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Alternative Fuels for Power Generation: Conversion Pathways, Performance Trade-Offs, and Deployment Readiness

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ABSTRACT

Decarbonizing power generation requires fuel options that can complement variable renewable electricity while reducing dependence on fossil resources. This review critically compares biofuels, hydrogen, ammonia, synthetic hydrocarbon fuels, and alcohol-based fuels with emphasis on production pathways, fuel properties, lifecycle greenhouse gas performance, infrastructure demands, and economic viability. The analysis shows that no single pathway dominates across all criteria. Biofuels benefit from comparatively high technological maturity and easier integration into existing assets, but sustainable feedstock availability constrains long-term scale-up. Green hydrogen offers the lowest carbon intensity among the reviewed options and can support flexible generation, yet storage penalties, supply-chain development, and current production cost remain major barriers. Synthetic fuels retain the strategic advantage of compatibility with legacy engines and handling systems, although their multi-step conversion routes impose significant efficiency and cost penalties. Ammonia is promising for large-scale storage and dispatchable power applications, but toxicity, combustion stability, and NOx mitigation must be addressed before broad deployment. Overall, future fuel selection should be guided by integrated assessments that simultaneously consider emissions, cost, energy density, infrastructure readiness, and sector-specific performance requirements.

1. Introduction

Deep decarbonization of power generation demands energy carriers that can do more than simply replace fossil fuels on a mass basis. They must also support dispatchability, seasonal storage, fuel security, and compatibility with evolving electricity systems. In this context, alternative fuels have moved from a peripheral research topic to a central component of transition planning, especially for applications where direct electrification is insufficient or operationally inflexible.

The term alternative fuels encompasses a broad family of resources, including bioethanol, biodiesel, hydrotreated biofuels, hydrogen, ammonia, synthetic hydrocarbons, and low-carbon alcohol fuels. Their relevance arises from their potential to lower lifecycle emissions, diversify feedstocks, and expand the operating envelope of power systems. However, these pathways differ markedly in feedstock origin, conversion route, energy density, safety profile, and infrastructure requirements, which means that direct comparison is essential before drawing deployment conclusions.

Biofuels remain the most commercially established group among the reviewed pathways. Their advantage lies in near-term implementability, particularly where liquid-fuel logistics and combustion assets are already available. Yet sustainability concerns linked to land use, feedstock competition, and variable lifecycle performance continue to shape the debate around their long-term role. Advanced biofuels derived from residues, wastes, and non-food biomass partly address these concerns, but they still face scale and cost challenges.

Hydrogen, synthetic fuels, and ammonia are often positioned as strategic options for the later stages of decarbonization. Green hydrogen offers very low direct carbon intensity and can be converted back to electricity through turbines or fuel cells, while synthetic fuels provide a drop-in route for existing thermal systems. Ammonia, in turn, is increasingly viewed as both a fuel and a hydrogen carrier. Despite these benefits, each option carries technical penalties related to storage, conversion efficiency, catalyst requirements, combustion behavior, or pollutant control.

A rigorous assessment of alternative fuels must therefore extend beyond nominal carbon savings. Production cost, technology maturity, lifecycle greenhouse gas emissions, energy density, infrastructure compatibility, and sectoral fit are all decisive. Policy design also matters: mandates, carbon pricing, blending rules, and public investment can accelerate certain pathways, while weak standards or inconsistent incentives can delay commercialization even when the underlying technology is technically credible.

Accordingly, this review synthesizes the literature through a comparative framework that links production pathways with environmental performance, techno-economic indicators, and deployment readiness. The objective is not to identify a universal winner, but to clarify where each fuel class is most competitive and which constraints must be overcome before wide-scale adoption in power generation and related energy sectors becomes feasible.

