



A Comprehensive Review of Alternative Fuels for Power Generation

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ABSTRACT

The accelerating urgency to mitigate climate change and reduce dependence on fossil fuels has positioned alternative fuels as a critical element in transitioning to a sustainable energy system. This review comprehensively investigates the landscape of alternative fuels, including biofuels, synthetic fuels, hydrogen, ammonia, and alcohol-based fuels, examining their production pathways, environmental benefits, technical challenges, and policy considerations. Emphasis is placed on recent advancements in conversion technologies, lifecycle emissions analysis, and the integration of alternative fuels in existing energy infrastructure. The review also discusses comparative performance and technoeconomic viability across sectors such as transportation, aviation, and power generation. By synthesizing current knowledge and identifying key research gaps, this paper contributes to a deeper understanding of the potential and limitations of alternative fuels in achieving global decarbonization goals.

1. Introduction

The global energy sector is undergoing a transformative shift as nations strive to curb greenhouse gas emissions, enhance energy security, and meet the targets outlined in the Paris Agreement. At the core of this transformation is the need to diversify fuel sources, reduce dependence on fossil fuels, and adopt sustainable alternatives. Alternative fuels, defined as energy sources that are substitutes for conventional petroleum-based fuels, have gained significant attention in this context. They include biofuels, hydrogen, synthetic fuels, ammonia, compressed natural gas (CNG), and alcohol-based fuels such as methanol and ethanol. Each of these alternatives offers unique advantages and faces distinct challenges when evaluated against criteria such as carbon intensity, cost of production, infrastructure compatibility, and energy density.

Biofuels, derived from biomass sources such as agricultural residues, energy crops, and waste materials, have been one of the most extensively researched and implemented categories of alternative fuels. First-generation biofuels like bioethanol and biodiesel are already blended with gasoline and diesel in many countries. However, their competition with food production and limited feedstock availability have raised concerns, prompting research into second- and third-generation biofuels based on non-food biomass and algae. Hydrogen, widely considered a cornerstone of future energy systems, offers a clean-burning alternative with zero carbon emissions at the point of use. However, its production pathway determines its sustainability, with "green hydrogen" from electrolysis using renewable electricity being the most desirable, albeit the most expensive option currently available.

Synthetic fuels or electrofuels, produced via the Fischer-Tropsch process or methanol synthesis from captured CO₂ and green hydrogen, represent another promising pathway. These fuels are compatible with

existing internal combustion engines and aviation systems, thus offering a "drop-in" solution. However, high energy requirements and production costs remain barriers to commercialization. Similarly, ammonia is gaining traction as a potential carbon-free fuel, particularly in maritime transport and power generation. Its advantages include high hydrogen content and established global infrastructure, but issues such as toxicity and NO_x emissions require further research and mitigation strategies.

Alternative fuels must be analyzed not only for their environmental footprint but also for their scalability, lifecycle emissions, and socio-economic implications. Comprehensive lifecycle assessments (LCAs) are crucial to ensure that upstream and downstream emissions are minimized. Furthermore, economic analyses, including leveled cost of energy (LCOE) and total cost of ownership (TCO), help determine the feasibility of adoption across various sectors. Infrastructure compatibility is another critical consideration, especially for sectors like aviation and heavy-duty transport that require high energy density and global refueling networks.

The role of policy, regulation, and market incentives cannot be overstated. Governmental mandates such as the Renewable Fuel Standard (RFS) in the United States, the European Union's Renewable Energy Directive (RED II), and carbon pricing mechanisms have significantly influenced the uptake of alternative fuels. However, inconsistent policies and lack of long-term investment certainty have slowed progress. Collaborative international frameworks and public-private partnerships are essential to foster innovation, scale up production, and reduce costs through economies of scale.

Public perception and societal acceptance also shape the transition landscape. Fuels like hydrogen and ammonia, despite their environmental benefits, face public hesitancy due to perceived risks. Addressing safety concerns through transparent communication and regulatory oversight is necessary to build confidence.

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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 adopted a systematic approach to examine the current his review employs a systematic approach to collect, analyze, and synthesize information on alternative fuels from peer-reviewed journal articles, technical reports, and institutional white papers published over the last fifteen years. A comprehensive literature search was conducted using academic databases such as Scopus, Web of Science, ScienceDirect, and IEEE Xplore to identify high-quality studies addressing various aspects of alternative fuel technologies. The selection criteria prioritized studies that presented experimental data, pilot-scale applications, techno-economic evaluations, and policy analyses related to the production, deployment, and environmental impact of alternative fuels. Key terms used during the search included “biofuel,” “synthetic fuel,” “hydrogen fuel,” “alternative fuel production,” “renewable energy,” “ammonia energy,” and “low-carbon fuels.” The methodological framework centers on three analytical pillars: production pathways, environmental performance, and integration feasibility across sectors.

