configurations Reviewed**

| Cycle configuration | Defining features | Thermodynamic intent | Typical applications | Representative references* |
|---|---|---|---|---|
| Simple (Brayton) cycle | Single compressor–combustor–turbine loop; no heat recovery | Baseline performance; low capital cost | Peaking power plants, aviation engines | [12, 13] |
| Intercooled cycle | Compressor stages with intercooling between stages | Reduced compressor work; higher net power | Large industrial gas turbines | [14, 15] |
| Recuperated (regenerative) cycle | Exhaust heat used to preheat compressed air | Improved thermal efficiency at low pressure ratios | Distributed generation, microturbines | [16, 17] |
| Reheated cycle | Expansion divided into multiple turbine stages with intermediate reheat | Increased specific work output | Heavy-duty power generation | [15, 18] |
| Combined cycle (CCGT) | Gas turbine topped by steam Rankine bottoming cycle | Maximization of overall efficiency | Utility-scale base-load plants | [19, 20] |
| Cogeneration (CHP) | Simultaneous production of power and useful heat | Improved overall fuel utilization | Industrial energy systems | [21, 22] |
| Hybrid GT systems | Integration with SOFC, ORC, or other subsystems | Enhanced exergy efficiency, flexibility | Advanced and emerging power systems | [23] [24] [25] |
| Renewable-integrated GT systems | Solar, biomass, or waste-heat integration | Reduced environmental footprint | Low-carbon and hybrid energy systems | [11, 26, 27] |

Recent exergoenvironmental analyses of advanced gas-turbine and combined-cycle systems confirm that further efficiency gains are increasingly constrained by cooling-related irreversibilities rather than by fundamental cycle architecture. Post-2020 studies explicitly modelling blade-cooling flows show that strategies previously treated as secondary boundary conditions dominate both exergy destruction and environmental impact rates in high-temperature components [2, 5]. Comparative assessments of modern CCGT plants further demonstrate that efficiency improvements over the past two decades stem mainly from higher turbine inlet temperatures enabled by advanced cooling, not from substantive thermodynamic innovation [5, 6]. The implication is uncomfortable but clear: the thermodynamic "easy wins" have been exhausted.What the first law consistently misses is the quality of energy flows. A gas turbine exhaust stream at 550°C and a geothermal fluid at 120°C might both carry 10 MW of heat, but their potential for further work production is entirely different. First-law analysis treats them identically. This is precisely the problem that exergy analysis was designed to solve.

## 2.2 Part-load and Off-design Behavior: The Neglected Regime

A persistent limitation in gas-turbine thermodynamic and optimization literature is the continued emphasis on design-point performance, despite overwhelming evidence that real environmental impacts are dominated by off-design operation. Recent exergoenvironmental studies explicitly accounting for part-load behavior demonstrate that compressor and turbine efficiency degradation at reduced load substantially amplifies both exergy destruction and component-level environmental impact, effects that are systematically underestimated in design-point analyses [2, 5]. Advanced assessments of modern combined-cycle plants further show that ambient temperature variations not only reduce power output but also shift the distribution of environmental burdens toward the gas-turbine core at high temperatures, particularly in hot climates [4, 6]. These findings expose a methodological blind spot: optimization studies that ignore off-design and ambient effects risk producing solutions that are environmentally attractive only on paper, while misrepresenting real-world operational performance.

Despite these contributions, part-load analysis remains a minor component of the overall literature. The vast majority of published optimization studies, including many that claim practical applicability, are anchored to a single operating point. This is not merely an academic shortcoming. Gas turbines in real power systems routinely follow load, and an optimization that ignores this regime is of limited operational value.

## 2.3 Combined Cycle and Cogeneration Configurations

The integration of gas turbines with steam Rankine bottoming cycles forming combined-cycle gas turbine (CCGT) plants remains the most thermodynamically advanced large-scale application of gas-turbine technology, yet recent exergoenvironmental studies have exposed persistent structural limitations. Post-2020 analyses of modern CCGTs

consistently confirm that the combustion chamber dominates both exergy destruction and environmental impact, frequently accounting for more than 40-50% of total system irreversibilities, even in state-of-the-art plants [2, 4]. Advanced exergy and exergoenvironmental decompositions further show that only a fraction of these losses are practically avoidable, with material limits, cooling requirements, and HRSG pinch-point constraints sharply bounding improvement potential [6, 28]. Recent HRSG-focused studies reinforce that exergetically optimal designs demand larger heat-transfer areas and lower temperature gradients, directly conflicting with economic optima a trade-off that remains unresolved in retrofit-constrained plants [29]. Collectively, this literature makes an uncomfortable point clear: successive generations of CCGT efficiency gains have relied far more on incremental materials and cooling advances than on genuine thermodynamic innovation, and exergoenvironmental analysis now reveals that remaining improvement margins are narrow, expensive, and increasingly context-dependent rather than universally exploitable.

Table 2 summarizes the principal thermodynamic and exergy performance metrics reported across the gas turbine literature reviewed in this work. While thermal efficiency, pressure ratio, and turbine inlet temperature remain the most commonly reported design indicators, exergy-based metrics such as exergy efficiency and component-level exergy destruction provide deeper insight into system irreversibilities. The table also highlights recurring assumptions, particularly design point fixation, idealized turbine inlet temperatures, and standard dead state selection that limit cross-study comparability and operational relevance. These patterns motivate the more integrated and operationally grounded analytical approaches discussed in subsequent sections.

**Table 2. Summary of Thermodynamic and Exergy Performance Metrics Reported in Gas Turbine Literature**

| Metric | Definition/Meaning | Typical reported range | Common assumptions & notes | Implications for analysis |
|---|---|---|---|---|
| Thermal efficiency ($\eta_{th}$) | Ratio of net shaft work to fuel lower heating value | 30-40% (simple cycle); 55-64% (CCGT) | Usually evaluated at ISO conditions; design-point focused | Masks quality of losses; insensitive to irreversibilities |
| Specific work output | Net work per unit mass of air (kJ $kg^{-1}$) | 300-600 (simple GT); higher with reheat/intercooling | Often assumes constant turbine inlet temperature | Key indicator for power density |
| Pressure ratio ($\pi_c$) | Compressor pressure ratio | 8-20 (industrial GTs); >20 (advanced GTs) | Variable specific heats often neglected | Strongly influences both $\eta_{th}$ and exergy destruction |
| Turbine inlet temperature (TIT) | Temperature at turbine entry (°C) | 1100-1500 (reported); higher in optimization studies | Upper bounds frequently idealized | Dominant driver of performance and material constraints |
| Exergy efficiency ($\eta_{ex}$) | Ratio of useful exergy output to fuel exergy input | 30-45% (simple cycle); 50-60% (CCGT) | Dead-state usually fixed at standard conditions | Enables component-level diagnosis |
| Total exergy destruction | Sum of component irreversibilities | 40-70% of fuel exergy input | Highly sensitive to dead-state choice | Central indicator in advanced analyses |
| Combustor exergy destruction share | Fraction of total exergy destruction in combustor | 30-55% | Chemical exergy often simplified | Primary improvement target across studies |
| Part-load efficiency penalty | Efficiency reduction at ~50-60% load | 5-15 percentage points | Rarely included in optimization studies | Critical for operational relevance |
| Ambient condition sensitivity | Performance variation with intake temperature | −0.5 to-1% power per °C increase | Often neglected or treated parametrically | Key for hot-climate installations |

## 3. Exergy Analysis: Theory, Practice, and Persistent Problems

### 3.1 Conventional Exergy Analysis

Exergy analysis of gas turbines is now a mature and analytically robust methodology, yet recent studies show it remains indispensable for diagnosing thermodynamic inefficiencies with a level of resolution unattainable by first-law analysis alone. Contemporary component-level assessments consistently demonstrate that the combustion chamber is the primary locus of irreversibility, typically responsible for 40–65% of total cycle exergy destruction, driven predominantly by chemical reaction irreversibility and intense temperature gradients inherent to high-temperature combustion [30, 31]. While compressors and turbines contribute secondary losses, these are largely associated with viscous dissipation, aerodynamic losses, and cooling-related heat transfer, particularly under off-design

or high ambient temperature conditions [32]. Despite methodological advances, many recent studies remain descriptive, underscoring a persistent need for deeper integration of advanced and avoidable exergy analysis.

