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Combustion-to-Work Conversion: A Cross-Platform Review of Thermo-Chemical Pathways, Cycles, and Emerging Low-Carbon Directions

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ABSTRACT

Combustion-to-work systems convert fuel chemical energy into mechanical power through coupled thermo-chemical processes and heat-engine cycles. This review synthesizes the pathway across reciprocating internal combustion engines, gas turbines, and combined cycles, emphasizing how irreversibilities accumulate from mixing and finite-rate chemistry to component aerodynamics, heat transfer, friction, and auxiliary loads. A loss-based framework is used to compare platforms on a consistent lower-heating-value basis and, where informative, through exergy destruction localization. The synthesis highlights that efficiency gains increasingly require coordinated improvements—heat-release shaping, effective expansion, minimized pressure drops, and recovery of high-quality exhaust exergy—rather than isolated component upgrades. Emissions are treated as intrinsic constraints that reshape the achievable optimum, with NOx, soot/PM, CO, and unburned hydrocarbons responding differently to temperature–mixture distributions, dilution, and residence time. Emerging directions are reviewed, including lean and staged combustors, low-temperature compression-ignition modes, hybridized operation, supercritical CO_2 bottoming cycles, and pressure-gain combustion. Finally, the review discusses fuel transitions (hydrogen, ammonia, sustainable and synthetic fuels) and the implications for stability, materials, and net climate benefit.

1. Introduction

Combustion-to-work conversion is the engineered pathway that transforms the chemical energy of fuels into useful mechanical work and, by extension, electricity. Even as renewable generation expands, combustion systems still underpin aviation, shipping, heavy-duty transport, distributed power, and many industrial services where high energy density, fast refueling, and compact powertrains matter. The pathway links fuel preparation, chemical kinetics, heat release, and a thermodynamic cycle that converts part of the released thermal energy into shaft work while rejecting the remainder as low-grade heat [1][2].

From a thermodynamic standpoint, combustion-to-work is constrained by the first and second laws. The maximum fraction of heat that can be converted to work depends on the temperature levels at which heat is added and rejected and on entropy generation caused by finite-rate reaction, imperfect mixing, friction, pressure losses, and heat transfer across finite temperature differences. Ideal cycles such as Otto, Diesel, Brayton, and Rankine provide reference limits, but real devices deviate because compression and expansion are not perfectly isentropic, heat addition is not reversible, and auxiliary systems consume work [3][4].

Historically, reciprocating internal combustion engines dominated road transport because of favorable part-load efficiency and packaging, while gas turbines enabled high power-to-weight ratios and continuous combustion suited to aviation and large-scale power. Stationary power systems evolved toward combined cycles, in which a Brayton topping cycle is paired with a Rankine bottoming cycle to recover exhaust heat and raise overall plant efficiency. These architectures illustrate a recurring theme: extracting more work from the same fuel requires both higher peak temperatures and careful recovery of exhaust energy[5][6].

Modern design treats combustion-to-work as multi-objective optimization. In addition to efficiency, systems must meet stringent limits on nitrogen oxides, carbon monoxide, unburned hydrocarbons, and particulate matter while maintaining durability, cost competitiveness, and robust operability over wide ambient and load conditions. Emissions constraints interact with combustion phasing, equivalence ratio, dilution, residence time, and peak temperature. Measures that raise peak temperature and pressure can increase efficiency but may increase NOx and heat loading, whereas measures that reduce peak temperature can suppress NOx but may penalize efficiency or stability [7][8].

Fuel–air preparation has become a first-class design variable for both engines and turbines. In engines, injection timing, atomization, spray–wall interactions, turbulence, and ignition delay govern the heat-release rate, knock margin, and soot formation. In turbines, premixing quality, swirl stabilization, staged injection, and dilution scheduling influence flame anchoring, thermoacoustic behavior, liner heat load, and emissions. Across platforms, higher injection pressures and precise metering enable closer-to-optimal phasing and allow combustion to be shaped in space and time to manage both losses and pollutant formation [9][10].

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Nomenclature

Abbreviation

AFR	Air–fuel ratio
BSFC	Brake specific fuel consumption
CCGT	Combined-cycle gas turbine
CFD	Computational fluid dynamics
EGR	Exhaust gas recirculation
HCCI	Homogeneous charge compression ignition
HRSG	Heat recovery steam generator
LHV	Lower heating value
RCCI	Reactivity controlled compression ignition

Symbol

η	Thermal efficiency (–)
$\dot{W}$	Power / work rate (W)
T	Temperature (K)

Electrification and hybridization reshape the pathway by changing how the combustion unit is dispatched. Electric machines can recover braking energy, provide torque fill, and allow the combustion subsystem to operate near higher-efficiency regions by smoothing transients and reducing time spent at low-efficiency points. In power grids with high shares of variable renewables, combustion turbines increasingly start, stop, and ramp, raising the importance of transient combustion stability, start-up emissions control, and thermal-mechanical fatigue management [11][12].

Waste-heat recovery remains a powerful lever for raising delivered work per unit fuel. Turbocharging, turbocompounding, variable valve actuation, and optimized charge motion can increase the indicated efficiency of engines and reduce pumping losses. In turbines and combined cycles, higher turbine inlet temperatures enabled by advanced materials, coatings, and cooling, along with improved compressor aerodynamics and heat-recovery steam generator designs, steadily raise performance. Emerging bottoming cycles such as supercritical carbon dioxide Brayton systems and advanced organic Rankine cycles extend recovery to smaller temperature lifts and more distributed installations [13][14].

Decarbonization intensifies interest in low-carbon fuels and combustion flexibility. Hydrogen offers zero carbon at the point of use but introduces challenges related to flashback, NOx control, storage, and materials compatibility. Ammonia and hydrogen–ammonia blends can simplify storage and enable carbon-free pathways, yet require careful management of ignition, flame speed, and pollutant formation, including potential nitrous oxide and NOx concerns. Biofuels and synthetic e-fuels can reduce lifecycle CO2 while leveraging existing infrastructure, but their net benefit depends on feedstock, process energy, and compatibility with modern combustion systems and aftertreatment [15][16].

Predictive design is difficult because combustion-to-work involves coupled turbulence, multiphase flows, radiation, detailed chemistry, and heat transfer, all interacting with moving boundaries and control systems. Modeling spans zero-dimensional cycle simulations and mean-value models used for controls, through three-dimensional CFD with reduced chemical mechanisms, to high-fidelity simulation of subsystems such as injectors and combustors. Experiments include optical diagnostics, shock tubes, laminar flame measurements, rapid compression machines, and full-scale engine or combustor rig testing. Bridging model scales and experimental conditions is therefore a central task for the field[17][18].

This review synthesizes the combustion-to-work pathway from chemical energy release through thermodynamic conversion and system integration. We emphasize how irreversibilities accumulate across the chain and how design levers—mixture preparation, heat-release shaping, component efficiency, and recovery of waste heat—can increase delivered work while meeting emissions and operability constraints. We also highlight emerging directions such as pressure-gain combustion, fuel-flexible combustors, and tightly coupled hybrid powertrains that blur traditional boundaries between combustion, cycles, and electrified systems [19][20].

A practical way to frame the pathway is as an exergy budget. Fuel chemical exergy enters the system and is destroyed through mixing, finite-rate chemistry, and heat transfer, while the remainder is converted to useful work and unavoidable low-grade waste heat. Exergy accounting is especially valuable when comparing technologies that appear similar in thermal efficiency but differ in the location and magnitude of irreversibilities, such as premixed versus diffusion flames, or recuperated cycles versus simple cycles.

Equally important is the role of control and operation. Modern combustion-to-work devices rarely operate at a single design point; instead they must deliver performance over changing load, ambient conditions, fuel quality, and component aging. Closed-loop sensing, combustion phasing control, variable geometry hardware, and model-based supervisory strategies determine whether theoretical improvements translate into real-world fuel savings and emissions compliance.

The remainder of this paper is organized around a consistent set of metrics and design levers. After defining key terms and symbols, we describe the methodology used to structure the review, including how representative operating conditions, loss categories, and emissions pathways are compared across platforms. We then present a results synthesis supported by illustrative figures and summary tables, followed by a discussion of cross-cutting insights and research gaps.