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Nomenclature

Abbreviation
SAF – Sustainable Aviation Fuel
LCA – Life Cycle Assessment
GHG – Greenhouse Gas
FT – Fischer–Tropsch
LHV – Lower Heating Value
CNG – Compressed Natural Gas
HVO – Hydrotreated Vegetable Oil
TCO – Total Cost of Ownership
LCOE – Levelized Cost of Energy

Symbol
η – Efficiency
ρ – Density
Q – Energy content

2. Methodology

This review followed a structured literature synthesis covering peer-reviewed journal articles, technical reports, and institutional assessments published primarily over the last fifteen years. Sources were identified through major academic databases including Scopus, Web of Science, ScienceDirect, and IEEE Xplore. The screening process prioritized studies that reported experimental results, pilot- or demonstration-scale evidence, lifecycle analyses, techno-economic evaluations, or policy-relevant deployment insights for alternative fuels.

The analytical framework was organized around three linked dimensions: production pathway, environmental performance, and deployment feasibility. For the pathway analysis, fuels were grouped by feedstock type and conversion route. Biofuels were tracked across fermentation, transesterification, thermochemical liquefaction, and gasification routes; hydrogen was separated into gray, blue, and green pathways; synthetic fuels were assessed through CO2-to-fuels and syngas-based synthesis routes; and ammonia was evaluated in relation to Haber-Bosch integration with low-carbon hydrogen supply.

Environmental performance was assessed using lifecycle thinking consistent with ISO 14040/44 principles. Emissions data were harmonized to common functional units, typically g CO2-eq/MJ, to improve comparability across fuel classes. Where literature values differed because of system boundaries or background electricity assumptions, the reported ranges were preserved rather than collapsed into a single deterministic value. Sensitivity was considered for influential factors such as electricity carbon intensity, capture efficiency, feedstock origin, and process yield [1-10].

Deployment feasibility was examined using indicators that affect real-world implementation: storage form, energy density, compatibility with existing engines or combustion assets, infrastructure modification requirements, safety constraints, and indicative production or abatement cost. Techno-economic information was compiled from academic studies and agency reports, while qualitative sectoral readiness was inferred from recurring patterns in the literature for road transport, aviation, shipping, and stationary power [11-15].

To support comparison, the extracted evidence was consolidated into three summary tables and recast into a new set of figures using harmonized ranges or relative scores. The visualizations therefore function as interpretive synthesis tools rather than standalone experimental results. Together, the tables and figures were used to identify recurring trade-offs between carbon intensity, cost, energy density, scalability, and infrastructure readiness across the reviewed fuel pathways [16-20].

Table 1. Comparative Physical and Environmental Properties of Alternative Fuels

Fuel Type	**LHV (MJ/kg)**	**Storage Form**	**GHG Emissions (g CO_2-eq/MJ)**
Bioethanol	26.8	Liquid	40–55
Biodiesel	37.8	Liquid	30–50
Hydrogen (green)	120.0	Compressed	<5
Ammonia	18.6	Liquid	8–25
Synthetic Diesel	43.2	Liquid	10–20

Table 2. Conversion Pathways, Efficiencies, and TRL

Fuel Type	**Feedstock**	**Conversion Process**
Biodiesel	Vegetable oils, waste fats	Transesterification
Bioethanol	Sugar/starch crops	Fermentation
Hydrogen (green)	Water + Renewable energy	Electrolysis

Table 3. Economic and Deployment Metrics

Fuel Type	**Production Cost ($/GJ)**	**Abatement Cost ($/t$CO_2$)**	**Scalability (1–5)**
Biodiesel	20–35	50–90	3
Hydrogen (green)	40–70	150–300	2
Ammonia	30–50	120–250	2

3. Results

The comparative evidence shows that alternative fuels occupy distinct positions in the transition landscape rather than forming a simple hierarchy of best to worst options. The revised figures reorganize the data into decision-oriented views that expose how carbon intensity, energy density, production cost, and infrastructure compatibility interact. Figures 1-4 focus on the core performance dimensions compiled from Tables 1-3 and from the reported ranges discussed throughout the reviewed literature.