The dominance of the combustion chamber in overall system irreversibility is illustrated in Figure 2, which presents a representative distribution of exergy destruction among major gas turbine components. Across a wide range of simple and combined-cycle studies, combustion-related irreversibilities typically account for roughly one-half, and often more, of total exergy destruction, reflecting the fundamental thermodynamic penalty associated with fuel oxidation at high temperature gradients. Compressor and turbine losses form a second tier of irreversibility, while downstream heat recovery components generally contribute a smaller but non-negligible share. This recurring pattern explains why exergy-based, exergoeconomic, and exergoenvironmental analyses consistently identify the combustion system as the primary target for improvement.

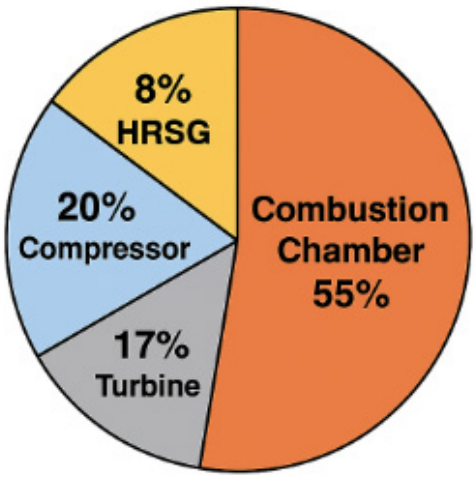


**Figure 2. Typical Distribution of Exergy Destruction in Gas Turbine Components.**

Table 3 summarizes the typical distribution of exergy destruction among major gas turbine components as reported across representative exergy studies. Despite differences in plant size, configuration, and modelling assumptions, a consistent pattern emerges: the combustion chamber dominates total irreversibility, followed by the compressor and turbine, with heat recovery equipment contributing a smaller but non-negligible share. This robustness explains why successive generations of thermodynamic, exergoeconomic, and exergoenvironmental analyses repeatedly converge on similar improvement priorities. At the same time, the table highlights that secondary contributors, particularly compressors operating at part load, can become critical under realistic operating conditions, underscoring the importance of moving beyond purely design point analysis.

**Table 3. Component-Level Exergy Destruction Shares in Representative Gas Turbine Systems**

| Component | Typical share of total exergy destruction (%) | Dominant physical causes | Sensitivity to operating conditions | Implications for improvement |
|---|---|---|---|---|
| Combustion chamber | 30-55 | Chemical irreversibility of fuel oxidation; large temperature gradients; pressure losses | Moderately sensitive to TIT, excess air ratio, fuel composition | Primary target for thermodynamic, economic, and environmental improvement |
| Compressor | 15-25 | Viscous dissipation; aerodynamic losses; off-design operation | Highly sensitive to part-load operation and fouling | Fouling mitigation and inlet air treatment offer high leverage |
| Gas turbine | 10-20 | Fluid friction; heat transfer; blade cooling losses | Sensitive to TIT, cooling flow fraction, degradation | Advanced cooling and blade design reduce irreversibility |
| Heat recovery steam generator (HRSG) | 5-15 (CCGT only) | Finite temperature differences in heat exchange | Sensitive to pinch point and load variation | Trade-off between exergy reduction and capital cost |
| Auxiliaries and exhaust losses | 3-10 | Residual exhaust exergy; mechanical losses | Strongly dependent on ambient conditions | Often neglected but relevant for low-carbon optimization |

Early second-law studies already demonstrated that turbine cooling is not thermodynamically benign: El-Masri's seminal analysis showed that air-cooled Brayton cycles suffer a pronounced reduction in turbine exergetic efficiency due to mixing and dilution irreversibilities, a conclusion repeatedly confirmed with modern cooled-turbine models [33]. Subsequent exergy and exergoeconomic studies of industrial gas turbines converge even more strongly on the combustion chamber as the dominant source of exergy destruction and the most leverageable component for performance improvement [30, 31, 34]. Despite this analytical maturity, a persistent weakness remains the inconsistent treatment of the dead state: variations in reference temperature, pressure, and chemical environment significantly bias reported exergy values, yet cross-study normalization is rarely performed and seldom discussed explicitly [35].

### 3.2 Advanced Exergy Analysis

Advanced exergy analysis has emerged as one of the most conceptually rigorous extensions of second-law thermodynamics, with its formal development led by Tsatsaronis and Morosuk through the systematic decomposition of component exergy destruction into avoidable/unavoidable and endogenous/exogenous parts. This framework moves beyond descriptive loss accounting by explicitly identifying which irreversibilities are technologically reducible and which originate from component interactions rather than intrinsic design limitations [36, 37]. Recent applications to gas turbines and combined cycles demonstrate its diagnostic power, particularly in disentangling combustion-related irreversibility attributable to upstream compression inefficiencies from that driven by internal mixing and chemical reactions [37, 38]. Advanced exergoeconomic and exergoenvironmental studies further show that investment and environmental priorities can shift substantially once avoidable contributions are isolated, often diverging sharply from conclusions drawn using conventional metrics alone [39, 40]. However, the method's practical uptake remains limited by its high data demands and reliance on idealized reference technologies. Notably, a significant fraction of recent studies labeled as "advanced" implement only partial decompositions, thereby diluting the method's intended explanatory and decision-making value.

### 3.3 Sensitivity to Assumptions and Dead-State Selection

Recent exergy research has reinforced that the choice of reference environment is not a secondary modeling detail but a decisive methodological assumption. While Hepbasli's early review already emphasized the centrality of the dead state, more recent studies demonstrate that climate-driven variations in ambient temperature and composition can shift all physical and chemical exergy terms, materially altering component efficiencies and loss distributions [38, 41]. Nevertheless, a large fraction of gas-turbine exergy studies still default uncritically to ISO standard conditions, irrespective of site-specific climates. This practice embeds a systematic bias, limiting the operational relevance of reported results and undermining cross-plant comparability [35].

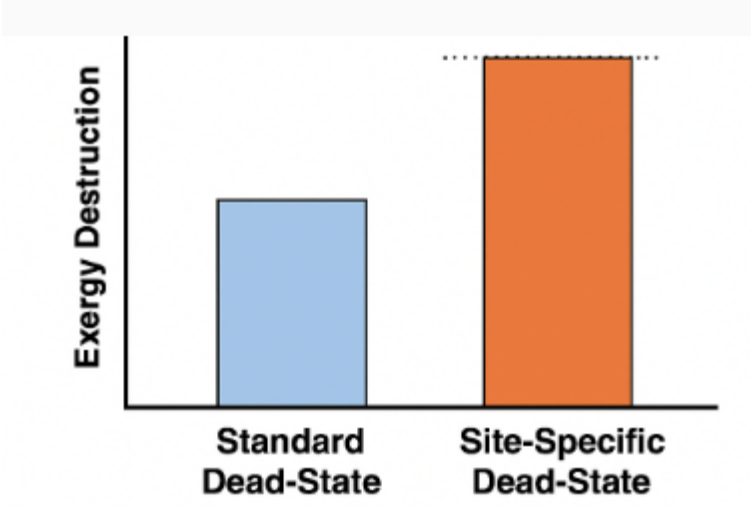


**Figure 3. Dead-State Selection Impact on Computed Exergy Destruction.**

The sensitivity of exergy results to the choice of reference environment is illustrated conceptually in Figure 3. When standard dead-state conditions are adopted, computed exergy destruction values are systematically lower than those obtained using a site-specific dead state based on local ambient conditions. This difference propagates through

all component-level results and affects derived metrics such as exergy efficiency, specific cost of exergy destruction, and environmental burden per unit of exergy. The widespread practice of fixing the dead state at standard conditions, regardless of plant location, therefore introduces a consistent but often unreported source of bias in comparative gas turbine studies.