2. Methodology

In reviewing the review framework, it is helpful to compare reciprocating and turbine platforms under consistent metrics. This synthesis shows that the literature spans combustion chemistry, thermodynamic cycles, component aerodynamics, and system-level controls, so a structured taxonomy is required. This synthesis clarifies that results are grouped by platform (engines, turbines, combined cycles) and then mapped onto shared loss categories. This synthesis reveals that the same definition of lower heating value basis and reference environment is used when discussing energy and exergy performance. Across reported studies, improvements that raise peak temperature or pressure ratio typically increase cycle efficiency, but they must be balanced against material limits, stability margins, and emissions formation pathways. For meaningful comparison, the review reports results in terms of brake or net efficiency, specific work, and normalized loss fractions, while also tracking how control constraints shift the optimum away from ideal-cycle predictions. [21][22]

Cycle definitions and baselines can be understood by separating thermodynamic limits from device-level losses. This synthesis demonstrates that ideal Otto, Diesel, and Brayton cycles are used as baselines to explain why compression ratio, pressure ratio, and heat-addition process shape efficiency. This synthesis reveals that real systems are compared at representative load points rather than only at full-load nameplate conditions. This synthesis highlights that where available, uncertainty bands are reported because small differences in boundary conditions can change inferred efficiencies. Across reported studies, improvements that raise peak temperature or pressure ratio typically increase cycle efficiency, but they must be balanced against material limits, stability margins, and emissions formation pathways. For meaningful comparison, the review reports results in terms of brake or net efficiency, specific work, and normalized loss fractions, while also tracking how control constraints shift the optimum away from ideal-cycle predictions. [23][24]

A cross-platform view of loss accounting highlights how chemical energy release interacts with flow work and heat transfer. This synthesis reveals that loss channels are defined consistently, including exhaust/stack losses, coolant and heat-transfer losses, friction and pumping losses, incomplete combustion, and auxiliary consumption. This synthesis demonstrates that exergy destruction is estimated from published temperature and composition data to identify where irreversibilities concentrate. This synthesis shows that comparisons distinguish between avoidable and unavoidable losses to prevent misleading conclusions. Across reported studies, improvements that raise peak temperature or pressure ratio typically increase cycle efficiency, but they must be balanced against material limits, stability margins, and emissions formation pathways. For meaningful comparison, the review reports results in terms of brake or net efficiency, specific work, and normalized loss fractions, while also tracking how control constraints shift the optimum away from ideal-cycle predictions. [25][26]

Table 1. Typical combustion-to-work platforms and representative performance ranges

Platform	Representative operating regime	Net/brake efficiency	Key levers / limits
SI engine (road)	Part-load to full-load; throttled to boosted	0.28–0.42	Knock, heat transfer, pumping; boosting and phasing control
CI engine (HD)	High load; unthrottled	0.38–0.47	Soot–NOx trade-off; injection rate shaping; aftertreatment backpressure
Simple-cycle GT	Mid-to-high load; firing-temperature limited	0.30–0.40	Turbine inlet temperature, pressure ratio, cooling & pressure losses

Table 2. Common combustion regimes in engines and turbines and their typical trade-offs

Combustion mode	Mixture/ignition characteristics	Main benefits	Primary challenges
Premixed SI	Premixed charge; spark ignition	Low soot; good transient response	Knock; throttling losses at light load
Diffusion CI	Stratified; autoignition with diffusion burn	High efficiency at load	Soot–NOx trade-off; aftertreatment complexity
Partially premixed CI	Enhanced premixing via injection strategy	Lower soot; smoother heat release	Control across load; sensitivity to conditions

Table 3. Representative fuel properties relevant to combustion-to-work conversion

Fuel	LHV (MJ/kg)	Stoichiometric AFR (kg air/kg fuel)
Natural gas (CH_4-rich)	≈50	≈17.2
Gasoline	≈43	≈14.7
Diesel	≈43	≈14.5

Emissions and constraints can be understood by separating thermodynamic limits from device-level losses. This synthesis reveals that NOx, soot/PM, CO, and UHC are tracked as co-evolving outputs rather than independent metrics. This synthesis clarifies that constraints such as knock, flashback, lean blowout, and thermoacoustic instability are treated as operational boundaries that limit attainable efficiency. This synthesis clarifies that aftertreatment and dilution strategies are included because they feed back into pumping work and overall efficiency. Across reported studies, improvements that raise peak temperature or pressure ratio typically increase cycle efficiency, but they must be balanced against material limits, stability margins, and emissions formation pathways. For meaningful comparison, the review reports results in terms of brake or net efficiency, specific work, and normalized loss fractions, while also tracking how control constraints shift the optimum away from ideal-cycle predictions. [27][28]

Fuels and properties can be understood by separating thermodynamic limits from device-level losses. This synthesis shows that fuels are characterized by LHV, stoichiometric air–fuel ratio, flame speed trends, ignition quality, and storage constraints. This synthesis reveals that lifecycle carbon intensity is discussed qualitatively to separate tailpipe emissions from well-to-wheel impacts. This synthesis demonstrates that fuel-flexible designs are compared by their ability to maintain stable combustion while meeting emissions limits. Across reported studies, improvements that raise peak temperature or pressure ratio typically increase cycle efficiency, but they must be balanced against material limits, stability margins, and emissions formation pathways. For meaningful comparison, the review reports results in terms of brake or net efficiency, specific work, and normalized loss fractions, while also tracking how control constraints shift the optimum away from ideal-cycle predictions. [29][30]

Modeling and experiments performance depends on coupled choices in combustion mode, component efficiency, and operating strategy. This synthesis reveals that a hierarchy of models is mapped to decisions they support, from control-oriented mean-value models to CFD for combustor and in-cylinder design. This synthesis demonstrates that experimental evidence is weighted by measurement fidelity and relevance to full-scale operating conditions. This synthesis reveals that special attention is given to optical diagnostics and transient measurements that connect chemistry to heat-release timing. Across reported studies, improvements that raise peak temperature or pressure ratio typically increase cycle efficiency, but they must be balanced against material limits, stability margins, and emissions formation pathways. For meaningful comparison, the review reports results in terms of brake or net efficiency, specific work, and normalized loss fractions, while also tracking how control constraints shift the optimum away from ideal-cycle predictions. [31][32]

A useful synthesis for data extraction begins with identifying the dominant irreversibilities along the chain. This synthesis demonstrates that reported values are normalized to common bases to enable cross-study comparison, including correction for ambient conditions where possible. This synthesis reveals that ranges are summarized rather than single-point values, reflecting platform diversity and different duty cycles. This synthesis demonstrates that when studies disagree, the review identifies the likely source of divergence such as boundary conditions or different efficiency definitions. Across reported studies, improvements that raise peak temperature or pressure ratio typically increase cycle efficiency, but they must be balanced against material limits, stability margins, and emissions formation pathways. For meaningful comparison, the review reports results in terms of brake or net efficiency, specific work, and normalized loss fractions, while also tracking how control constraints shift the optimum away from ideal-cycle predictions. [33][34]

A cross-platform view of technology grouping highlights how chemical energy release interacts with flow work and heat transfer. This synthesis clarifies that combustion strategies are categorized by mixture preparation and ignition mode, enabling comparison of premixed, partially premixed, and diffusion regimes. This synthesis reveals that advanced concepts such as HCCI, RCCI, and pressure-gain combustion are evaluated using the same loss accounting framework. This synthesis shows that hybridization is treated as a system-level architecture that changes the required operating envelope of the combustion unit. Across reported studies, improvements that raise peak temperature or pressure ratio typically increase cycle efficiency, but they must be balanced against material limits, stability margins, and emissions formation pathways. For meaningful comparison, the review reports results in terms of brake or net efficiency, specific work, and normalized loss fractions, while also tracking how control constraints shift the optimum away from ideal-cycle predictions. [35][36]

Evaluation metrics can be understood by separating thermodynamic limits from device-level losses. This synthesis demonstrates that thermal efficiency is complemented by exergy efficiency to capture the penalty of low-grade heat rejection. This synthesis shows that specific power and power density are tracked because they drive packaging and cost, especially in transport applications. This synthesis highlights that transient response and durability are included as metrics that can dominate real-world performance. Across reported studies, improvements that raise peak temperature or pressure ratio typically increase cycle efficiency, but they must be balanced against material limits, stability margins, and emissions formation pathways. For meaningful comparison, the review reports results in terms of brake or net efficiency, specific work, and normalized loss fractions, while also tracking how control constraints shift the optimum away from ideal-cycle predictions. [37][38]