Figure 1 presents lifecycle greenhouse gas intensity as an interval plot rather than a single-point comparison. This representation makes the dispersion in reported values explicit. Conventional gasoline and diesel remain clustered near the upper end of the scale, whereas green hydrogen, synthetic diesel, and ammonia occupy much lower carbon-intensity windows when supported by low-carbon upstream pathways. Bioethanol and biodiesel still provide meaningful reductions, but their ranges are broader because feedstock source, cultivation burden, and process configuration exert a stronger influence on final emissions.

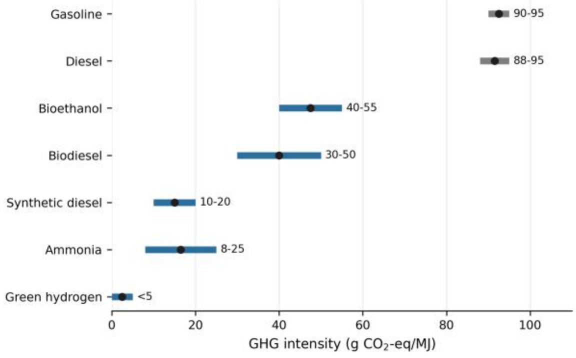

Fig. 1. Interval plot of lifecycle greenhouse gas intensity ranges for selected conventional and alternative fuels. The range format preserves literature variability and highlights the carbon penalty avoided by low-carbon production pathways.

Figure 2 recasts lower heating value into an ordered lollipop plot, which clarifies the large spread in gravimetric energy density across fuel classes.

Green hydrogen clearly dominates on a mass basis, while synthetic diesel and biodiesel occupy an intermediate band that remains attractive for thermal applications requiring higher energy content in manageable storage volumes. Ammonia and bioethanol appear lower on the ranking, indicating that energy delivery per unit mass is a more significant constraint for these pathways.

The cost dispersion compiled in Figure 3 underscores why high environmental performance does not automatically translate into near-term deployment. Biodiesel retains the lowest indicative production-cost window among the fuels included in the economic comparison, whereas green hydrogen and ammonia remain materially more expensive under current market conditions. Synthetic fuels exhibit the widest and highest cost range because carbon capture, hydrogen production, and fuel synthesis must all be integrated in sequence, amplifying capital intensity and conversion losses.

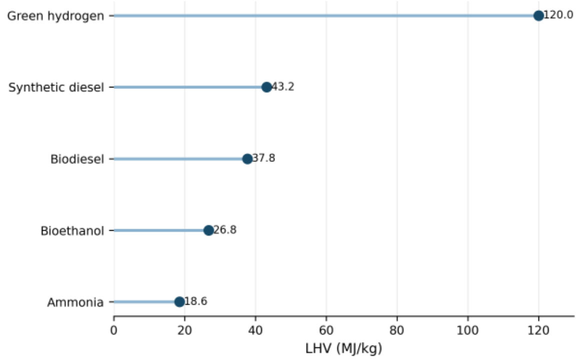

Fig. 2. Ordered lollipop representation of lower heating value for representative alternative fuels, illustrating the wide spread in gravimetric energy density across fuel classes.

Infrastructure readiness is summarized in Figure 4 through a sector-fuel compatibility matrix. The pattern is strongly application dependent. Liquid biofuels align most closely with road transport because they can exploit existing storage, blending, and engine platforms. Synthetic diesel stands out in aviation because drop-in compatibility is strategically valuable where fleet replacement is slow and certification requirements are strict. Ammonia scores highest in shipping, reflecting strong interest in long-duration fuel storage and maritime decarbonization, while green hydrogen shows its clearest advantage in stationary power where centralized storage and dedicated handling systems are more feasible.

Taken together, Figures 1-4 indicate that the principal performance trade-off is not between carbon and cost alone, but between carbon, cost, and system integration. Fuels with strong environmental performance frequently require new supply chains or specialized equipment, while mature fuels with easier deployment tend to deliver smaller reductions or face sustainability constraints. This is particularly evident for biofuels, which perform well on maturity and compatibility but less well on long-term feedstock scalability.