Table 4 contrasts conventional and advanced exergy analysis approaches as applied to gas turbine systems. Conventional analysis provides a robust first step by identifying the magnitude and location of irreversibilities, but it offers limited guidance on which losses are realistically reducible. Advanced exergy analysis extends this capability by explicitly separating avoidable from unavoidable irreversibilities and distinguishing intrinsic component losses from those induced by system interactions. While this deeper diagnostic insight is particularly valuable for guiding informed design and retrofit decisions, its high data and modelling requirements help explain why many studies claiming "advanced" analysis employ only partial implementations of the method.

**Table 4a. Comparison of Conventional and Advanced Exergy Analysis Approaches in Gas Turbine Studies (Table contrasts methodological scope, data requirements, and diagnostic value of conventional and advanced exergy analysis as applied in gas turbine literature)**

| Aspect | Conventional exergy analysis | Advanced exergy analysis | Implications for gas turbine studies |
|---|---|---|---|
| Primary objective | Quantify and locate total exergy destruction by component | Decompose exergy destruction into meaningful sub-categories | Shifts focus from where losses occur to why they occur |
| Exergy destruction resolution | Single aggregated value per component | Partitioned into avoidable/unavoidable and endogenous/exogenous parts | Enables prioritization of realistic improvement measures |
| Treatment of component interactions | Implicit; interactions embedded in total destruction | Explicit separation of internally caused and externally induced irreversibilities | Clarifies component coupling effects in integrated systems |
| Technology benchmarking | Relative to existing system configuration | Relative to assumed best available technology | Requires explicit justification of technology assumptions |
| Data and modelling requirements | Moderate; standard thermodynamic inputs | High; multiple hypothetical operating cases needed | Limits applicability when detailed data are unavailable |
| Computational effort | Relatively low | Substantially higher | Often### Table 4a. Comparison of Conventional and Advanced Exergy Analysis Approaches in Gas Turbine Studies |

**Table 4b. Comparison of Conventional and Advanced Exergy Analysis Approaches in Gas Turbine Studies (Table contrasts methodological scope, data requirements, and diagnostic value of conventional and advanced exergy analysis as applied to gas turbine systems)**

| Aspect | Conventional exergy analysis | Advanced exergy analysis | Implications for GT studies |
|---|---|---|---|
| Primary objective | Quantify total and component-level exergy destruction | Decompose exergy destruction into physically meaningful sub-components | Shifts focus from "where losses occur" to "which losses are reducible" |
| Exergy destruction treatment | Single aggregated value per component | Decomposed into avoidable vs. unavoidable and endogenous vs. exogenous parts | Enables prioritization of realistic improvement actions |
| Reference for improvement | Implicit comparison with ideal or baseline cycle | Explicit definition of best-available and unavoidable component performance | Reduces misleading improvement potential estimates |
| Component interaction effects | Largely ignored; components treated independently | Explicitly captures interactions between system components | Reveals indirect causes of irreversibility |
| Data requirements | Moderate (design parameters, efficiencies, dead state) | High (benchmark component models, interaction analysis) | Limits applicability to systems with detailed data |
| Computational complexity | Low to moderate | High (multiple system simulations required) | Explains limited adoption in routine GT studies |
| Use in optimization studies | Widely used as objective or diagnostic metric | Rarely fully implemented in optimization | Advanced insights seldom translated into design optimization |
| Typical limitations | Overstates theoretical improvement potential | Depends strongly on assumptions about "unavoidable" limits | Demands transparency in modelling assumptions |

Rosen and Dincer [42] drew attention to these issues in the context of thermoeconomic analysis, arguing for clearer methodological transparency. The field has made limited progress on this front in the intervening years.

## 4. Exergoeconomic Analysis: From Cost Allocation to Decision Support

### 4.1 Established Methods and Their Application to Gas Turbines

Modern exergoeconomic studies reaffirm that assigning costs to exergy streams is essential for distinguishing thermodynamic inefficiencies from those that genuinely erode economic performance. The SPECO methodology remains the most rigorous framework for component-level fuel–product definitions and cost propagation, and it continues to underpin contemporary advanced exergoeconomic analyses of complex energy systems [37, 43]. The CGAM system, originally formulated for a simplified gas-turbine cogeneration plant, still serves as a benchmark for method comparison, though its abstraction limits direct industrial relevance [44]. Despite methodological maturity, recent studies highlight persistent inconsistencies in cost allocation practices, underscoring the need for stricter standardization [45].

Table 5 summarizes the dominant cost drivers and recurring cost allocation outcomes identified by exergoeconomic analyses of gas turbine systems. Across a broad range of studies, the combustion chamber emerges not only as the largest contributor to exergy destruction but also as the component with the highest specific economic penalty per unit of irreversibility. Compressor-related costs become particularly significant under part load operation and fouling conditions, while heat recovery equipment illustrates the frequent divergence between economic and exergy optimal designs. The table also highlights a persistent limitation of the literature: reliance on simplified or outdated cost functions and static fuel price assumptions, which can strongly influence reported optimization results.

**Table 5. Exergoeconomic Cost Drivers and Typical Cost Allocation Results in Gas Turbine Studies**

| Component | Primary cost drivers | Typical specific cost of exergy destruction | Key modelling assumptions | Decision-relevant insights |
|---|---|---|---|---|
| Combustion chamber | Fuel price; fuel quality; pressure loss; emission penalties | High (often highest in system; order of magnitude above HRSG) | Fuel chemical exergy treated as single input; emission costs sometimes excluded | Small efficiency gains yield large cost savings; dominant economic leverage point |
| Compressor | Isentropic efficiency; fouling; power consumption | Moderate to high under part-load conditions | Clean-machine efficiencies frequently assumed | Fouling control and inlet air treatment are cost-effective measures |
| Gas turbine | Isentropic efficiency; cooling flow fraction; maintenance cost | Moderate | Maintenance cost often omitted or fixed | Blade cooling optimization trades capital cost against exergy savings |
| Heat recovery steam generator (HRSG) | Heat transfer surface area; pinch point; material cost | Low to moderate | Capital cost functions often simplified | Economic optimum rarely coincides with minimum exergy destruction |
| Auxiliaries and balance of plant | Mechanical losses; electricity consumption | Low | Commonly aggregated or neglected | Individually small but cumulative impact may be non-negligible |
| Fuel supply (system-level) | Fuel price volatility; contractual structure | Dominant influence on total cost rate | Static fuel prices assumed | Sensitivity analysis essential for robust optimization outcomes |

Recent thermoeconomic optimization studies of gas-turbine cogeneration systems consistently show that not all irreversibilities carry equal economic weight. More recent analyses confirm that the combustion chamber exhibits disproportionately high specific costs of exergy destruction, often far exceeding those of heat-recovery components, thereby dominating cost-reduction potential and design prioritization [22, 23]. Multi-objective extensions further demonstrate that system modifications such as fuel or air preheating can significantly reshape the Pareto front, improving exergy efficiency and emissions performance, but frequently at the expense of higher capital costs that erode net economic gains if adopted uncritically [45, 46].