Synthesis and gap identification performance depends on coupled choices in combustion mode, component efficiency, and operating strategy. This synthesis shows that the review converts dispersed results into comparable plots and tables to reveal robust trends and remaining uncertainties. This synthesis demonstrates that gaps are identified where loss breakdowns or emissions trade-offs are not reported in a comparable way. This synthesis reveals that recommendations focus on experiments and models that can reduce the largest sources of uncertainty for next-generation designs. Across reported studies, improvements that raise peak temperature or pressure ratio typically increase cycle efficiency, but they must be balanced against material limits, stability margins, and emissions formation pathways. For meaningful comparison, the review reports results in terms of brake or net efficiency, specific work, and normalized loss fractions, while also tracking how control constraints shift the optimum away from ideal-cycle predictions. [39][40]

3. Results

Reciprocating engines: baseline conversion and dominant losses studies consistently report that the dominant losses shift with load and ambient conditions, so conclusions based only on rated points can be misleading. Evidence indicates that brake efficiency is largely set by indicated efficiency minus friction and pumping penalties, with heat transfer and exhaust enthalpy forming the largest energy outflows. Evidence indicates that higher compression ratio generally increases thermal efficiency, but knock and peak-pressure constraints often require dilution, cooled EGR, or advanced ignition strategies. Evidence indicates that combustion duration and phasing relative to top dead center strongly influence both work extraction and heat transfer losses. When plotted on a normalized basis, the best-performing configurations reduce a combination of exhaust enthalpy losses and internal irreversibilities, often by increasing effective expansion and improving heat recovery. However, these gains are bounded by material temperature limits, compressor or turbocharger surge margins, and the need to maintain stable, low-emissions combustion over transients. Reported data also show that control authority and sensing quality determine how closely an engine or combustor can track its optimum, particularly under strict emissions constraints. Overall, the synthesis supports using energy and exergy loss maps rather than single efficiencies, because the maps reveal where future research and design can yield the highest return. [41]

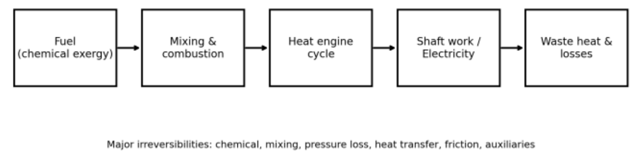

Fig. 1. Schematic of the combustion-to-work chain and major loss channels absorption chiller, RO unit, and MD/HDH polisher with recovered heat streams.

A central finding in Turbocharging, downsizing, and gas exchange optimization is that efficiency gains are rarely attributable to a single change; rather, they arise from coordinated improvements in combustion, gas exchange, and component aerodynamics. Evidence indicates that boosting increases charge density and enables downsizing, which can reduce friction via smaller displacement while maintaining torque demand. Evidence indicates that improved turbine and compressor efficiency shifts more exhaust exergy into useful boost, but increased backpressure can raise pumping work if not carefully managed. Evidence indicates that advanced valve timing and variable geometry help manage the trade-off between scavenging, residual fraction, and turbo response. When plotted on a normalized basis, the best-performing configurations reduce a combination of exhaust enthalpy losses and internal irreversibilities, often by increasing effective expansion and improving heat recovery. However, these gains are bounded by material temperature limits, compressor or turbocharger surge margins, and the need to maintain stable, low-emissions combustion over transients. Reported data also show that control authority and sensing quality determine how closely an engine or combustor can track its optimum, particularly under strict emissions constraints. Overall, the synthesis supports using energy and exergy loss maps rather than single efficiencies, because the maps reveal where future research and design can yield the highest return. [42]

Lean-burn and dilution strategies for efficiency and NOx control studies consistently report that the dominant losses shift with load and ambient conditions, so conclusions based only on rated points can be misleading. Evidence indicates that lean operation reduces pumping losses in throttled SI engines and can lower combustion temperatures, yet it can increase cycle-to-cycle variability and misfire risk. Evidence indicates that high dilution via EGR or excess air can suppress NOx, but it lengthens combustion and raises unburned hydrocarbon and CO if mixing and ignition are not robust. Evidence indicates that high-energy ignition systems and pre-chambers can extend lean limits by creating hot turbulent jets that accelerate burning. When plotted on a normalized basis, the best-performing configurations reduce a combination of exhaust enthalpy losses and internal irreversibilities, often by increasing effective expansion and improving heat recovery. However, these gains are bounded by material temperature limits, compressor or turbocharger surge margins, and the need to maintain stable, low-emissions combustion over transients. Reported data also show that control authority and sensing quality determine how closely an engine or combustor can track its optimum, particularly under strict emissions constraints. Overall, the synthesis supports using energy and exergy loss maps rather than single efficiencies, because the maps reveal where future research and design can yield the highest return. [43]

Compression-ignition combustion modes and soot–NOx trade-offs studies consistently report that the dominant losses shift with load and ambient conditions, so conclusions based only on rated points can be misleading. Evidence indicates that diesel diffusion combustion naturally produces high efficiency at high load, but local rich zones promote soot formation and require aftertreatment and high injection pressures. Evidence indicates that low-temperature combustion concepts attempt to avoid soot by premixing and lowering peak temperature, but they often face controllability and narrow operating windows. Evidence indicates that multiple injections and rate shaping provide a practical means to balance noise, efficiency, and emissions. When plotted on a normalized basis, the best-performing configurations reduce a combination of exhaust enthalpy losses and internal irreversibilities, often by increasing effective expansion and improving heat recovery. However, these gains are bounded by material temperature limits, compressor or turbocharger surge margins, and the need to maintain stable, low-emissions combustion over transients. Reported data also show that control authority and sensing quality determine how closely an engine or combustor can track its optimum, particularly under strict emissions constraints. Overall, the synthesis supports using energy and exergy loss maps rather than single efficiencies, because the maps reveal where future research and design can yield the highest return. [44]

HCCI, RCCI, and partially premixed combustion results across the literature can be synthesized by tracking how heat-release timing and pressure ratio shape the work output. Evidence indicates that autoignition-based modes reduce throttling losses and can lower NOx and soot by operating at lower temperatures and more homogeneous mixtures. Evidence indicates that the main challenge is controlling the start of combustion and burn rate over load and speed, which motivates stratification, variable valve timing, and dual-fuel strategies. Evidence indicates that reported demonstrations show efficiency potential, but durable, sensor-based control remains a key barrier for wide deployment. When plotted on a normalized basis, the best-performing configurations reduce a combination of exhaust enthalpy losses and internal irreversibilities, often by increasing effective expansion and improving heat recovery. However, these gains are bounded by material temperature limits, compressor or turbocharger surge margins, and the need to maintain stable, low-emissions combustion over transients. Reported data also show that control authority and sensing quality determine how closely an engine or combustor can track its optimum, particularly under strict emissions constraints. Overall, the synthesis supports using energy and exergy loss maps rather than single efficiencies, because the maps reveal where future research and design can yield the highest return. [45]

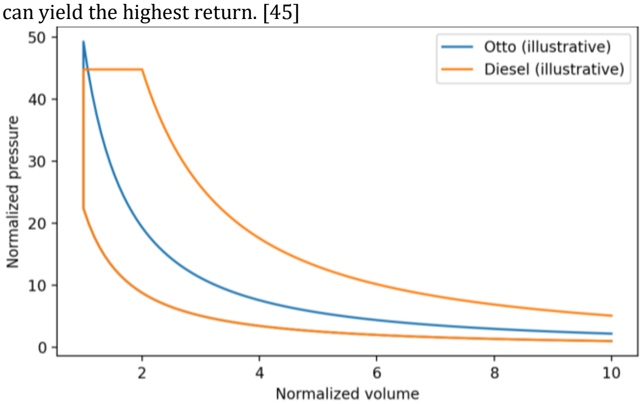

Fig. 2. Idealized p–V diagrams for Otto and Diesel cycles.