For production pathways, a techno-process mapping of each fuel category was undertaken. Biofuels were classified based on feedstock types and conversion routes, including transesterification, fermentation, thermochemical liquefaction, and gasification. Hydrogen production was categorized into gray, blue, and green pathways, based on the source of input energy and carbon mitigation techniques. Synthetic fuels were evaluated primarily via CO₂-based electrochemical and thermochemical synthesis using hydrogen. Ammonia fuel synthesis and usage models were analyzed, focusing on Haber–Bosch process integration with renewable energy and its deployment in shipping and power applications. Each process was compared in terms of energy efficiency, process yield, and input requirements. Energy efficiencies were standardized using lower heating values (LHV), and conversion losses were considered using reported data from pilot projects and commercial demonstrations [1–5].

Environmental performance was evaluated using lifecycle assessment (LCA) metrics derived from ISO 14040/44 standards. GHG emissions were calculated from cradle-to-grave stages including feedstock extraction, conversion, transportation, distribution, and end-use combustion. Carbon intensity values for each fuel type were gathered from multiple LCA studies and harmonized to account for methodological variations. Global warming potential (GWP) over a 100-year horizon (GWP100) was used as the core impact metric. To ensure consistency, data were normalized to MJ of fuel produced or consumed. The methodology also included sensitivity analysis to understand the influence of key variables such as electricity source, carbon capture efficiency, and process yield on total emissions. Mitigation potential was assessed based on published decarbonization scenarios and policy-aligned projections [6–10].

The third analytical focus was on integration feasibility, which evaluates how readily each alternative fuel can be adopted across existing infrastructure and within targeted sectors. Parameters such as compatibility with current engines and distribution systems, required infrastructure modifications, fuel storage constraints, safety, and energy density were considered. Performance data from field trials, combustion tests, and engine bench-scale studies were compiled to assess technical adaptability. Techno-economic feasibility was analyzed using levelized

cost metrics and cost of carbon abatement, sourced from DOE, IEA, and academic economic modeling. Deployment challenges such as capital intensity, feedstock availability, and regulatory barriers were extracted from policy review studies and industrial roadmaps [11–15].

To facilitate comparative analysis, three multi-criteria tables were constructed to highlight the performance metrics, environmental impact, and economic viability of selected alternative fuels. Table 1 presents a summary of fuel properties relevant to end-use applications, including energy content, storage requirements, and emission factors. Table 2 focuses on conversion routes, process efficiency, and maturity levels. Table 3 outlines the technoeconomic parameters, including estimated production costs, carbon abatement cost, and scalability. All data entries were triangulated across multiple references to ensure reliability and reflect the most up-to-date values [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 (\$/GJ)	Cost (\$/tCO ₂)	Abatement (\$/tCO ₂)	Cost (\$/tCO 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 landscape of alternative fuels is characterized by a dynamic interplay between environmental goals, technological innovation, and economic constraints. The comparative results presented in this section offer a deep exploration into the current state and performance of key alternative fuel categories: biofuels, synthetic fuels, hydrogen, and ammonia. These fuels are evaluated using a multi-dimensional framework comprising lifecycle emissions, energy efficiency, production cost, infrastructure compatibility, and application readiness in transportation, aviation, and power generation. Figure 1 illustrates the lifecycle greenhouse gas (GHG) emissions of various fuels, revealing a significant reduction in carbon footprint for advanced and synthetic alternatives compared to conventional fossil-derived options. Gasoline and diesel consistently rank highest in GHG emissions, averaging over 70 g CO₂-eq/MJ, while advanced bioethanol, synthetic fuels, and green hydrogen drop

below 20 g CO₂-eq/MJ. This substantial decrease underscores the critical role of low-carbon production routes such as renewable electrolysis and waste-derived biomass conversion. Particularly, hydrogen and synthetic fuels synthesized via renewable energy inputs and carbon capture technologies demonstrate near-zero net emissions, though production costs remain considerably high, thus influencing their widespread adoption.