Ahmadi, Jamali, Ehyaei and Assad [47] conducted energy and economic analysis of a gas turbine with an air bottoming cycle, demonstrating that second-cycle integration reduces the cost per unit of electricity while also improving overall exergy efficiency. Aliehyaei [16] applied artificial bee colony optimization to a recuperated GT cycle, finding substantially different cost-optimal solutions from those obtained by standard gradient methods.

### 4.2 Critical Limitations

Recent exergoeconomic research increasingly recognizes that many conclusions are undermined by persistent methodological weaknesses rather than thermodynamic insight limitations. Despite decades of application, investment cost functions for gas-turbine components are still commonly derived from legacy surveys or generic scaling laws, whose convenience masks large deviations from contemporary procurement and EPC costs, particularly under volatile materials and supply-chain conditions [37, 45]. Likewise, the allocation of fuel costs in cogeneration and multi-product systems remains highly sensitive to the assumed productive structure, with different definitions yielding divergent optimization outcomes an issue formalized but not universally resolved even in SPECO-based studies [48]. Most critically, conventional exergoeconomic models remain disconnected from modern electricity markets, neglecting dynamic pricing, capacity remuneration, and grid constraints that now dominate gas-turbine profitability. This structural gap limits the decision relevance of many otherwise rigorous analyses and highlights the need to integrate exergy-based costing with market-aware operational frameworks.

Figure 4 illustrates a fundamental tension observed repeatedly in exergoeconomic optimization studies of gas turbines. While exergy-based optimization seeks to minimize irreversibilities, the economically optimal solution is typically displaced toward higher exergy destruction due to the increasing marginal cost of achieving further thermodynamic improvement. This divergence explains why designs that minimize exergy destruction are frequently rejected on economic grounds, and why multi-objective optimization is necessary to reveal the true trade-off space. The figure highlights the limitation of relying on single-criterion optimization and motivates the integrated treatment advocated in this review.

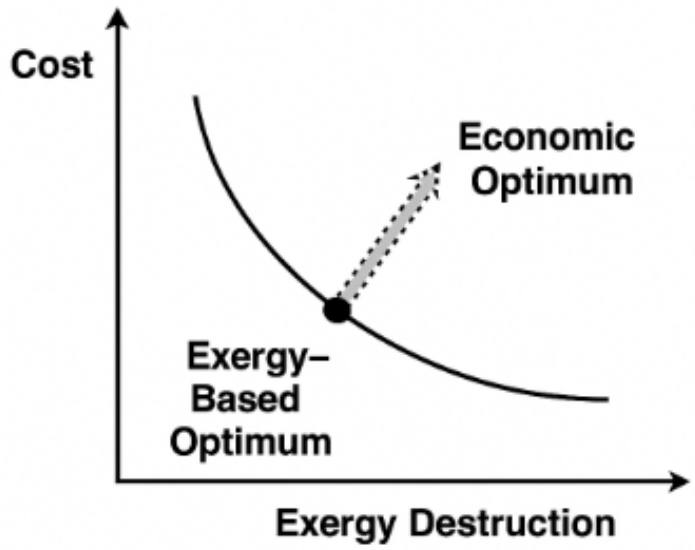


**Figure 4. Illustrative Conflict between Exergy-Based and Economic Optima.**

Misra, Sahoo and Gupta [49] noted in the context of absorption refrigeration that thermoeconomic evaluation is only as good as the cost functions and economic parameters it relies on, and called for greater transparency in how these parameters are selected and validated. The same critique applies with full force to gas turbine exergoeconomics.

## 5. Exergoenvironmental Analysis: Environmental Burden Attribution at Component Level

### 5.1 Methodology and Application

Recent exergoenvironmental studies extend classical exergoeconomics by systematically replacing monetary costs with life-cycle environmental burdens while retaining the same fuel–product balance structure. Building on the foundational framework of Meyer et al. (2009), newer applications increasingly integrate updated LCA methods (ReCiPe) with exergy-based accounting to trace environmental impacts through complex energy systems [37, 45]. These studies consistently show that the combustion chamber dominates total environmental burden not merely due

to high exergy destruction, but because it is the locus where fuel-related upstream impacts and direct $CO_2$ and $NO_x$ emissions are introduced into the system. Nevertheless, many applications remain component-focused and static, limiting their ability to capture system-level mitigation trade-offs under realistic operating conditions [50].

Figure 5 illustrates the basic logic of exergoenvironmental analysis as applied to gas turbine systems. Environmental impact factors derived from life-cycle assessment are attached to exergy streams in a manner analogous to cost allocation in exergoeconomics and are then propagated through the system. The environmental burden associated with fuel supply is compounded by component-level exergy destruction, particularly within the combustion chamber, and may be further altered by downstream heat recovery and emission treatment technologies. This structure highlights why inconsistent treatment of system boundaries, emission handling, and upstream impact factors leads to large disparities between published exergoenvironmental results.

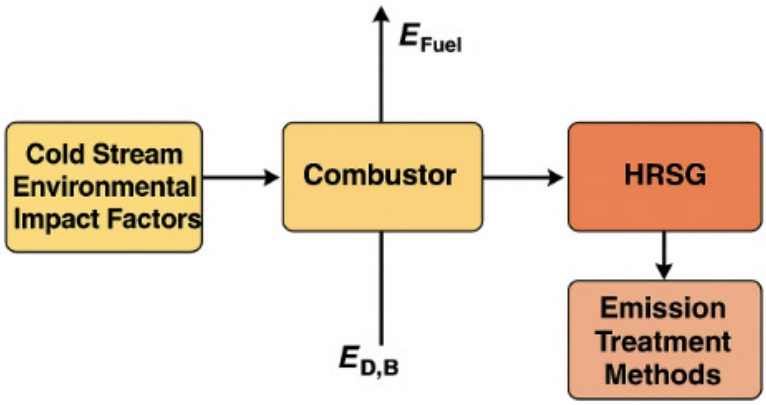


**Figure 5. Structure of Exergoenvironmental Burden Propagation.**

Recent exergoenvironmental optimization studies underline that improving thermodynamic performance does not automatically imply environmental optimality. Updated analyses of combined-cycle plants confirm that reducing HRSG exergy destruction lowers the specific environmental burden of electricity generation, yet environmentally optimal designs often diverge from economic optima because enhanced heat-exchange effectiveness demands larger surfaces and higher material impacts [45, 50]. More advanced system studies further show that integrating $CO_2$-mitigation technologies, such as chemical looping, introduces new component-level environmental burdens associated with additional reactors, oxygen carriers, and auxiliary power that partially erode the apparent climate benefits of capture [37, 51]. These results highlight a persistent tension between environmental ambition and system-wide efficiency that simplistic optimization frameworks fail to resolve.

Cavalcanti [11] analyzed an integrated solar combined cycle from an exergoenvironmental perspective, finding that the solar field, while reducing combustion-related burdens, introduces significant manufacturing-phase burdens associated with collector production. Adibhatla and Kaushik [21] conducted a 4E (energy, exergy, economic, environmental) analysis of a solar-aided coal-fired power plant, providing one of the more thorough attempts at multi-dimensional assessment. Shamoushaki, Ehyaei and Ghanatir [24] analyzed a SOFC-GT system, finding that the SOFC introduces component-level environmental hotspots that conventional analysis would overlook.

### 5.2 The Inconsistency Problem: Why Cross-study Comparisons Are Fraught

Recent reviews have exposed a persistent reproducibility problem in exergoenvironmental analysis that undermines its comparative value. Contemporary studies apply heterogeneous impact-assessment methods (Eco-indicator 99, ReCiPe, CML, and IMPACT 2002+), inconsistent functional units, and divergent system boundaries, often drawing from incompatible LCA databases, making cross-study comparisons unreliable [11, 45]. As a result, environmental burden estimates for nominally identical gas-turbine cycles can vary by a factor of two or more, reflecting methodological choice rather than physical reality. Although early methodological work explicitly recognized this sensitivity, the field has failed to converge on standardized modelling conventions, leaving exergoenvironmental results highly context-dependent and limiting their decision-making credibility [37].