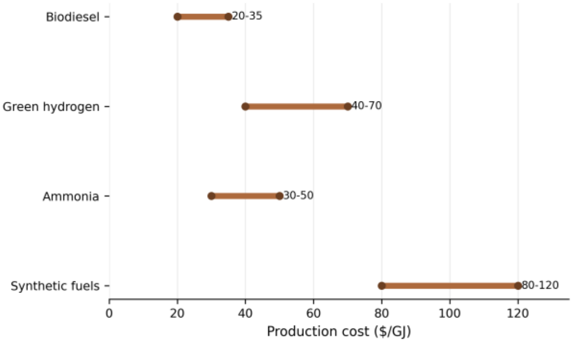

Fig. 3. Range-lollipop plot of indicative production-cost windows for selected alternative fuels. The figure emphasizes the cost penalty associated with hydrogen- and synthesis-based routes under present conditions.

The sectoral interpretation reinforces this divergence. For near-term road transport and distributed thermal systems, bioethanol and biodiesel remain practical transitional options because they can leverage existing infrastructure. For aviation and other long-range applications, synthetic fuels retain unique value because molecular compatibility matters as much as carbon intensity. Shipping and large stationary systems appear better matched to ammonia and hydrogen, respectively, provided that safety engineering and combustion control continue to improve.

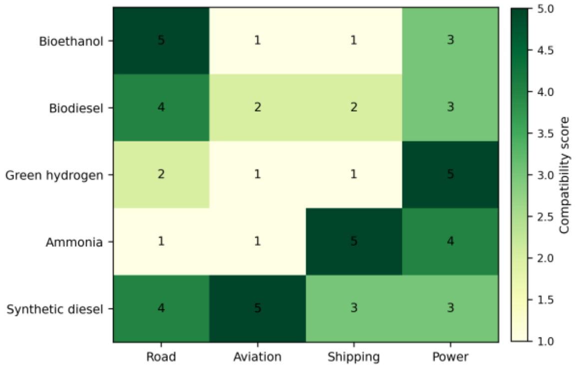

Fig. 4. Relative infrastructure compatibility matrix across major sectors. Higher scores indicate better alignment with existing assets, handling practices, and operational requirements.

The reviewed literature also points to the importance of hybridization and carbon management. Synthetic fuels linked to captured CO2, and bioenergy pathways coupled with carbon capture, can materially improve lifecycle performance relative to standalone fuel production. However, such integration raises system complexity and often shifts the economic bottleneck from combustion hardware to upstream conversion and purification steps.

Overall, the results confirm that alternative fuels should be treated as a portfolio of complementary pathways. Green hydrogen offers the strongest emissions position, synthetic fuels provide compatibility benefits, biofuels contribute deployable short-term gains, and ammonia offers strategic potential for long-duration energy storage and carbon-free fuel trade. The appropriate choice depends on whether the priority is immediate implementation, deep carbon reduction, legacy-system compatibility, or large-scale storage.

Accordingly, a credible transition strategy for power generation and adjacent sectors is likely to rely on sequencing rather than substitution by a single fuel class. Mature liquid fuels can support early deployment, while hydrogen-, ammonia-, and CO2-derived pathways expand as infrastructure, policy support, and renewable electricity availability improve.

4. Discussion

The revised comparison makes one point especially clear: alternative fuels should not be assessed through a winner-takes-all logic. Each pathway solves a different part of the decarbonization problem, and each one carries a different combination of carbon benefit, conversion penalty, and implementation burden. A robust transition strategy therefore requires portfolio design rather than technology singularity.

Biofuels remain relevant because they offer the shortest route to deployment. Their strength lies in compatibility with mature combustion systems and liquid-fuel logistics, which lowers entry barriers for utilities and industrial operators seeking incremental carbon reductions. At the same time, their long-term contribution will depend on whether advanced feedstocks can displace food-linked biomass and whether lifecycle accounting properly captures land-use and supply-chain burdens.

Hydrogen is strongest where low-carbon electricity is abundant and where centralized handling can offset its storage disadvantages. In stationary power, hydrogen can support turbines, fuel cells, and hybrid energy systems, particularly when rapid response or long-duration storage is required. Even so, the infrastructure challenge remains substantial. Compression, liquefaction, materials compatibility, leakage management, and safety standards all add cost and slow deployment relative to pathways that exploit existing liquid-fuel networks.