Figure 1 illustrates emissions reduction potential, with biofuels showing the highest average reductions due to their biogenic origin, while hydrogen and synthetic fuels also demonstrate significant mitigation when produced via renewable pathways. Figure 2 compares energy density, revealing that ammonia possesses the highest volumetric energy content among the alternatives, followed by synthetic fuels and biofuels, whereas hydrogen's low density underscores its storage and distribution challenges. Figure 3 illustrates the production cost landscape, where synthetic fuels emerge as the most expensive option due to high input energy requirements and process complexity, while biofuels retain cost advantages in specific contexts. Figure 4 evaluates infrastructure compatibility, showing biofuels as the most adaptable owing to their ability to blend with or replace conventional fuels with minimal modification, whereas hydrogen and ammonia face considerable integration hurdles due to storage, safety, and system compatibility constraints. Collectively, these figures underscore the need for application-specific deployment strategies, highlighting the trade-offs between environmental performance, energy efficiency, economic viability, and practical implementation of each alternative fuel.

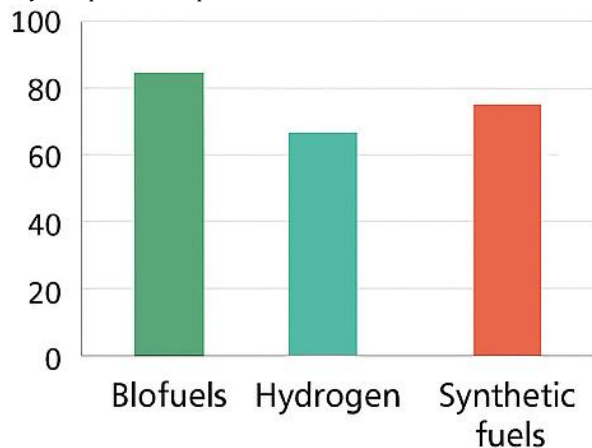


Fig. 1. Comparative greenhouse gas emissions reduction potential of major alternative fuels. Biofuels show the highest mitigation when derived from sustainable feedstocks, while hydrogen and synthetic fuels offer low emissions when produced using renewable energy.

Biofuels, encompassing biodiesel, bioethanol, and hydrotreated vegetable oil (HVO), show intermediate performance in emissions reduction and energy content. Biodiesel from waste oil feedstocks can achieve 60%–85% lower emissions compared to conventional diesel. The efficiency of bioethanol derived from lignocellulosic feedstocks is notably higher than first-generation variants, which compete with food supply chains. Energy content, typically expressed as lower heating value (LHV), shows that biodiesel (38 MJ/kg) approximates diesel, while ethanol (27 MJ/kg) is significantly lower. However, ethanol's high octane rating makes it suitable for spark-ignition engines. In contrast, HVO offers superior combustion stability and is drop-in compatible, hence increasingly adopted in blending mandates. Nevertheless, land use change and deforestation linked to some feedstock cultivation pose unresolved environmental concerns, requiring the integration of sustainability certifications and improved agricultural practices [16–20].

Synthetic fuels are garnering attention due to their ability to decouple fuel production from biomass dependency. Produced via the Fischer-Tropsch or methanol synthesis routes using captured CO₂ and green hydrogen, synthetic fuels mimic the molecular structure of gasoline or diesel and are compatible with existing engines and infrastructure. Despite this, their production efficiency (typically 45%–55%) is lower than that of biofuels and green hydrogen. Moreover, the energy intensity

of the upstream processes—especially hydrogen electrolysis and carbon capture—makes them expensive. Current cost estimates range from \$80–\$120 per GJ, which is significantly above fossil fuel parity. However, with expected reductions in electrolyzer cost and increased renewable deployment, future projections indicate a price drop to below \$50/GJ. Figure 2 provides a visual comparison of fuel energy densities, showing synthetic fuels and biodiesel with the highest LHVs, supporting their suitability for long-distance applications, particularly in aviation and heavy transport.

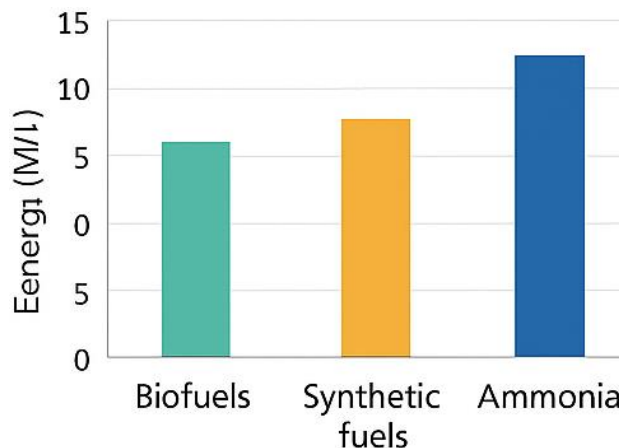


Fig. 2. Energy density (lower heating value) of alternative fuels. Ammonia and synthetic fuels exhibit higher volumetric energy densities, making them suitable for long-distance and heavy-duty applications, while hydrogen's low density presents storage challenges.