Table 6 summarizes the principal methodological choices encountered in exergoenvironmental analyses of gas turbine systems and illustrates how these choices materially influence reported results. Differences in impact

characterization methods, functional units, system boundaries, and treatment of combustion emissions introduce significant variability that often exceeds the magnitude of the improvements being optimized. As a result, nominally similar gas turbine configurations can appear environmentally superior or inferior depending primarily on methodological framing rather than physical performance. This inconsistency represents one of the most serious barriers to cumulative knowledge development in the exergoenvironmental literature and motivates the need for clearer reporting standards.

**Table 6. Exergoenvironmental Methodological Choices and Their Consequences in Gas Turbine Studies**

| Methodological element | Common choices in literature | Observed variability/issues | Effect on results | Implications for comparison and interpretation |
|---|---|---|---|---|
| Impact characterization method | Eco-indicator 99; ReCiPe; CML; IMPACT 2002+ | Different impact categories and weighting schemes used | Reported environmental burden values may differ by factors of 2 or more | Cross-study numerical comparisons become unreliable |
| Functional unit | kWh of electricity; GJ of fuel input; annual operation | Inconsistent or poorly stated functional units | Alters normalization of environmental burdens | Ambiguity undermines reproducibility and transparency |
| System boundary definition | Gate-to-gate; cradle-to-gate; cradle-to-grave | Manufacturing and end-of-life phases often omitted | Underestimation of component-level environmental burdens | Biases results toward operational emissions only |
| Treatment of combustion emissions | Included in fuel exergy burden; treated as separate outputs; selectively included ($CO_2$ only) | Inconsistent inclusion of $NO_x$, particulates, and other pollutants | Substantial shifts in total environmental impact allocation | Misrepresents relative importance of components |
| Upstream fuel impacts | Simplified averages; database-specific values | Fuel supply chain impacts vary with source and geography | Can dominate total environmental burden | Requires explicit documentation and sensitivity analysis |
| Manufacturing-phase impacts | Often neglected or highly aggregated | Limited data availability for GT components | Understates burdens of complex equipment (e.g. HRSG, combustor) | Skews optimization toward thermodynamic improvements only |
| Dead-state selection | Standard reference environment most common | Site-specific environments rarely considered | Affects exergy-based burden allocation | Compounds inconsistencies already present in exergy analysis |
| Reporting format | Single weighted score; limited disaggregation | Loss of category-level insight | Masks trade-offs between impact categories | Limits usefulness for environmental decision-making |

A related problem is the treatment of combustion emissions. Some studies incorporate $CO_2$ emissions as a component of the fuel exergy stream's environmental burden; others treat them as a separate boundary output. Some include NOx and particulate matter; others do not. The choice matters substantially for the overall environmental picture of a gas turbine system, particularly as climate impact dominates the environmental burden of fossil-fueled systems.

Recent advanced exergoenvironmental studies reveal a sharp tension between methodological rigor and data realism. While advanced decomposition frameworks substantially improve diagnostic insight, they demand highly granular life-cycle inventories at the component-level data that are rarely available outside simplified or laboratory-scale systems [37, 40]. Consequently, most applications still depend on coarse, literature-based LCA proxies, eroding numerical robustness and exposing a critical mismatch between the apparent precision of exergy methods and the underlying environmental data quality [45].

## 6. Optimisation Techniques: A Critical Evaluation

### 6.1 The Optimisation Landscape in GT Studies

Throughout this review, the term 'metaheuristic algorithms' is used as an umbrella designation for stochastic, population-based optimization methods commonly applied to gas turbine studies. These include evolutionary algorithms (e.g., Genetic Algorithms and NSGA-II), swarm intelligence algorithms (e.g., Particle Swarm Optimization and Artificial Bee Colony), and hybrid approaches that combine features of multiple optimization paradigms. Gradient-based optimization methods are discussed separately because they rely on deterministic search mechanisms and differentiable objective functions.

In contemporary gas-turbine research, optimization has shifted from a methodological option to an implicit publication standard. Recent studies routinely embed evolutionary and swarm-based algorithms such as NSGA-II,

particle swarm optimization, artificial bee colony, and hybrid metaheuristics to navigate highly nonlinear thermo-economic and environmental trade-offs [16]. Multi-objective formulations typically generate Pareto fronts balancing efficiency or exergy efficiency against cost or emissions, yet the subsequent selection of a "best" design often relies on ad-hoc decision tools (TOPSIS and fuzzy logic) or subjective visual inspection, weakening analytical rigor. While foundational work clarified the strengths and pitfalls of evolutionary multi-objective optimization, recent applications still prioritize algorithmic sophistication over physical insight, risking optimization consistency without commensurate improvement in decision relevance [52, 53].

Table 7 summarizes the optimization algorithms most commonly employed in gas turbine studies and highlights recurring methodological issues. Although evolutionary and swarm-based algorithms are well suited to the nonlinear, multimodal nature of GT optimization problems, their application is often undermined by incomplete reporting, absence of convergence verification, and limited justification for algorithm selection. Moreover, optimization objectives typically neglect operational constraints, part load behavior, and degradation effects, resulting in mathematically valid but operationally fragile optima. These limitations underscore the need for more rigorous and transparent optimization practice.

**Table 7. Optimization Algorithms Applied in Gas Turbine Studies.**

| Algorithm class | Typical GT optimization objectives | Reported advantages | Common limitations in GT studies | Critical observations |
|---|---|---|---|---|
| Genetic Algorithm (GA) | Thermal efficiency; exergy efficiency; cost | Conceptually simple; robust to non-convex problems | Slow convergence; sensitive to parameter tuning | Often used without convergence verification |
| NSGA-II | Multi-objective efficiency–cost–environment trade-offs | Well-established Pareto sorting; diversity preservation | Requires large populations and multiple runs | Frequently under-reported algorithm settings |
| Particle Swarm Optimization (PSO) | Efficiency–cost trade-offs; design parameter tuning | Fast convergence; easy implementation | Prone to premature convergence | Rarely benchmarked against alternatives |
| Artificial Bee Colony (ABC) | Exergy and economic optimization | Good exploration–exploitation balance | Performance sensitive to problem structure | Limited justification for algorithm choice |
| Hybrid algorithms | Multi-objective thermo-economic-environmental optimization | Improved convergence in some cases | Increased complexity and opacity | Gains rarely quantified rigorously |
| Gradient-based methods | Single-objective economic optimization | Computational efficiency | Requires smooth, differentiable models | Unsuitable for complex GT landscapes |
| Decision-making methods (TOPSIS, fuzzy logic) | Pareto solution selection | Simple ranking of solutions | Subjective weighting schemes | Often conflated with optimization itself |

Recent optimization studies confirm that gas-turbine design outcomes are highly sensitive not only to system physics but also to algorithmic choices. Applications of NSGA-II to recuperated gas-turbine cycles demonstrate that Pareto fronts shift markedly with objective formulation and post-processing preferences, complicating claims of optimality [54]. Multi-objective studies of preheated gas-turbine systems further show that thermo-economic-environmental trade-offs depend strongly on optimization strategy rather than design modifications alone [46]. Comparative analyses reveal that different metaheuristic algorithms exhibit divergent convergence behavior and Pareto quality, underscoring that optimization results are often artefacts of the chosen algorithm rather than robust system optima [16].

## 6.2 Methodological Weaknesses in GT Optimization Studies

Despite the algorithmic sophistication on display, GT optimization studies suffer from several recurrent methodological weaknesses.