Gas turbines: Brayton cycle performance drivers results across the literature can be synthesized by tracking how heat-release timing and pressure ratio shape the work output. Evidence indicates that turbine inlet temperature and overall pressure ratio set the thermodynamic potential, while compressor and turbine isentropic efficiencies determine the realized performance. Evidence indicates that cooling flows and leakage reduce the effective temperature ratio and therefore lower cycle efficiency even when firing temperature rises. Evidence indicates that recuperation can raise part-load efficiency for smaller turbines, but pressure drops in heat exchangers and off-design matching can limit benefits. When plotted on a normalized basis, the best-performing configurations reduce a combination of exhaust enthalpy losses and internal irreversibilities, often by increasing effective expansion and improving heat recovery. However, these gains are bounded by material temperature limits, compressor or turbocharger surge margins, and the need to maintain stable, low-emissions combustion over transients. Reported data also show that control authority and sensing quality determine how closely an engine or combustor can track its optimum, particularly under strict emissions constraints. Overall, the synthesis supports using energy and exergy loss maps rather than single efficiencies, because the maps reveal where future research and design can yield the highest return. [46]

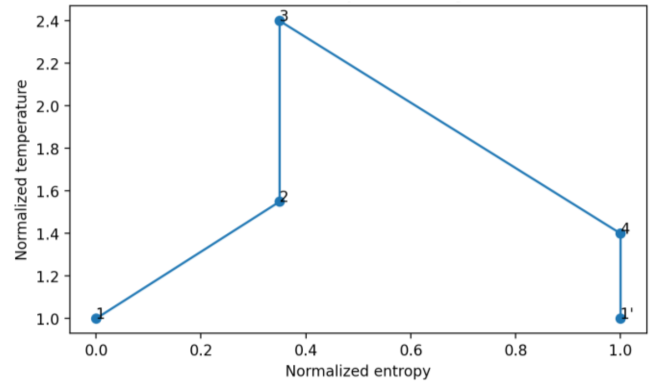

Fig. 3. T–s diagram for a simple Brayton cycle

Combustor design and emissions in lean premixed systems studies consistently report that the dominant losses shift with load and ambient conditions, so conclusions based only on rated points can be misleading. Evidence indicates that lean premixed combustion can reduce NOx by lowering peak flame temperature, but it increases susceptibility to thermoacoustic instability and lean blowout. Evidence indicates that swirl stabilization and staged fueling expand the stable operating range, yet they introduce mixing non-uniformity that can affect both emissions and liner durability. Evidence indicates that water or steam dilution can suppress NOx and moderate temperature, but it imposes efficiency penalties and adds system complexity. When plotted on a normalized basis, the best-performing configurations reduce a combination of exhaust enthalpy losses and internal irreversibilities, often by increasing effective expansion and improving heat recovery. However, these gains are bounded by material temperature limits, compressor or turbocharger surge margins, and the need to maintain stable, low-emissions combustion over transients. Reported data also show that control authority and sensing quality determine how closely an engine or combustor can track its optimum, particularly under strict emissions constraints. Overall, the synthesis supports using energy and exergy loss maps rather than single efficiencies, because the maps reveal where future research and design can yield the highest return. [47]

Combined cycle plants and heat recovery limits studies consistently report that the dominant losses shift with load and ambient conditions, so conclusions based only on rated points can be misleading. Evidence indicates that CCGT efficiency gains primarily come from recovering high-temperature exhaust heat into steam generation, reducing the exergy destroyed in single-cycle exhaust rejection. Evidence indicates that pinch-point constraints in the heat recovery steam generator and condenser temperature govern how much heat can be effectively converted to additional work. Evidence indicates that triple-pressure HRSGs and reheat stages improve recovery, but they increase cost and operational complexity. When plotted on a normalized basis, the best-performing configurations reduce a combination of exhaust enthalpy losses and internal irreversibilities, often by increasing effective expansion and improving heat recovery. However, these gains are bounded by material temperature limits, compressor or turbocharger surge margins, and the need to maintain stable, low-emissions combustion over transients. Reported data also show that control authority and sensing quality determine how closely an engine or combustor can track its optimum, particularly under strict emissions constraints. Overall, the synthesis supports using energy and exergy loss maps rather than single efficiencies, because the maps reveal where future research and design can yield the highest return. [48]

Supercritical CO2 and advanced bottoming cycles studies consistently report that the dominant losses shift with load and ambient conditions, so conclusions based only on rated points can be misleading. Evidence indicates that sCO2 cycles can offer compact turbomachinery and high efficiency at moderate temperature levels, making them attractive for waste-heat recovery and next-generation power plants. Evidence indicates that cycle performance depends on recuperator effectiveness and pressure drop, which can dominate net efficiency especially at small scale. Evidence indicates that integration studies show benefits when sCO2 matches the temperature glide of the heat source, but materials and sealing challenges remain. When plotted on a normalized basis, the best-performing configurations reduce a combination of exhaust enthalpy losses and internal irreversibilities, often by increasing effective expansion and improving heat recovery. However, these gains are bounded by material temperature limits, compressor or turbocharger surge margins, and the need to maintain stable, low-emissions combustion over transients. Reported data also show that control authority and sensing quality determine how closely an engine or combustor can track its optimum, particularly under strict emissions constraints. Overall, the synthesis supports using energy and exergy loss maps rather than single efficiencies, because the maps reveal where future research and design can yield the highest return. [49]

Pressure-gain combustion and detonation concepts results across the literature can be synthesized by tracking how heat-release timing and pressure ratio shape the work output. Evidence indicates that pressure-gain combustion aims to increase cycle efficiency by adding heat at rising pressure rather than at constant pressure, reducing compressor work for a given turbine work. Evidence indicates that rotating detonation engines and pulse detonation combustors show promising pressure ratios in experiments, but achieving stable, low-loss operation at practical scales is challenging. Evidence indicates that integration into gas turbines requires managing unsteadiness, mixing, and component matching. When plotted on a normalized basis, the best-performing configurations reduce a combination of exhaust enthalpy losses and internal irreversibilities, often by increasing effective expansion and improving heat recovery. However, these gains are bounded by material temperature limits, compressor or turbocharger surge margins, and the need to maintain stable, low-emissions combustion over transients. Reported data also show that control authority and sensing quality determine how closely an engine or combustor can track its optimum, particularly under strict emissions constraints. Overall, the synthesis supports using energy and exergy loss maps rather than single efficiencies, because the maps reveal where future research and design can yield the highest return. [50]

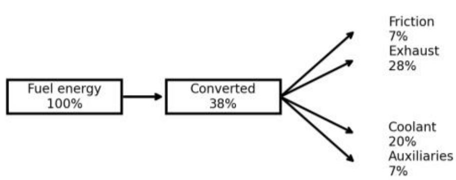

Fig. 4 Normalized fuel-energy conversion to shaft work and losses.

A central finding in Low-carbon fuels: hydrogen, ammonia, and e-fuels in engines and turbines is that efficiency gains are rarely attributable to a single change; rather, they arise from coordinated improvements in combustion, gas exchange, and component aerodynamics. Evidence indicates that hydrogen enables high flame speed and wide flammability but can increase NOx unless temperature is controlled through lean burn or dilution. Evidence indicates that ammonia's low reactivity and potential NOx/N2O pathways require either cracking, pilot fuels, or advanced ignition strategies to achieve acceptable stability. Evidence indicates that drop-in synthetic fuels can preserve existing architectures, but their net climate benefit depends on upstream electricity and CO2 sourcing. When plotted on a normalized basis, the best-performing configurations reduce a combination of exhaust enthalpy losses and internal irreversibilities, often by increasing effective expansion and improving heat recovery. However, these gains are bounded by material temperature limits, compressor or turbocharger surge margins, and the need to maintain stable, low-emissions combustion over transients. Reported data also show that control authority and sensing quality determine how closely an engine or combustor can track its optimum, particularly under strict emissions constraints. Overall, the synthesis supports using energy and exergy loss maps rather than single efficiencies, because the maps reveal where future research and design can yield the highest return. [51]

Aftertreatment, auxiliaries, and system-level penalties results across the literature can be synthesized by tracking how heat-release timing and pressure ratio shape the work output. Evidence indicates that aftertreatment systems reduce tailpipe emissions but can impose backpressure, thermal management requirements, and ammonia slip control that affect efficiency. Evidence indicates that auxiliary loads such as pumps, compressors, and cooling fans can materially reduce net efficiency, particularly in small-scale systems. Evidence indicates that system optimization therefore requires co-design of the combustion unit, controls, and balance-of-plant. When plotted on a normalized basis, the best-performing configurations reduce a combination of exhaust enthalpy losses and internal irreversibilities, often by increasing effective expansion and improving heat recovery. However, these gains are bounded by material temperature limits, compressor or turbocharger surge margins, and the need to maintain stable, low-emissions combustion over transients. Reported data also show that control authority and sensing quality determine how closely an engine or combustor can track its optimum, particularly under strict emissions constraints. Overall, the synthesis supports using energy and exergy loss maps rather than single efficiencies, because the maps reveal where future research and design can yield the highest return. [52]