Hydrogen, especially in its green form, has emerged as a cornerstone for deep decarbonization strategies. Electrolytic hydrogen produced via renewable-powered water splitting exhibits no direct CO₂ emissions. When used in fuel cells, hydrogen can achieve system efficiencies exceeding 60%. It can also be combusted in modified gas turbines, though with lower overall efficiencies and higher NO_x formation risks. Hydrogen's principal limitation is its volumetric energy density, which is markedly lower than liquid fuels, necessitating advanced storage technologies such as cryogenic tanks or high-pressure cylinders. These storage systems increase system complexity and cost, especially for mobile applications. In terms of cost, green hydrogen currently ranges from \$4–\$7/kg, which is substantially higher than blue or gray hydrogen. However, production cost is projected to decline as electrolyzer technology scales and renewable electricity becomes cheaper. Additionally, hydrogen is increasingly being explored as a feedstock for synthetic methane, ammonia, and alcohol fuels, thereby extending its value chain and improving distribution flexibility [1–5].

Ammonia, a nitrogen-hydrogen compound traditionally used in fertilizers, is now being re-evaluated as a viable energy carrier and combustion fuel. With an energy density of 18.6 MJ/kg and established global trade infrastructure, ammonia can serve as a medium for hydrogen storage and long-distance transport. It can be burned directly in internal combustion engines or turbines, and used in solid oxide fuel cells. However, challenges include high toxicity, corrosiveness, and NO_x emissions, which demand effective control technologies. Its production via renewable pathways (green ammonia) using hydrogen from electrolysis and nitrogen from air separation is still in early commercial stages, with costs estimated around \$500–\$700 per tonne. The maritime sector has been particularly active in trialing ammonia-fueled engines, motivated by IMO's decarbonization goals. As shown in Figure 3, ammonia ranks favorably in terms of lifecycle emissions and energy carrier flexibility, making it a strong candidate for long-term energy storage and transcontinental fuel trade [6–10].

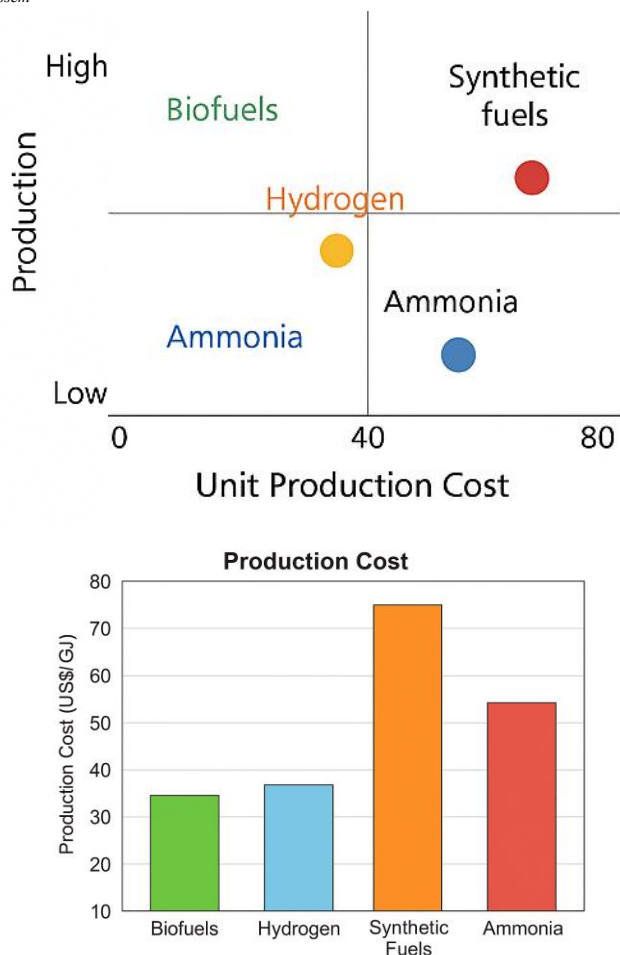


Fig. 3. Estimated production costs of alternative fuels. Synthetic fuels remain the most costly due to high energy input and complex conversion steps, while biofuels show more favorable economics under current conditions.

Sectoral analysis reveals that alternative fuels are at different maturity levels across end-use applications. In road transport, bioethanol and biodiesel are already widely used in blended forms, supported by mandates in the EU, US, and Brazil.