Synthetic fuels occupy a strategically important but economically difficult position. Their principal value is not maximum efficiency, but system compatibility. Because they can be formulated for legacy combustion assets, they offer a practical route for decarbonizing applications that cannot be readily electrified or rapidly re-equipped. The penalty is upstream complexity: carbon capture, hydrogen generation, conditioning, and synthesis each consume energy and capital. As a result, synthetic fuels become more attractive only when carbon constraints, fuel standards, or infrastructure lock-in are given high weight in decision making.

Ammonia presents a different type of proposition. It is less attractive as a universally deployable fuel than as a strategic carrier for large-scale storage and maritime or stationary applications. Existing global trade infrastructure works in its favor, but toxicity, corrosiveness, low flame speed, and NOx formation remain serious design constraints. Its future role will therefore depend on burner development, after-treatment performance, and the economics of coupling ammonia production with low-carbon hydrogen supply.

These technical distinctions are inseparable from socioeconomic and regulatory considerations. Feedstock geography, renewable electricity availability, water demand, industrial capability, and public acceptance will influence which fuels scale in which regions. Transition planning must therefore be location specific. A pathway that is attractive in a biomass-rich region may be inferior in a solar-rich, water-constrained system where hydrogen or ammonia becomes more competitive despite higher present costs.

Lifecycle rigor is also essential. Reported carbon benefits vary widely when assumptions change regarding background electricity, carbon-capture efficiency, fertilizer use, land-use change, or transport distance. This uncertainty does not diminish the value of alternative fuels; rather, it underscores the need for transparent system boundaries and harmonized reporting. Without such rigor, pathway comparisons can become misleading and policy support may be directed toward options whose apparent benefits are not robust.

Figures 5-7 synthesize the evidence from a decision perspective. Figure 5 translates lifecycle carbon intensity into an avoided-emissions view relative to a fossil benchmark, showing why green hydrogen and synthetic diesel attract policy interest despite cost barriers. Figure 6 combines emissions and cost in a bubble plot with energy density embedded as the bubble size, making the trade-off structure visually explicit. Figure 7 then condenses the assessment into a multi-criteria score matrix, which is useful for screening but also highlights that strong performance on one criterion rarely coincides with strength on all others.

From a systems standpoint, the most credible pathway forward is staged deployment. Mature liquid fuels can provide immediate but partial decarbonization, while hydrogen, ammonia, and synthetic fuels expand as renewable power, carbon-management infrastructure, and sector-specific standards mature. This staged approach aligns better with industrial turnover rates, financing cycles, and infrastructure replacement realities than abrupt substitution strategies.

Research priorities should therefore focus on three fronts: lowering the cost of low-carbon hydrogen and fuel synthesis, improving combustion and emissions control for ammonia and hydrogen-based systems, and strengthening sustainability governance for bio-based fuels. Equally important is the integration of fuel pathways with carbon capture, storage, and grid-balancing systems, since future competitiveness will increasingly depend on how well fuels function within broader energy networks rather than as isolated commodities.

In practical terms, the discussion suggests that future power-generation fuel systems will be hybrid, regionally differentiated, and policy shaped. The decisive question is not which fuel is universally best, but which combination of fuels offers the best fit for a given resource base, infrastructure legacy, and decarbonization timetable.

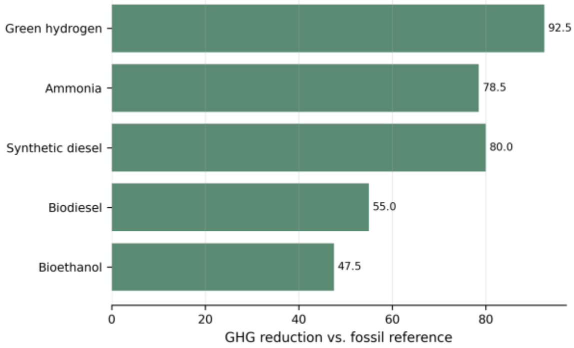

Fig. 5. Waterfall-style summary of indicative lifecycle greenhouse gas reductions relative to a 95 g CO2-eq/MJ fossil reference. Larger values indicate stronger decarbonization potential.