Loss maps and exergy destruction localization studies consistently report that the dominant losses shift with load and ambient conditions, so conclusions based only on rated points can be misleading. Evidence indicates that exergy analysis often identifies the combustor or in-cylinder heat release as the single largest site of exergy destruction due to chemical irreversibility and heat transfer. Evidence indicates that heat recovery can reduce the penalty of exhaust losses but cannot eliminate the irreversibility of combustion itself, which motivates research into staged or catalytic pathways. Evidence indicates that component improvements shift the relative importance of losses, so future gains increasingly require integrated, multi-domain optimization. When plotted on a normalized basis, the best-performing configurations reduce a combination of exhaust enthalpy losses and internal irreversibilities, often by increasing effective expansion and improving heat recovery. However, these gains are bounded by material temperature limits, compressor or turbocharger surge margins, and the need to maintain stable, low-emissions combustion over transients. Reported data also show that control authority and sensing quality determine how closely an engine or combustor can track its optimum, particularly under strict emissions constraints. Overall, the synthesis supports using energy and exergy loss maps rather than single efficiencies, because the maps reveal where future research and design can yield the highest return. [53]

Illustrative figures and synthesized trends studies consistently report that the dominant losses shift with load and ambient conditions, so conclusions based only on rated points can be misleading. Evidence indicates that schematic energy-flow diagrams help connect microscopic combustion processes to macroscopic losses and work output, clarifying where improvements can have leverage. Evidence indicates that p–V and T–s representations remain valuable for interpreting how heat-release shaping and pressure ratio affect work, even for highly complex real cycles. Evidence indicates that contour maps of emissions proxies versus mixture and temperature illustrate why some operating points are inherently constrained by chemistry. When plotted on a normalized basis, the best-performing configurations reduce a combination of exhaust enthalpy losses and internal irreversibilities, often by increasing effective expansion and improving heat recovery. However, these gains are bounded by material temperature limits, compressor or turbocharger surge margins, and the need to maintain stable, low-emissions combustion over transients. Reported data also show that control authority and sensing quality determine how closely an engine or combustor can track its optimum, particularly under strict emissions constraints. Overall, the synthesis supports using energy and exergy loss maps rather than single efficiencies, because the maps reveal where future research and design can yield the highest return. [54]

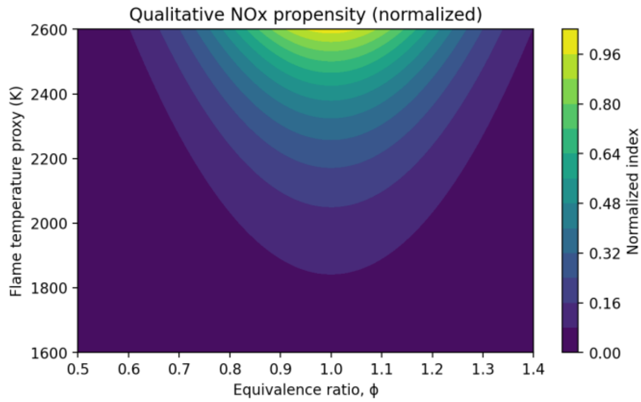

Fig. 5. Qualitative NOx formation landscape as a function of equivalence ratio and flame temperature proxy (normalized).

Materials, cooling, and temperature capability results across the literature can be synthesized by tracking how heat-release timing and pressure ratio shape the work output. Evidence indicates that higher firing temperatures improve cycle potential, but blade metal temperature is limited by creep, oxidation, and thermal fatigue, necessitating complex cooling schemes. Evidence indicates that thermal barrier coatings and improved cooling effectiveness reduce the penalty of cooling air extraction, yet they add manufacturing complexity and may degrade over time. Evidence indicates that in engines, advanced alloys and improved heat management enable higher peak pressures and compression ratios, but they also raise mechanical losses if not paired with friction reduction. When plotted on a normalized basis, the best-performing configurations reduce a combination of exhaust enthalpy losses and internal irreversibilities, often by increasing effective expansion and improving heat recovery. However, these gains are bounded by material temperature limits, compressor or turbocharger surge margins, and the need to maintain stable, low-emissions combustion over transients. Reported data also show that control authority and sensing quality determine how closely an engine or combustor can track its optimum, particularly under strict emissions constraints. Overall, the synthesis supports using energy and exergy loss maps rather than single efficiencies, because the maps reveal where future research and design can yield the highest return. [55]

Friction, lubrication, and mechanical efficiency improvements studies consistently report that the dominant losses shift with load and ambient conditions, so conclusions based only on rated points can be misleading. Evidence indicates that measured friction mean effective pressure decreases with optimized ring packs, surface texturing, low-viscosity lubricants, and reduced accessory drive loads. Evidence indicates that at light load, pumping and accessory losses can dominate, so variable displacement oil pumps and smart thermal management deliver disproportionate benefits. Evidence indicates that mechanical losses and heat-transfer losses interact because wall temperatures and viscosity change with operating strategy. When plotted on a normalized basis, the best-performing configurations reduce a combination of exhaust enthalpy losses and internal irreversibilities, often by increasing effective expansion and improving heat recovery. However, these gains are bounded by material temperature limits, compressor or turbocharger surge margins, and the need to maintain stable, low-emissions combustion over transients. Reported data also show that control authority and sensing quality determine how closely an engine or combustor can track its optimum, particularly under strict emissions constraints. Overall, the synthesis supports using energy and exergy loss maps rather than single efficiencies, because the maps reveal where future research and design can yield the highest return. [56]

Waste-heat recovery in transport applications results across the literature can be synthesized by tracking how heat-release timing and pressure ratio shape the work output. Evidence indicates that bottoming cycles recover a fraction of exhaust enthalpy, but packaging, transient heat availability, and condenser temperature limit practical recovery in vehicles. Evidence indicates that thermoelectric generators provide compact conversion but remain constrained by material figure of merit and thermal contact resistances. Evidence indicates that turbocompounding can be efficient because it leverages high-quality exhaust exergy directly on the shaft, yet it requires careful drivetrain integration. When plotted on a normalized basis, the best-performing configurations reduce a combination of exhaust enthalpy losses and internal irreversibilities, often by increasing effective expansion and improving heat recovery. However, these gains are bounded by material temperature limits, compressor or turbocharger surge margins, and the need to maintain stable, low-emissions combustion over transients. Reported data also show that control authority and sensing quality determine how closely an engine or combustor can track its optimum, particularly under strict emissions constraints. Overall, the synthesis supports using energy and exergy loss maps rather than single efficiencies, because the maps reveal where future research and design can yield the highest return. [57]

Distributed generation, microturbines, and CHP studies consistently report that the dominant losses shift with load and ambient conditions, so conclusions based only on rated points can be misleading. Evidence indicates that combined heat and power improves overall fuel utilization by using low-grade heat for buildings or processes, effectively increasing the useful exergy extracted from fuel. Evidence indicates that microturbines benefit from recuperation and low emissions, but their small scale amplifies relative pressure drops and heat-exchanger losses. Evidence indicates that real-world CHP performance depends on matching heat-to-power ratio with site demand and maintaining high availability. When plotted on a normalized basis, the best-performing configurations reduce a combination of exhaust enthalpy losses and internal irreversibilities, often by increasing effective expansion and improving heat recovery. However, these gains are bounded by material temperature limits, compressor or turbocharger surge margins, and the need to maintain stable, low-emissions combustion over transients. Reported data also show that control authority and sensing quality determine how closely an engine or combustor can track its optimum, particularly under strict emissions constraints. Overall, the synthesis supports using energy and exergy loss maps rather than single efficiencies, because the maps reveal where future research and design can yield the highest return. [58]