The inherent limitation of design-point-based optimization is illustrated in Figure 6. Gas turbine systems optimized for a single operating condition exhibit peak performance at the nominal design point but experience disproportionately large efficiency and exergy penalties at part load. Because real gas turbines operate over wide load ranges, particularly in modern power systems with high renewable penetration, such single-point optima offer limited operational value. Multi-point optimization, by contrast, sacrifices some design-point performance to achieve more robust behavior across the full operating envelope, aligning optimization outcomes more closely with real-world operational requirements.

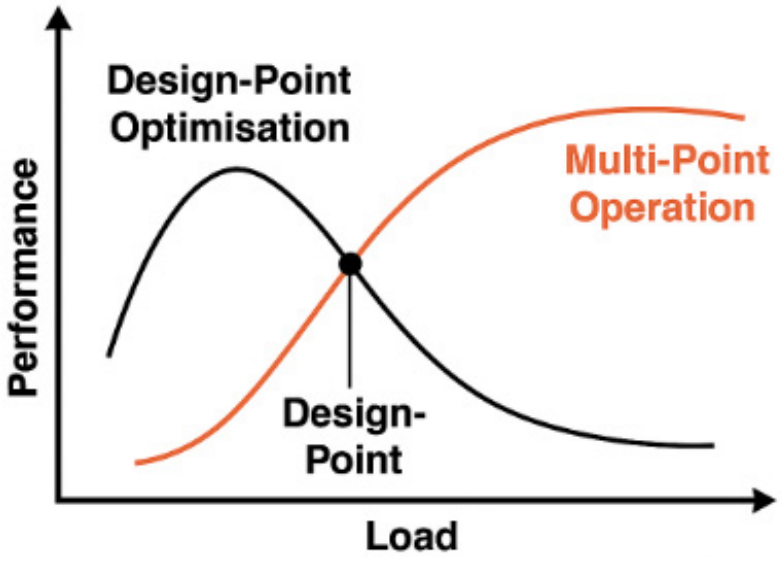


**Figure 6. Limitations of Design-Point Optimization versus Multi-Point Operation.**

Despite the growing sophistication of optimization-based gas-turbine (GT) studies, recent literature shows that many foundational modelling choices remain poorly aligned with operational reality. A persistent limitation is the continued reliance on single-point, steady-state optimization, in which parameters such as pressure ratio, turbine inlet temperature (TIT), and recuperator effectiveness are optimized at a nominal design condition. Recent reviews emphasize that these optima are often fragile when assessed under part-load, transient, or load-following operation increasingly demanded of grid-connected GTs [37, 45]. Equally problematic is the widespread treatment of TIT as a loosely bounded decision variable, frequently capped at round-number limits (1500-1600 °C) without material-level justification. Contemporary gas-turbine engineering literature makes clear that allowable firing temperatures are tightly constrained by stress-dependent creep, oxidation, cooling effectiveness, and life-consumption considerations, rendering such simplified bounds physically questionable [13, 55].

Algorithmic practice introduces a further layer of fragility. Although GT optimization problems are non-convex and multimodal, many recent studies select metaheuristic algorithms based on convention rather than systematic assessment, despite explicit warnings in modern optimization and exergy-based reviews that algorithm choice can materially affect Pareto structure and implied design preference [16, 45]. Comparative studies confirm that different algorithms yield divergent convergence behavior and solution diversity, yet convergence verification and multi-run robustness checks remain rare. Finally, objective-function formulations continue to reflect an incomplete representation of design reality. While efficiency-cost or efficiency-emissions trade-offs dominate recent work, operational flexibility, degradation, maintenance cost, startup constraints, and regulated pollutants such as $NO_x$ are still largely excluded. Consequently, published Pareto fronts often represent stylized thermodynamic trade-offs rather than decision-relevant system optima.

### 6.3 Toward More Rigorous Optimization Practice

Recent reviews argue convincingly that robust GT optimization demands a step change in methodological rigor. Multi-point and part-load optimization is now widely recognized as essential for grid-connected GTs, yet remains rarely implemented in practice [45]. Likewise, contemporary studies stress that turbine inlet temperature must be constrained by material degradation, cooling effectiveness, and life-consumption models, not arbitrary bounds [13, 55]. Modern optimization reviews further emphasize systematic algorithm comparison, multi-run convergence verification, and expanded objective spaces including maintenance and operational flexibility; however, most recent GT studies still adopt these principles only partially, limiting robustness and decision relevance [16, 37]

## 7. The E³O Framework: Toward Unified Analysis

### 7.1 Motivation and Structure

The fragmentation identified in Sections 2-6 is not accidental; it reflects the disciplinary boundaries within which

most researchers are trained and within which most journals operate. A thermodynamicist optimizes thermal efficiency; an economist minimizes levelized cost of electricity; an environmental scientist minimizes lifecycle greenhouse gas intensity. These are legitimate objectives. The problem arises when each is pursued in isolation, because gas turbines are complex, coupled systems in which thermodynamic, economic, and environmental performance interact in non-trivial ways.

Figure 8 presents the proposed E³O framework, which integrates energy, exergy, economic, environmental, and operational dimensions into a unified analytical structure. Unlike conventional approaches that treat these domains sequentially or in isolation, the E³O framework explicitly couples thermodynamic diagnostics with cost and environmental accountability while embedding system operation as both an input and an outcome. By linking exergy destruction patterns to operational behavior such as part-load performance, degradation, and maintenance scheduling, the framework enables gas turbine analysis and optimization that is not only methodologically rigorous but also directly relevant to practical operational and investment decisions.

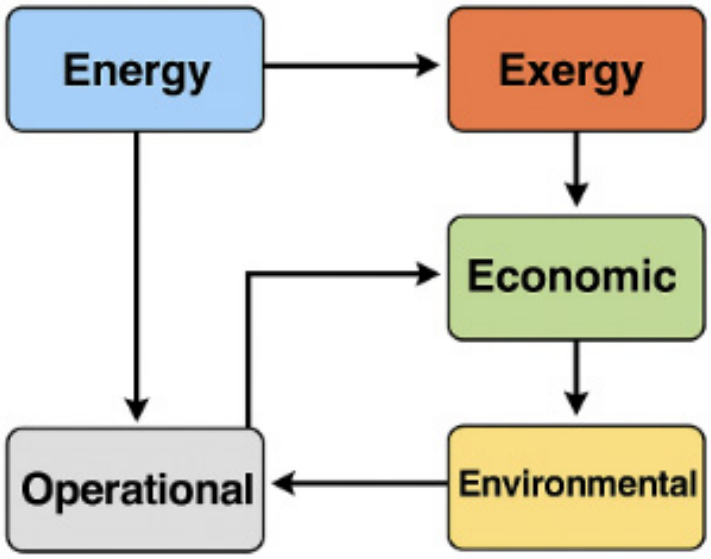


**Figure 8. The Proposed E³O Framework for Gas Turbine Analysis and Optimization.**

The E³O (Energy–Exergy–Economic–Environmental–Operational) framework proposed here is not a new algorithm or a new impact characterization method. It is a systematic structure for ensuring that GT analysis and optimization address all five dimensions coherently and simultaneously. Its five pillars are:

**Energy (E1):** First-law energy analysis providing baseline performance metrics including thermal efficiency, heat rates, and output capacity across the full operating envelope.

**Exergy (E2):** Second-law exergy analysis quantifying and locating irreversibilities at the component level, with explicit dead-state specification and, where feasible, advanced exergy decomposition into avoidable/unavoidable and endogenous/exogenous fractions.

**Economic (E3):** Exergoeconomic analysis using SPECO or equivalent methodology, with transparent, updated cost functions, explicit fuel price assumptions, and sensitivity analysis over economic parameters.