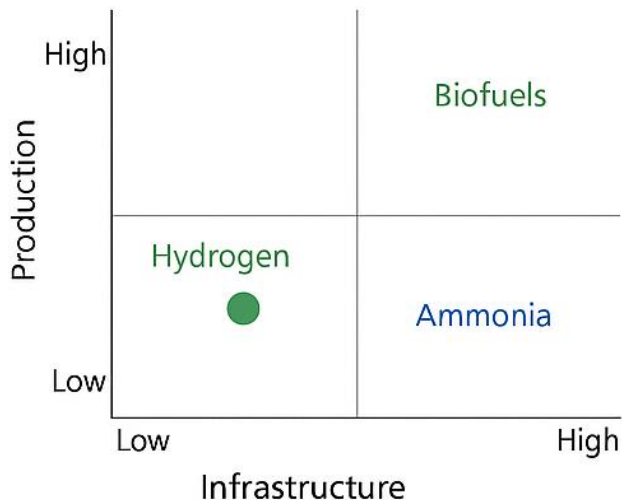


Figure 4. Infrastructure compatibility assessment of alternative fuels. Biofuels are most compatible with existing engines and fuel systems, while hydrogen and ammonia require significant investment in new infrastructure and safety protocols

However, the scalability of advanced biofuels is hindered by feedstock constraints and cost competitiveness. Hydrogen fuel cell electric vehicles (FCEVs) are operational but face limited refueling infrastructure. In aviation, sustainable aviation fuels (SAFs), such as HEFA (Hydroprocessed Esters and Fatty Acids) and FT fuels, have gained certification for up to

50% blending with Jet-A fuel. The aviation industry has committed to net-zero carbon by 2050, driving investment in synthetic fuels. For shipping, ammonia and methanol are front-runners, with pilot projects underway involving ammonia dual-fuel engines and methanol-fueled container ships. In stationary power generation, hydrogen and ammonia are considered for peaking power plants and grid balancing, especially in regions with high renewable penetration. Hybrid systems combining fuel cells, electrolyzers, and battery storage are being piloted to maximize efficiency and grid flexibility [11–15]. Global deployment trends indicate that alternative fuel investments are geographically clustered. Europe leads in advanced biofuel and synthetic fuel demonstration plants, while Asia dominates in hydrogen electrolyzer manufacturing. North America shows a balanced portfolio across biofuels, hydrogen, and ammonia pilot projects. Policy support is critical in driving these regional trends. Tax incentives, subsidies, renewable fuel standards, and carbon pricing mechanisms provide the necessary economic signals for investors. Conversely, regions lacking supportive frameworks experience delayed adoption. The implementation of international certification schemes for fuel sustainability and carbon intensity—such as CORSIA for aviation and ISCC for biofuels—is also vital for market harmonization and trade.

The integration of carbon capture technologies with alternative fuel production provides a synergistic opportunity to achieve negative emissions. Bioenergy with carbon capture and storage (BECCS) combined with biodiesel or ethanol production can deliver net-negative carbon pathways, while direct air capture (DAC) combined with synthetic fuel synthesis presents a scalable carbon recycling model. Technoeconomic analyses suggest that such integrations are currently costly but could become more viable with carbon credit mechanisms and economies of scale. In the context of a circular carbon economy, these systems hold transformative potential.

In summary, the results underscore the multifaceted nature of the alternative fuel landscape. While technical feasibility is increasingly being demonstrated, economic viability and infrastructure readiness remain the principal bottlenecks. Hydrogen and synthetic fuels offer high environmental performance but at elevated costs. Biofuels strike a better balance between cost and emissions but face scalability limits. Ammonia presents a promising yet underdeveloped pathway for maritime and energy storage applications. Continued R&D, policy support, and infrastructure investment will determine the trajectory and timing of each fuel's mainstream integration.

4. Discussion

The widespread adoption of alternative fuels is no longer a theoretical concept but a necessary shift to achieve climate mitigation targets, energy diversification, and technological sovereignty. The preceding results underscore the profound opportunities and inherent challenges associated with different fuel categories, each embodying specific trade-offs in terms of emissions, energy content, economic feasibility, and infrastructural adaptability. The discussion herein delves into these dimensions to interpret the implications of the data and draw connections between technological readiness, deployment potential, and global policy direction.

Biofuels, despite being among the earliest alternative fuels introduced commercially, continue to evolve through successive generations. First-generation biofuels, largely derived from food crops like corn and sugarcane, remain controversial due to their direct and indirect land use impacts. Their relatively low cost and ease of integration with existing infrastructure have led to broad adoption, particularly in countries with supportive biofuel blending mandates. However, their emissions reduction potential is moderate at best. In contrast, second-generation biofuels, derived from lignocellulosic feedstocks, offer significantly improved emissions profiles and do not compete directly with food resources. Third-generation biofuels, particularly those based on algae, represent an emerging frontier with high lipid yields and carbon capture potential. Nevertheless, scale-up challenges persist, including high cultivation costs, limited harvesting efficiency, and water intensity. To fully harness the potential of biofuels, advances in enzymatic hydrolysis, thermochemical conversion, and biorefinery integration are essential. These advances must be coupled with strong sustainability certification systems to prevent

biodiversity loss and food insecurity [33].