Aviation propulsion: combustor constraints and efficiency trends results across the literature can be synthesized by tracking how heat-release timing and pressure ratio shape the work output. Evidence indicates that overall efficiency in turbofans is shaped by both thermal efficiency and propulsive efficiency, making pressure ratio, bypass ratio, and turbine cooling central to performance. Evidence indicates that lean-burn and staged combustors aim to reduce NOx while preserving stability across altitude relight and transient acceleration requirements. Evidence indicates that sustainable aviation fuels largely preserve combustion behavior but can influence soot precursor chemistry and particulate emissions depending on aromatic content. When plotted on a normalized basis, the best-performing configurations reduce a combination of exhaust enthalpy losses and internal irreversibilities, often by increasing effective expansion and improving heat recovery. However, these gains are bounded by material temperature limits, compressor or turbocharger surge margins, and the need to maintain stable, low-emissions combustion over transients. Reported data also show that control authority and sensing quality determine how closely an engine or combustor can track its optimum, particularly under strict emissions constraints. Overall, the synthesis supports using energy and exergy loss maps rather than single efficiencies, because the maps reveal where future research and design can yield the highest return. [59]

A central finding in Combustion stability and transient operability is that efficiency gains are rarely attributable to a single change; rather, they arise from coordinated improvements in combustion, gas exchange, and component aerodynamics. Evidence indicates that transients introduce additional loss mechanisms such as compressor surge avoidance and enriched fueling for stability, which can temporarily increase emissions and reduce efficiency. Evidence indicates that dynamic matching of turbochargers or compressor maps with fuel scheduling is a control problem that often dominates real-world fuel consumption in stop–start duty cycles. Evidence indicates that fast sensing and closed-loop combustion control reduce variability and enable operation closer to limits without violating emissions constraints. When plotted on a normalized basis, the best-performing configurations reduce a combination of exhaust enthalpy losses and internal irreversibilities, often by increasing effective expansion and improving heat recovery. However, these gains are bounded by material temperature limits, compressor or turbocharger surge margins, and the need to maintain stable, low-emissions combustion over transients. Reported data also show that control authority and sensing quality determine how closely an engine or combustor can track its optimum, particularly under strict emissions constraints. Overall, the synthesis supports using energy and exergy loss maps rather than single efficiencies, because the maps reveal where future research and design can yield the highest return. [60]

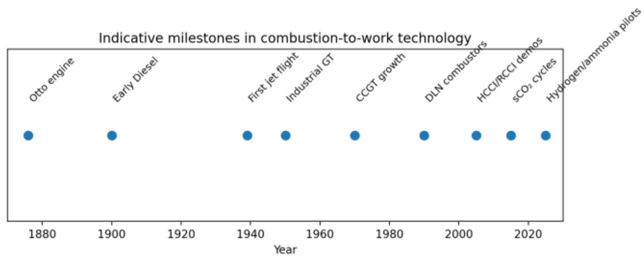

Fig. 6. *Selected milestones in combustion-to-work technologies*

Carbon management and the role of capture-ready combustion-to-work studies consistently report that the dominant losses shift with load and ambient conditions, so conclusions based only on rated points can be misleading. Evidence indicates that exhaust composition and temperature determine the feasibility of post-combustion capture, making lean-burn dilution, excess air, and oxy-fuel concepts relevant to work-producing systems. Evidence indicates that capture systems impose parasitic loads that must be included in net efficiency comparisons, shifting the optimal operating point and sometimes favoring higher-pressure, higher-temperature cycles. Evidence indicates that integration studies suggest that heat integration between capture and power cycles can reduce the effective penalty, but it requires careful matching of temperature levels. When plotted on a normalized basis, the best-performing configurations reduce a combination of exhaust enthalpy losses and internal irreversibilities, often by increasing effective expansion and improving heat recovery. However, these gains are bounded by material temperature limits, compressor or turbocharger surge margins, and the need to maintain stable, low-emissions combustion over transients. Reported data also show that control authority and sensing quality determine how closely an engine or combustor can track its optimum, particularly under strict emissions constraints. Overall, the synthesis supports using energy and exergy loss maps rather than single efficiencies, because the maps reveal where future research and design can yield the highest return.

Digitalization, diagnostics, and data-driven optimization studies consistently report that the dominant losses shift with load and ambient conditions, so conclusions based only on rated points can be misleading. Evidence indicates that high-frequency pressure sensing, ion sensing, and exhaust gas estimation enable combustion phasing control and early detection of instability or misfire. Evidence indicates that data-driven surrogate models accelerate design-space exploration when coupled with physics-based constraints, especially for multi-fidelity optimization of combustors and injectors. Evidence indicates that the combination of digital twins and advanced actuation, such as variable geometry and staged fueling, supports operation closer to optimum under varying fuels. When plotted on a normalized basis, the best-performing configurations reduce a combination of exhaust enthalpy losses and internal irreversibilities, often by increasing effective expansion and improving heat recovery. However, these gains are bounded by material temperature limits, compressor or turbocharger surge margins, and the need to maintain stable, low-emissions combustion over transients. Reported data also show that control authority and sensing quality determine how closely an engine or combustor can track its optimum, particularly under strict emissions constraints. Overall, the synthesis supports using energy and exergy loss maps rather than single efficiencies, because the maps reveal where future research and design can yield the highest return.

A central finding in Synthesis of cross-platform efficiency ceilings is that efficiency gains are rarely attributable to a single change; rather, they arise from coordinated improvements in combustion, gas exchange, and component aerodynamics. Evidence indicates that reciprocating engines approach high indicated efficiencies when combustion is fast and near-constant-volume, but heat transfer and friction prevent full realization at the brake level. Evidence indicates that gas turbines excel at high power density and can achieve high net efficiencies in combined cycles, yet they incur cooling and pressure-loss penalties that rise with firing temperature. Evidence indicates that the synthesis indicates that future gains are increasingly incremental and require system-level co-design rather than isolated component improvements. When plotted on a normalized basis, the best-performing configurations reduce a combination of exhaust enthalpy losses and internal irreversibilities, often by increasing effective expansion and improving heat recovery. However, these gains are bounded by material temperature limits, compressor or turbocharger surge margins, and the need to maintain stable, low-emissions combustion over transients. Reported data also show that control authority and sensing quality determine how closely an engine or combustor can track its optimum, particularly under strict emissions constraints. Overall, the synthesis supports using energy and exergy loss maps rather than single efficiencies, because the maps reveal where future research and design can yield the highest return.

A central finding in Interpretation of the illustrative figures is that efficiency gains are rarely attributable to a single change; rather, they arise from coordinated improvements in combustion, gas exchange, and component aerodynamics. Evidence indicates that the schematic in Figure 1 emphasizes that improvements can target different stages, and the same stage can be limited by multiple coupled constraints. Evidence indicates that the idealized p–V and T–s diagrams in Figures 2 and 3 are useful for interpreting how heat addition and expansion ratio determine work, even when real processes are non-ideal. Evidence indicates that the Sankey and contour visualizations in Figures 4 and 5 highlight, respectively, energy loss fractions and the chemical basis of emissions constraints, while Figure 6 frames the historical trajectory of key design concepts. When plotted on a normalized basis, the best-performing configurations reduce a combination of exhaust enthalpy losses and internal irreversibilities, often by increasing effective expansion and improving heat recovery. However, these gains are bounded by material temperature limits, compressor or turbocharger surge margins, and the need to maintain stable, low-emissions combustion over transients. Reported data also show that control authority and sensing quality determine how closely an engine or combustor can track its optimum, particularly under strict emissions constraints. Overall, the synthesis supports using energy and exergy loss maps rather than single efficiencies, because the maps reveal where future research and design can yield the highest return.