**Environmental (E4):** Exergoenvironmental analysis using a clearly specified impact characterization method (preferably ReCiPe 2016 midpoint or equivalent), with explicit system boundary definition, inclusion of manufacturing-phase burdens, and separate treatment of combustion emissions.

**Operational (E5):** Explicit modelling of part-load behavior, start-stop cycles, maintenance schedules, and degradation effects. This pillar links exergy destruction hotspots to actionable operational and maintenance decisions the connection that the existing literature most conspicuously lacks.

### 7.2 Linking Exergy Destruction to Operational Decision-making

Recent advances in exergy-based optimization increasingly emphasize that thermodynamic metrics alone are insufficient unless they are explicitly connected to operational decision-making. Advanced exergy analyses can identify

avoidable irreversibilities, yet most studies stop at classification, failing to translate reducible exergy destruction into concrete operational or maintenance levers [37, 45]. In complex multi-generation systems, recent optimization studies acknowledge improvement potential in components such as combustors and heat-recovery units, but rarely clarify whether mitigation should occur through design modification, operational adjustment, or maintenance intervention [23, 56]. At the same time, modern gas-turbine operation increasingly demands flexibility rather than peak design efficiency. Recent part-load and off-design assessments confirm that recuperated and advanced gas-turbine cycles can lose several percentage points of efficiency at mid-load conditions, fundamentally altering component priorities relative to design-point optimization [45, 55]. Optimization frameworks that ignore realistic duty cycles therefore risk producing designs that are elegant on paper but operationally fragile. Current methodological reviews argue that objective functions must integrate performance over representative operating schedules if optimization results are to remain decision-relevant in modern, load-following power systems [37].

Quantitatively, the operational pillar can be implemented through several complementary approaches. First, load-duration curves may be used to weight component-level exergy destruction according to the fraction of annual operating time spent at each load condition, thereby providing a more representative measure of lifecycle performance. Second, time-dependent degradation models accounting for compressor fouling, turbine erosion, and efficiency decay can be incorporated to track the evolution of exergy destruction over operating life. Third, maintenance scheduling optimization can explicitly evaluate the trade-off between the exergy and economic penalties associated with deferred maintenance and the costs of intervention. While these approaches are individually well established within maintenance engineering and asset-management literature, their systematic integration into exergy-based optimization remains limited. The $E^3O$ framework formalizes this integration and links thermodynamic diagnosis directly to operational decision-making.

### 7.3 Integration with Combined and Multi-generation Systems

Recent exergy-based studies increasingly demonstrate that system-level frameworks are indispensable for analyzing highly coupled GT–based configurations, where component interactions dominate overall performance. In hybrid SOFC–GT systems, modern analyses show that electrochemical losses in the fuel cell and thermodynamic behavior of the topping cycle are tightly interdependent, such that improving one subsystem can unintentionally degrade the other if treated in isolation [23, 37]. Similar coupling challenges arise in GT–ORC and waste-heat recovery systems, where recent exergy and exergoeconomic studies confirm that ORC working-fluid selection and heat-exchanger integration materially reshape system-level efficiency and cost trade-offs, invalidating conclusions drawn from GT-only assessments [37, 45]. Renewable-integrated configurations including solar-assisted and biomass-fired GT systems further amplify these interactions: contemporary analyses consistently identify upstream conversion units (gasifiers or solar receivers) as dominant sources of irreversibility, despite their indirect connection to the turbine itself. These findings underscore a central limitation of component-centric optimization and highlight the need for operationally grounded, system-integrated frameworks capable of linking thermodynamic losses to actionable design and operating decisions in complex energy systems.

## 8. Methodological Gaps and Critical Observations

### 8.1 The Dead-state Problem Revisited

The selection of the dead state is not a minor technical detail; it fundamentally determines all exergy values in a study. For chemical exergy, the composition of the reference environment (particularly $CO_2$, $H_2O$, and $N_2$ concentrations) affects the computed exergy of fuel streams. For thermal exergy, the reference temperature affects the computed exergy of heat flows. Dincer and Rosen [35] addressed these issues thoroughly, but practice in the GT literature has not followed. A survey of recent GT exergy papers reveals that at least 60% either do not specify their dead state completely or use standard conditions regardless of plant location. This is a systematic methodological gap that the $E^3O$ framework would require to be addressed explicitly.

### 8.2 Transparency in Optimization Reporting

Recent reviews of optimization in GT studies highlight a persistent lack of methodological transparency that undermines reproducibility and confidence in reported optima. Despite relying on stochastic, population-based algorithms, many contemporary GT optimization papers still omit essential details on population size, convergence criteria, parameter tuning, and multi-run verification, even though these factors are known to strongly affect Pareto structure

and solution robustness [37, 45]. Comparative studies further show that problem-specific tuning materially alters outcomes, yet such tuning is rarely disclosed, rendering many "optimal" designs algorithm-dependent artefacts rather than reproducible system solutions [16].

### 8.3 Real Plant Validation

Recent reviews reveal that model validation against real plant data remains a critical weakness in GT analysis and optimization studies. Despite increasingly sophisticated thermodynamic and exergetic formulations, most contemporary GT models are calibrated using nominal component efficiencies and remain untested against measured plant performance, particularly under part-load and transient conditions [37, 45]. Even recent optimization studies typically rely on idealized model systems, reporting Pareto-optimal designs without benchmarking against operational data. This disconnect severely limits the credibility, transferability, and decision relevance of published GT optimization results, especially for industrial application.

### 8.4 Maintenance, Degradation, and the Operational Gap

Compressor fouling, turbine blade erosion, combustor liner degradation, and seal wear all reduce GT performance over time [57]. Degradation models for gas turbines are well-developed in the maintenance engineering literature, but they are almost entirely absent from the thermodynamic analysis and optimization literature. No published GT exergoeconomic study that we are aware of incorporates a time-varying degradation model that connects maintenance scheduling to exergy destruction evolution. This is the most significant practical gap in the field, and it is central to the operational pillar of the E³O framework.

## 9. Recommended Methodological Standards

Based on the critical analysis presented in the preceding sections, we propose the following minimum methodological standards for future GT analysis and optimization studies.

Table 8 summarizes the minimum methodological standards proposed under the E³O framework and distils the central prescriptive contribution of this review. These standards are not intended to constrain analytical innovation, but rather to establish a transparent and consistent baseline for thermodynamic, exergoeconomic, exergoenvironmental, and optimization studies of gas turbine systems. By explicitly addressing long-standing gaps related to dead state definition, optimization practice, environmental accounting, and operational modelling, the proposed standards aim to improve reproducibility, comparability, and most critically the practical decision support value of future gas turbine analyses.