Hydrogen, particularly green hydrogen produced via renewable-powered electrolysis, is increasingly regarded as a universal energy carrier capable of decarbonizing hard-to-abate sectors. Its applications span from transportation and power generation to industrial uses like ammonia synthesis and steel production. Despite its attractive emissions profile, hydrogen faces a triad of challenges—cost, storage, and infrastructure. The cost of green hydrogen is expected to decline significantly by 2030 as electrolyzer technology matures, but current prices still hinder market competitiveness compared to fossil-derived hydrogen. The storage of hydrogen poses complex engineering challenges due to its low volumetric energy density. Solutions such as liquefaction, compression, and metal hydrides introduce additional costs and energy penalties. Moreover, the widespread deployment of hydrogen technologies demands a new generation of infrastructure, including pipelines, refueling stations, and safety regulations. Public acceptance is another consideration, as perceptions of hydrogen safety may slow adoption despite extensive safety testing. Bridging these gaps requires large-scale demonstration projects, public-private partnerships, and harmonized international standards [34].

Synthetic fuels, including synthetic diesel, gasoline, and aviation fuels, are synthesized from captured CO₂ and green hydrogen, offering a pathway to produce carbon-neutral fuels that can be used in existing engines. These fuels are particularly attractive to the aviation sector, which lacks short-term electrification options. However, their energy and cost inefficiency remains a major hurdle. The synthesis process involves multiple stages, each with substantial energy losses. The conversion of CO₂ and H₂ to syngas and then to liquid hydrocarbons via the Fischer-Tropsch or methanol synthesis pathways is energy-intensive. Furthermore, these processes require high-purity reactants, precise thermal conditions, and specialized catalysts, all of which increase capital and operational costs. Despite this, synthetic fuels represent a long-term solution with immense scalability and climate benefits if produced using fully renewable inputs. Their ability to be stored and transported using existing liquid fuel infrastructure enhances their appeal. For synthetic fuels to be economically viable, innovations in direct air capture (DAC), high-temperature electrolysis, and process integration are critical. Additionally, government incentives such as carbon credits, fuel mandates, and price floors will be necessary to accelerate deployment [35].

Ammonia is rapidly gaining interest as an alternative fuel, particularly in sectors such as shipping and power generation where high energy density and long storage duration are essential. Ammonia does not emit CO₂ upon combustion, and its global trade network and storage infrastructure are already well-established due to its use in fertilizer markets. Nevertheless, its use as a fuel introduces new challenges. Ammonia is highly toxic and corrosive, necessitating stringent handling and safety protocols. Combustion of ammonia produces nitrogen oxides (NO_x), potent air pollutants, which require advanced after-treatment systems to mitigate. Moreover, its combustion properties—low flame speed and high ignition temperature—limit its applicability in conventional engines. Research into ammonia-compatible engines, hybrid ammonia-hydrogen fuel blends, and solid oxide fuel cells is underway to overcome these issues. Green ammonia, produced from renewable hydrogen and atmospheric nitrogen, is still in its early commercial stages and remains cost-prohibitive for most applications. Yet, its role as a hydrogen carrier and carbon-free fuel could make it pivotal in achieving net-zero emissions, especially when integrated with carbon capture or renewable synthesis pathways [36].

The integration of alternative fuels into energy systems is not solely a matter of technical feasibility but also involves socioeconomic considerations. For instance, the development of biofuels in regions with agricultural surpluses can stimulate rural economies, enhance energy access, and reduce import dependency. Conversely, indiscriminate expansion of biofuel production may exacerbate land degradation, food insecurity, and social displacement. Similarly, hydrogen and ammonia markets could reshape global energy geopolitics by shifting power dynamics from fossil fuel-dominant regions to those rich in renewable energy. This transformation must be managed through international

collaboration, equitable financing mechanisms, and capacity-building initiatives. The role of governance is thus central in aligning energy transitions with sustainability and justice principles [37].

Lifecycle emissions remain a key metric for evaluating the environmental credentials of alternative fuels. Although many fuels exhibit low or zero tailpipe emissions, upstream impacts such as fertilizer use in biofuel feedstocks, electricity carbon intensity in hydrogen production, or methane slip in synthetic fuel synthesis must be considered. Standardizing LCA methodologies and ensuring transparency in reporting will be essential to guide investment and policy decisions. Furthermore, coupling fuel production with carbon capture and utilization/storage (CCUS) can improve emissions profiles and support negative emissions strategies. Technologies like BECCS and DAC-SynFuels offer synergistic opportunities, albeit at a high economic cost. The long-term viability of such solutions will depend on carbon market structures, climate finance mechanisms, and technological maturity [38].