4. Discussion

A key implication of Loss localization and what it means for research priorities is that local improvements can be lost at the system level unless boundary conditions and parasitic loads are accounted for. First, the largest exergy destructions often occur during heat release and mixing, so improvements in combustor or in-cylinder design can have leverage even when component efficiencies are already high. First, heat-transfer reductions deliver diminishing returns unless they are coupled with increased effective expansion and reduced friction, because the saved heat otherwise leaves as exhaust. First, future work should report both energy and exergy loss breakdowns to enable comparable assessments. Second, the same control and sensing limitations that shape emissions compliance also determine whether an architecture can consistently exploit its theoretical efficiency potential. Third, the energy transition shifts the objective from maximizing gross efficiency to maximizing net climate benefit, which depends on fuel pathways, operational patterns, and the feasibility of carbon management options. [61]

Efficiency–emissions coupling highlights why many reported gains are duty-cycle dependent and therefore must be interpreted in the context of real operating maps. First, emissions constraints are not external add-ons but intrinsic boundaries that reshape the optimal operating point, especially for NOx and soot. First, dilution, staging, and low-temperature strategies shift the temperature–mixture field and therefore the chemistry, but they also change efficiency through pumping and stability penalties. First, comparisons should include aftertreatment backpressure and thermal management because they can offset combustion-side gains. Second, the same control and sensing limitations that shape emissions compliance also determine whether an architecture can consistently exploit its theoretical efficiency potential. Third, the energy transition shifts the objective from maximizing gross efficiency to maximizing net climate benefit, which depends on fuel pathways, operational patterns, and the feasibility of carbon management options. [62]

A key implication of Role of hybridization is that local improvements can be lost at the system level unless boundary conditions and parasitic loads are accounted for. First, hybrid powertrains do not eliminate combustion-to-work conversion but change where and when it is used, often making steady high-efficiency operation more valuable than peak power density. First, the benefit depends on battery size and duty cycle, so apples-to-apples comparison requires system simulations with realistic drive or mission profiles. First, control coordination between electric and combustion subsystems is essential, and it can be as impactful as hardware changes. Second, the same control and sensing limitations that shape emissions compliance also determine whether an architecture can consistently exploit its theoretical efficiency potential. Third, the energy transition shifts the objective from maximizing gross efficiency to maximizing net climate benefit, which depends on fuel pathways, operational patterns, and the feasibility of carbon management options. [63]

A key implication of Fuel transition and combustion stability is that local improvements can be lost at the system level unless boundary conditions and parasitic loads are accounted for. First, hydrogen and ammonia introduce new stability and materials challenges, implying that combustor design must expand its operating envelope while maintaining low NOx. First, drop-in e-fuels reduce infrastructure barriers but shift the decarbonization burden upstream to electricity and CO2 sourcing. First, future reviews should distinguish tailpipe carbon from lifecycle carbon and should avoid treating fuels as interchangeable without property-aware analysis. Second, the same control and sensing limitations that shape emissions compliance also determine whether an architecture can consistently exploit its theoretical efficiency potential. Third, the energy transition shifts the objective from maximizing gross efficiency to maximizing net climate benefit, which depends on fuel pathways, operational patterns, and the feasibility of carbon management options. [64]

A key implication of Pressure-gain combustion realism is that local improvements can be lost at the system level unless boundary conditions and parasitic loads are accounted for. First, pressure-gain concepts offer attractive thermodynamic arguments, but the net benefit is sensitive to losses from unsteadiness, mixing, and component matching. First, scalable integration requires durability and noise control, not just short-duration demonstrations. First, standardized metrics for pressure-gain effectiveness and efficiency accounting would accelerate comparison across laboratories. Second, the same control and sensing limitations that shape emissions compliance also determine whether an architecture can consistently exploit its theoretical efficiency potential. Third, the energy transition shifts the objective from maximizing gross efficiency to maximizing net climate benefit, which depends on fuel pathways, operational patterns, and the feasibility of carbon management options. [65]

Materials and temperature capability underscores that combustion-to-work is best treated as a coupled thermo-chemical-control problem rather than a single efficiency number. First, raising temperature capability is a decades-long driver of efficiency in turbines and high-performance engines, but it comes with cooling and maintenance penalties. First, coatings and additive manufacturing can improve cooling effectiveness, yet degradation mechanisms must be included when assessing long-term net efficiency. First, research gaps include coupled models of thermal barrier aging, fouling, and their impact on cycle matching. Second, the same control and sensing limitations that shape emissions compliance also determine whether an architecture can consistently exploit its theoretical efficiency potential. Third, the energy transition shifts the objective from maximizing gross efficiency to maximizing net climate benefit, which depends on fuel pathways, operational patterns, and the feasibility of carbon management options. [66]

Data quality and reproducibility underscores that combustion-to-work is best treated as a coupled thermo-chemical-control problem rather than a single efficiency number. First, the literature frequently reports peak efficiencies without full boundary conditions, making it difficult to compare across platforms. First, uncertainty quantification is often missing for emissions and efficiency, despite sensitivity to ambient and measurement choices. First, community benchmarks and open datasets would strengthen the field and reduce duplicated effort. Second, the same control and sensing limitations that shape emissions compliance also determine whether an architecture can consistently exploit its theoretical efficiency potential. Third, the energy transition shifts the objective from maximizing gross efficiency to maximizing net climate benefit, which depends on fuel pathways, operational patterns, and the feasibility of carbon management options. [67]

Control, sensing, and actuation highlights why many reported gains are duty-cycle dependent and therefore must be interpreted in the context of real operating maps. First, modern combustion-to-work systems are increasingly limited by control authority rather than purely by thermodynamic potential. First, high-bandwidth sensing enables operation closer to limits, but it must be paired with robust algorithms that handle sensor drift and component aging. First, opportunities exist for physics-informed machine learning that respects conservation laws while leveraging large datasets. Second, the same control and sensing limitations that shape emissions compliance also determine whether an architecture can consistently exploit its theoretical efficiency potential. Third, the energy transition shifts the objective from maximizing gross efficiency to maximizing net climate benefit, which depends on fuel pathways, operational patterns, and the feasibility of carbon management options. [68]

Integration with carbon capture and negative emissions underscores that combustion-to-work is best treated as a coupled thermo-chemical-control problem rather than a single efficiency number. First, capture-ready operation can change optimal excess air and temperature levels, influencing both efficiency and emissions. First, the parasitic load of capture must be considered on a net basis, and heat integration can mitigate penalties when temperature levels are matched. First, future work should consider combined optimization of the work-producing cycle and capture subsystem rather than sequential design. Second, the same control and sensing limitations that shape emissions compliance also determine whether an architecture can consistently exploit its theoretical efficiency potential. Third, the energy transition shifts the objective from maximizing gross efficiency to maximizing net climate benefit, which depends on fuel pathways, operational patterns, and the feasibility of carbon management options. [69]

Research gaps in multi-fuel validation underscores that combustion-to-work is best treated as a coupled thermo-chemical-control problem rather than a single efficiency number. First, many combustors are designed for a narrow fuel range, and scaling laws for fuel-flexible operation are not yet mature. First, pilot-scale demonstrations should include transient operation and start-up/shutdown because these regimes can dominate emissions in practice. First, diagnostics that link species fields to heat-release and acoustics remain essential for validating models under new fuels. Second, the same control and sensing limitations that shape emissions compliance also determine whether an architecture can consistently exploit its theoretical efficiency potential. Third, the energy transition shifts the objective from maximizing gross efficiency to maximizing net climate benefit, which depends on fuel pathways, operational patterns, and the feasibility of carbon management options. [70]

Cross-sector outlook highlights why many reported gains are duty-cycle dependent and therefore must be interpreted in the context of real operating maps. First, transport will likely follow a mixed landscape where electrification expands but combustion persists in heavy-duty and long-range segments. First, stationary power may see reduced utilization hours yet higher cycling, increasing the importance of durability and low-emissions transient capability. First, industrial heat applications may adopt fuel-flexible burners and electrified assistance, requiring new metrics for overall efficiency and productivity. Second, the same control and sensing limitations that shape emissions compliance also determine whether an architecture can consistently exploit its theoretical efficiency potential. Third, the energy transition shifts the objective from maximizing gross efficiency to maximizing net climate benefit, which depends on fuel pathways, operational patterns, and the feasibility of carbon management options. [71]

A key implication of Toward unified metrics is that local improvements can be lost at the system level unless boundary conditions and parasitic loads are accounted for. First, reporting only lower-heating-value efficiency can hide the role of exhaust temperature and quality of waste heat. First, exergy efficiency, specific work, and pollutant indices provide a more transferable basis across engines, turbines, and CHP systems. First, standardizing these metrics would make reviews and meta-analyses more informative. Second, the same control and sensing limitations that shape emissions compliance also determine whether an architecture can consistently exploit its theoretical efficiency potential. Third, the energy transition shifts the objective from maximizing gross efficiency to maximizing net climate benefit, which depends on fuel pathways, operational patterns, and the feasibility of carbon management options. [72]

Implications for education and practice highlights why many reported gains are duty-cycle dependent and therefore must be interpreted in the context of real operating maps. First, engineers benefit from learning combustion chemistry and thermodynamics as a single coupled system, not as separate courses. First, design teams increasingly require multi-domain tools that connect CFD, cycle simulation, and controls in a consistent workflow. First, open-source tooling and modular reduced mechanisms can accelerate adoption of best practices across organizations. Second, the same control and sensing limitations that shape emissions compliance also determine whether an architecture can consistently exploit its theoretical efficiency potential. Third, the energy transition shifts the objective from maximizing gross efficiency to maximizing net climate benefit, which depends on fuel pathways, operational patterns, and the feasibility of carbon management options. [73]