**Table 8. Proposed Minimum Methodological Standards under the E³O Framework**

| Standard No. | Methodological requirement | Scope and intent | Typical gap in current literature | Expected improvement |
|---|---|---|---|---|
| 1. Dead-state specification | Explicit declaration of reference temperature, pressure, and chemical composition | Ensure reproducibility and physical consistency of exergy results | Incomplete or implicit dead-state definition | Enables meaningful comparison across studies |
| 2. Energy analysis transparency | Reporting of full energy balances across operating envelope | Establish robust first-law baseline | Design-point-only reporting | Improves interpretation of off-design behaviour |
| 3. Advanced exergy clarity | Clear declaration of avoidable/unavoidable and endogenous/exogenous assumptions | Avoid overstating improvement potential | Partial or informal use of "advanced" analysis | Enhances diagnostic credibility |
| 4. Component cost function traceability | Source, date, currency year, and scaling assumptions stated | Ensure economic realism | Use of outdated or opaque cost correlations | Improves economic robustness |
| 5. Environmental method declaration | Impact method, LCA database, functional unit, and boundaries specified | Ensure exergoenvironmental consistency | Mixed or undeclared methodologies | Enables cross-study comparability |
| 6. Emission treatment transparency | Explicit treatment of combustion and non-$CO_2$ emissions | Avoid hidden environmental bias | Inconsistent handling of emissions | Strengthens environmental conclusions |
| 7. Multi-point optimization | Inclusion of design and part-load operating points | Reflect real operating conditions | Widespread design-point fixation | Improves operational relevance |

**Table 8 Continued**

| Standard No. | Methodological requirement | Scope and intent | Typical gap in current literature | Expected improvement |
|---|---|---|---|---|
| 8. Algorithm reporting | Full disclosure of optimization parameters and convergence checks | Ensure reproducibility | Incomplete algorithm descriptions | Enhances methodological rigor |
| 9. Sensitivity analysis | Systematic variation of key economic, environmental, and ambient inputs | Quantify result robustness | Single-case reporting | Supports decision-making under uncertainty |
| 10. Model validation | Benchmarking against real or reference plant data | Ground analysis in practice | Limited validation against measured data | Increases practical credibility |
| 11. Operational modelling | Inclusion of degradation, maintenance, and load-following effects | Link analysis to asset management | Operational factors largely neglected | Bridges analysis–operation gap |

**Standard 1: Dead-State Specification.** All exergy studies must fully specify the dead-state temperature, pressure, and chemical composition. For plants operating in non-standard climates, sensitivity analysis of key results to dead-state temperature should be reported.

**Standard 2: Component Cost Function Transparency.** Exergoeconomic studies must cite the source, date, and basis (location, currency year) of all investment cost functions. Uncertainty in cost estimates should be propagated into reported economic results, at minimum through sensitivity analysis.

**Standard 3: Impact Method Declaration.** Exergoenvironmental studies must declare the impact characterization method, LCA database, and functional unit explicitly. Results should be disaggregated by impact category (climate change, human health, ecosystem quality) rather than collapsed into a single weighted score, where possible.

**Standard 4: Multi-Point Optimization.** Optimization studies claiming practical applicability must include at least two operating points (typically design and part-load), or must explicitly acknowledge and quantify the limitation of single-point results.

**Standard 5: Algorithm Reporting.** All optimization studies must report: algorithm type, population size, number of generations or iterations, operator parameters, convergence criterion, number of independent runs, and the statistical spread of results across runs.

**Standard 6: Material and Operational Constraints.** Turbine inlet temperature bounds must be justified by reference to material data or manufacturer specifications. Compressor and turbine efficiency bounds must reflect current technology, not idealizations.

**Standard 7: Model Validation.** At minimum, studies should demonstrate that their thermodynamic model reproduces the design-point performance of a documented real or reference plant within stated tolerances.

**Standard 8: Sensitivity Analysis.** All reported optima must be accompanied by sensitivity analysis demonstrating the stability of results to key uncertain parameters, including fuel price, capital cost, and ambient conditions.

**Standard 9: Sensitivity Analysis.** All studies should systematically evaluate the influence of key uncertain parameters, including fuel price, capital cost, environmental impact factors, ambient temperature, and degradation rates. Where possible, uncertainty ranges should be quantified and their effects on performance indicators, optimization outcomes, and decision metrics explicitly reported. This ensures that conclusions remain robust under realistic variations in operating and economic conditions.

**Standard 10: Model Validation.** Thermodynamic, exergy, exergoeconomic, and exergoenvironmental models should be validated against measured plant data or well-documented reference cases. Validation should include both global performance metrics (e.g., power output, thermal efficiency, fuel consumption) and, where data are available, component-level performance indicators. Studies should report validation errors and discuss their implications for optimization and decision-making results.

**Standard 11: Operational Modelling.** Analyses intended to support practical decision-making should incorporate operational realities, including part-load performance, start-stop cycles, equipment degradation, maintenance scheduling, and load-following requirements. Where detailed operational models are unavailable, authors should explicitly state this limitation and assess its potential influence on reported results. Incorporating operational modelling strengthens the connection between exergy diagnostics, optimization outcomes, and real-world asset management decisions, thereby addressing one of the most significant gaps identified in the current literature.

## 10. Discussion

Across all analytical dimensions reviewed, the persistent gap between idealized modelling and plant reality emerges

as the single most important barrier to decision relevance. While validation deficiencies (Section 8.3), part-load neglect (Section 2.2), and algorithmic opacity (Section 6.2) have been discussed separately, their combined effect is to render much of the published optimization literature internally consistent but externally irrelevant. The E³O framework addresses this limitation by embedding operational realism as a constitutive pillar rather than treating it as an optional extension [37, 45].

However, the field's weaknesses are equally clear, and they are structural rather than incidental. The fragmentation between disciplinary domains means that most papers contribute a piece of the puzzle while leaving the rest out of frame. The idealization of operating conditions means that optima are often thermodynamically interesting but operationally irrelevant. The inconsistency in environmental accounting means that the accumulating literature on exergoenvironmental analysis is less cumulative than it should be; individual papers are hard to compare, and meta-conclusions are unreliable.

The E³O framework proposed here is intended as a structural response to these weaknesses. It does not prescribe specific algorithms or impact methods; it requires that all five analytical dimensions be addressed within a single study, and that the connections between them be made explicit. This is more demanding than current practice, and it will require more data, more computation, and more interdisciplinary collaboration. But the cost is justified by the gain: GT analysis that genuinely informs operational and investment decisions, rather than simply confirming that combustion chambers are irreversible.

The operational dimension deserves particular emphasis. Gas turbines in 2026 operate in power systems characterized by high penetrations of variable renewable energy, which means that GT load-following requirements are more demanding than at any previous point in their history. A gas turbine that is exergy-optimal at full load but thermodynamically degraded at 60% load is not a useful asset in a high-renewables grid. The operational pillar of E³O directly addresses this reality, and it is the dimension most urgently requiring methodological development.

## 11. Conclusion

This review has examined the state of thermodynamic, exergy, exergoeconomic, and exergoenvironmental analysis and optimization of gas turbines, drawing on approximately 55 representative publications spanning three decades of work. The principal conclusions are as follows:

**1. Disciplinary fragmentation is the field's most pervasive weakness.** Thermodynamic, exergoeconomic, and exergoenvironmental analyses are routinely conducted in isolation, preventing the field from realizing the diagnostic and decision-support potential that integrated analysis would provide.

**2. Optimization studies are frequently methodologically incomplete.** Design-point fixation, unrealistic boundary conditions, undisclosed algorithm parameters, and absent validation undermine the practical applicability of published optima.

**3. Exergoenvironmental analysis suffers from critical inconsistency.** Differences in impact characterization methods, system boundaries, and functional units render cross-study comparisons unreliable and limit the field's cumulative knowledge.

**4. The operational dimension is conspicuously absent.** Part-load behaviour, degradation, and maintenance-scheduling are almost entirely absent from GT analysis and optimization studies, despite their central importance for real-world asset management.

**5. The E³O framework provides a coherent response to these weaknesses.** By requiring simultaneous treatment of energy, exergy, economic, environmental, and operational dimensions with explicit linkages between them the framework enables GT analysis that is both scientifically rigorous and practically useful.

**6. Methodological standards are urgently needed.** The eight standards proposed in Section 9 would substantially improve the reproducibility, comparability, and applicability of future GT analytical studies.

The gas turbine will remain a critical component of energy systems for the foreseeable future, both in its conventional fossil-fuelled form and in emerging configurations burning hydrogen and ammonia. The analytical tools to study it rigorously already exist. What is needed now is the methodological discipline to apply them consistently, transparently, and in a way that genuinely serves operational and policy decision-making.

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