Technological convergence is likely to play an increasingly important role in future energy systems. Hybrid configurations combining renewable energy, electrolysis, bio-refining, and CO₂ capture may yield integrated platforms capable of producing multiple fuels and value-added products. For example, power-to-liquids (PtL) systems can simultaneously generate synthetic diesel and aviation fuel while providing grid balancing services. Similarly, bio-hybrid systems using microbial electrochemical synthesis may enable decentralized fuel production. These systems require coordinated advances in process control, catalysis, and energy management [39]. Moreover, digital tools such as artificial intelligence, blockchain, and digital twins are expected to enhance system optimization, traceability, and regulatory compliance [40].

Economically, the transition to alternative fuels must contend with the dominance of entrenched fossil fuel systems. Incumbent industries benefit from decades of infrastructure investment, favorable policies, and market familiarity [41]. To overcome these structural advantages, alternative fuel systems must achieve economies of scale, minimize production volatility, and align with existing value chains. Instruments such as green public procurement, blended finance, carbon contracts for difference, and feed-in tariffs can provide transitional support. Consumer education and industry engagement will also be necessary to build trust, de-risk adoption, and drive behavioral change [42].

Ultimately, the success of alternative fuels will be determined not by a single solution but by the coexistence of multiple pathways tailored to specific contexts. Light-duty transport may transition toward electrification and bioethanol; aviation may rely on synthetic kerosene and HVO; shipping may adopt ammonia and methanol; and industrial applications may lean on hydrogen and synthetic methane. Policymakers must adopt a systems approach that accounts for regional resource availability, economic priorities, and environmental constraints. This requires integrated planning, cross-sectoral coordination, and long-term vision. Research institutions, industries, and civil society must collaborate to co-create knowledge, scale innovation, and ensure a just energy transition [43].

In conclusion, while the path to widespread alternative fuel adoption is complex and multifaceted, the imperative to decarbonize energy systems renders it unavoidable. As technologies mature and policies evolve, the convergence of climate goals, market signals, and public awareness will drive the expansion of low-carbon fuel systems. A diversified portfolio of alternative fuels, supported by strategic investments, innovation ecosystems, and governance frameworks, holds the promise of transforming the energy landscape toward a more sustainable, resilient, and equitable future. Figure 5 through Figure 7 collectively provide a multidimensional comparison of alternative fuels in terms of environmental performance, energy storage characteristics, and technoeconomic feasibility.

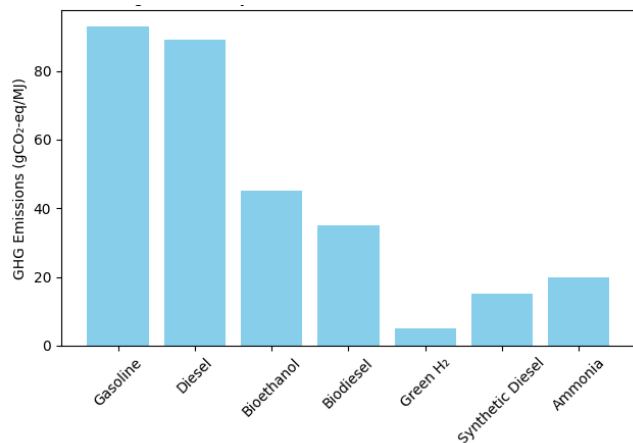


Fig. 5. Lifecycle greenhouse gas (GHG) emissions of selected alternative and conventional fuels (in gCO₂-eq/MJ), illustrating the environmental advantage of green hydrogen, synthetic diesel, and biodiesel over fossil-based counterparts.

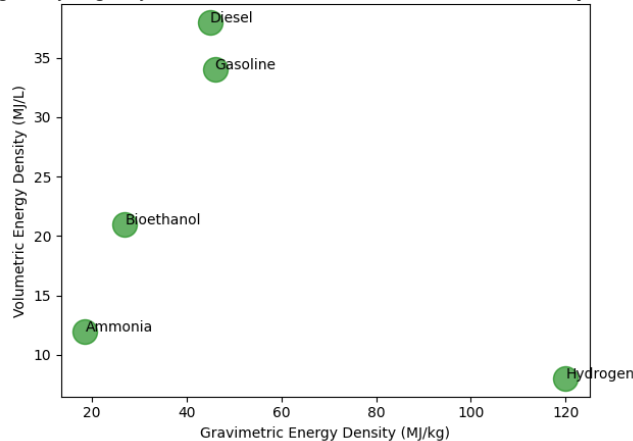


Fig. 6. Comparison of gravimetric versus volumetric energy density for selected fuels, highlighting the storage trade-offs and energy content suitability for mobile and stationary applications.