A key implication of Limitations of this review is that local improvements can be lost at the system level unless boundary conditions and parasitic loads are accounted for. First, illustrative figures are synthesized to emphasize trends and do not replace detailed vendor or proprietary maps. First, the focus on conversion to work necessarily simplifies other objectives such as noise, cost, and specific emissions regulations. First, nevertheless, the loss-based framework provides a practical basis for comparing technologies and identifying leverage points. Second, the same control and sensing limitations that shape emissions compliance also determine whether an architecture can consistently exploit its theoretical efficiency potential. Third, the energy transition shifts the objective from maximizing gross efficiency to maximizing net climate benefit, which depends on fuel pathways, operational patterns, and the feasibility of carbon management options. [74]

A key implication of Future directions is that local improvements can be lost at the system level unless boundary conditions and parasitic loads are accounted for. First, progress will come from integrated design that simultaneously addresses heat-release shaping, component efficiency, control, and fuel flexibility. First, high-temperature materials, advanced manufacturing, and improved heat exchangers will continue to enable higher cycle potential. First, breakthroughs may also arise from new combustion paradigms that reduce chemical irreversibility or enable pressure gain with acceptable losses. Second, the same control and sensing limitations that shape emissions compliance also determine whether an architecture can consistently exploit its theoretical efficiency potential. Third, the energy transition shifts the objective from maximizing gross efficiency to maximizing net climate benefit, which depends on fuel pathways, operational patterns, and the feasibility of carbon management options. [75]

Summary of cross-cutting insights highlights why many reported gains are duty-cycle dependent and therefore must be interpreted in the context of real operating maps. First, no single technology dominates across all constraints; instead, the best choice depends on mission, fuel, and operating map. First, the most robust improvements are those that reduce multiple loss channels at once, such as increasing effective expansion while maintaining fast, stable combustion. First, the pathway will remain central in the energy system, so incremental and breakthrough improvements both have high societal value. Second, the same control and sensing limitations that shape emissions compliance also determine whether an architecture can consistently exploit its theoretical efficiency potential. Third, the energy transition shifts the objective from maximizing gross efficiency to maximizing net climate benefit, which depends on fuel pathways, operational patterns, and the feasibility of carbon management options. [76]

A key implication of Closing perspective is that local improvements can be lost at the system level unless boundary conditions and parasitic loads are accounted for. First, combustion-to-work research is increasingly interdisciplinary, connecting fuels, chemistry, thermodynamics, materials, and digital control. First, because constraints are coupled, the most informative studies report complete boundary conditions, loss breakdowns, and emissions outcomes together. First, the review's framework can serve as a template for future assessments as fuels and operating requirements continue to evolve. Second, the same control and sensing limitations that shape emissions compliance also determine whether an architecture can consistently exploit its theoretical efficiency potential. Third, the energy transition shifts the objective from maximizing gross efficiency to maximizing net climate benefit, which depends on fuel pathways, operational patterns, and the feasibility of carbon management options. [77]

A key implication of Combustion noise and human acceptance is that local improvements can be lost at the system level unless boundary conditions and parasitic loads are accounted for. First, combustion noise and pressure rise rates are increasingly relevant as engines adopt fast heat-release strategies and as turbines operate nearer stability limits. First, noise constraints can force less aggressive phasing or staging, which slightly reduces efficiency but improves acceptance and durability. First, future work should include acoustics and vibration metrics alongside efficiency and emissions. Second, the same control and sensing limitations that shape emissions compliance also determine whether an architecture can consistently exploit its theoretical efficiency potential. Third, the energy transition shifts the objective from maximizing gross efficiency to maximizing net climate benefit, which depends on fuel pathways, operational patterns, and the feasibility of carbon management options. [78]

Water use and environmental constraints highlights why many reported gains are duty-cycle dependent and therefore must be interpreted in the context of real operating maps. First, water or steam injection can be effective for NOx suppression and power augmentation, yet it introduces water demand, corrosion risks, and efficiency penalties from pumping and treatment. First, in arid regions, water constraints may favor dry low-NOx designs or alternative approaches such as catalytic combustion. First, life-cycle assessment should therefore include local resource constraints, not only carbon metrics. Second, the same control and sensing limitations that shape emissions compliance also determine whether an architecture can consistently exploit its theoretical efficiency potential. Third, the energy transition shifts the objective from maximizing gross efficiency to maximizing net climate benefit, which depends on fuel pathways, operational patterns, and the feasibility of carbon management options. [79]

Part-load operation and utilization underscores that combustion-to-work is best treated as a coupled thermo-chemical-control problem rather than a single efficiency number. First, many systems operate far more hours at part load than at rated conditions, so part-load efficiency and emissions can dominate annual performance. First, recuperation, variable geometry, and hybridization can shift part-load performance upward, but only if controls are tuned for real duty cycles. First, reporting utilization-weighted efficiency provides a more meaningful basis for comparing technologies. Second, the same control and sensing limitations that shape emissions compliance also determine whether an architecture can consistently exploit its theoretical efficiency potential. Third, the energy transition shifts the objective from maximizing gross efficiency to maximizing net climate benefit, which depends on fuel pathways, operational patterns, and the feasibility of carbon management options. [80]

Thermal management as a system problem underscores that combustion-to-work is best treated as a coupled thermo-chemical-control problem rather than a single efficiency number. First, coolant and oil temperature control affects friction, heat transfer, and aftertreatment light-off, creating coupled objectives. First, smart thermal strategies can reduce warm-up losses and enable faster catalyst activation, improving both fuel economy and emissions in short-trip operation. First, the field needs integrated thermal network models validated under realistic transients. Second, the same control and sensing limitations that shape emissions compliance also determine whether an architecture can consistently exploit its theoretical efficiency potential. Third, the energy transition shifts the objective from maximizing gross efficiency to maximizing net climate benefit, which depends on fuel pathways, operational patterns, and the feasibility of carbon management options.

Standards and policy feedback highlights why many reported gains are duty-cycle dependent and therefore must be interpreted in the context of real operating maps. First, regulatory cycles and test procedures influence technology choices and can accelerate certain pathways, such as lean-burn with aftertreatment or hybrid architectures. First, policy signals also influence fuel availability, which determines whether fuel-flexible combustors are economically valuable. First, transparent, comparable metrics help align engineering research with policy-driven objectives without distorting technical conclusions. Second, the same control and sensing limitations that shape emissions compliance also determine whether an architecture can consistently exploit its theoretical efficiency potential. Third, the energy transition shifts the objective from maximizing gross efficiency to maximizing net climate benefit, which depends on fuel pathways, operational patterns, and the feasibility of carbon management options.

Finally, it is worth noting that many promising concepts fail not for lack of thermodynamic merit but because of integration hurdles. These include manufacturability, maintenance burden, fuel logistics, and the ability to validate models across scales. Closing this gap requires joint experimental–computational campaigns, shared benchmarks, and design methods that explicitly trade performance against robustness..

5. Conclusion

Combustion-to-work conversion remains a foundational energy pathway, and its future performance hinges on integrated reductions in irreversibility across chemistry, mixing, heat transfer, pressure losses, and mechanical parasitics. The synthesis in this review shows that the most robust efficiency gains come from coordinated strategies that shape heat release, increase effective expansion, recover high-quality exhaust exergy, and maintain stable low-emissions operation across realistic duty cycles. Emissions are not external constraints added after the fact; they are intrinsic boundaries that reshape the achievable optimum through temperature–mixture distributions and through aftertreatment and thermal-management penalties. Across platforms, incremental advances will continue to come from higher temperature capability, improved turbomachinery and boosting, lower friction, smarter thermal control, and better sensors and algorithms that keep operation close to optimal without crossing stability limits. At the same time, fuel transitions to hydrogen, ammonia, and synthetic fuels will require fuel-aware combustor and engine designs that preserve operability while controlling NOx and other pollutants. Finally, standardized reporting of boundary conditions and loss breakdowns, together with multi-fuel and transient validation, is essential to translate laboratory progress into reliable gains in delivered work and net climate benefit.

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