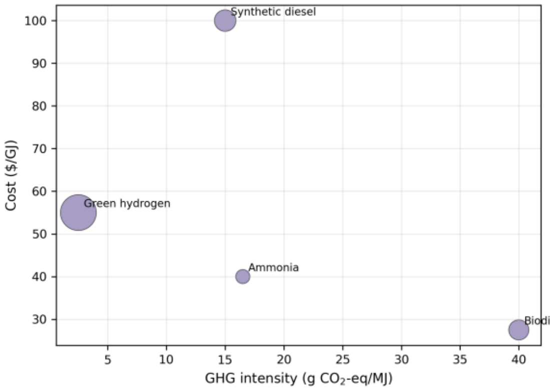

Fig. 6. Trade-off bubble plot linking midpoint lifecycle carbon intensity and midpoint production cost. Bubble size reflects lower heating value, allowing emissions, cost, and energy density to be read simultaneously.

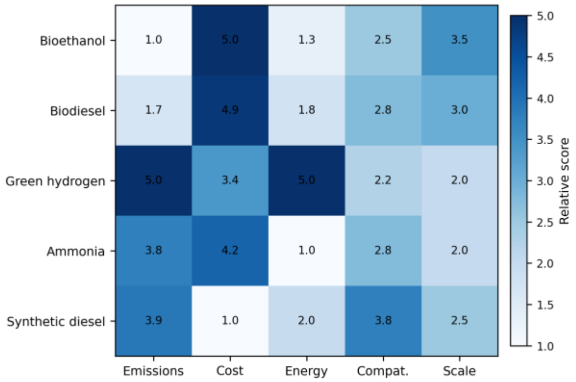

Fig. 7. Multi-criteria score matrix comparing emissions, cost, energy density, compatibility, and scalability. The values are relative synthesis scores derived from the harmonized evidence summarized in Tables 1-3 and the narrative review.

The broader implication is that alternative fuels should be evaluated as infrastructure strategies as much as chemical options. When interpreted in that way, the figures show that deployment readiness, not theoretical fuel quality alone, will determine which pathways achieve meaningful scale first.

5. Conclusion

This review shows that alternative fuels can make a substantial contribution to power-sector decarbonization, but only when they are matched to the operational and infrastructural realities of the target application. Their value lies not in replacing fossil fuels through a single universal route, but in expanding the menu of technically and strategically viable low-carbon energy carriers.

Among the reviewed pathways, biofuels remain the most deployable in the near term because of their maturity and compatibility with existing assets. Green hydrogen offers the strongest carbon-performance advantage, especially for future flexible power systems, but still faces major cost and storage barriers. Synthetic fuels are compelling where drop-in compatibility is essential, while ammonia is particularly promising for long-duration storage, shipping-related applications, and carbon-free fuel trade if combustion and safety challenges can be controlled.

The comparative evidence also confirms that lifecycle emissions, production cost, and infrastructure readiness must be evaluated together. A fuel with excellent theoretical carbon performance may still struggle commercially if it depends on immature supply chains or substantial equipment replacement. Conversely, an easily deployable fuel may deliver only partial decarbonization if upstream sustainability is weak or feedstock scale is limited.

Progress will therefore depend on coordinated advances in process efficiency, catalyst and reactor design, storage and combustion systems, lifecycle accounting, and policy design. Regional strategies should reflect local resource endowments: biomass-rich systems may prioritize advanced biofuels, whereas renewable-electricity-rich regions may move more rapidly toward hydrogen-, ammonia-, or synthetic-fuel platforms.

In sum, the transition to low-carbon fuels for power generation will be plural, staged, and highly context dependent. With sustained investment, transparent sustainability criteria, and application-specific deployment planning, alternative fuels can become a durable pillar of a more resilient and deeply decarbonized energy system.

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