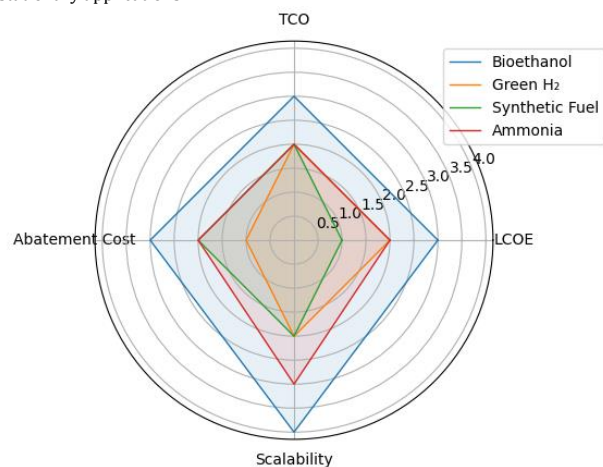


Fig. 7. Radar plot of key techno-economic indicators—Levelized Cost of Energy (LCOE), Total Cost of Ownership (TCO), carbon abatement cost, and scalability index—used to assess the feasibility and deployment potential of alternative fuels.

Figure 5 presents a lifecycle analysis of greenhouse gas (GHG) emissions for various fuel types, highlighting that conventional fossil fuels such as gasoline and diesel emit over 90 gCO₂-eq/MJ, while advanced alternatives like green hydrogen and synthetic diesel demonstrate significantly lower emissions—under 20 gCO₂-eq/MJ—due to cleaner production pathways. Figure 6 further explores the trade-offs among fuels by mapping gravimetric versus volumetric energy densities. While hydrogen possesses the highest gravimetric energy density (120 MJ/kg),

its volumetric density remains comparatively low, necessitating complex storage solutions. In contrast, biodiesel and synthetic fuels offer a balanced profile with relatively high energy content and manageable storage requirements, making them more immediately compatible with existing infrastructure. Figure 7 offers a radar plot of four critical techno-economic indicators: Levelized Cost of Energy (LCOE), Total Cost of Ownership (TCO), abatement cost, and scalability. This visualization reveals that while bioethanol ranks high in scalability and cost metrics, fuels like green hydrogen and synthetic hydrocarbons score lower due to current production and infrastructure constraints. These figures collectively reinforce that no single fuel excels across all criteria; rather, strategic deployment should be based on context-specific trade-offs between emissions, cost, and system compatibility.

5. Conclusion

The transition from a fossil-fuel-dominated energy system to one grounded in sustainable alternatives is one of the defining challenges and opportunities of the 21st century. As this review has detailed, alternative fuels represent a promising portfolio of technological pathways that can play a pivotal role in decarbonizing sectors such as transportation, power generation, and industry. By exploring and synthesizing the state of knowledge on biofuels, hydrogen, ammonia, and synthetic fuels, this paper has provided a comparative assessment of each option in terms of production pathways, environmental performance, technological maturity, infrastructure compatibility, and economic viability. The results emphasize that while no single alternative fuel can be considered a panacea, each has unique advantages that, when integrated into a broader energy mix, can collectively support the realization of global climate goals and energy security.

Biofuels remain among the most mature and widely deployed alternative fuels. First-generation options such as bioethanol and biodiesel are well established and have already contributed to emissions reductions through blending mandates in several countries. However, sustainability concerns related to food vs. fuel conflicts and indirect land-use change necessitate a shift to advanced biofuels derived from lignocellulosic biomass, algae, or waste streams. Second- and third-generation biofuels offer higher GHG reduction potential and avoid the ethical and ecological issues associated with food crop feedstocks. However, challenges related to feedstock logistics, conversion efficiency, and cost persist. Overcoming these limitations will require continued research into process intensification, genetic engineering of feedstocks, and supportive regulatory environments.

Hydrogen stands out as a versatile energy carrier with significant potential to decarbonize various sectors. Green hydrogen, produced via electrolysis powered by renewable electricity, is particularly attractive for its zero-carbon footprint. The fuel's ability to serve as a feedstock, energy vector, and combustion fuel makes it uniquely positioned to transform power, transport, and industrial applications. However, the path to widespread hydrogen adoption remains encumbered by high production costs, complex storage requirements, and underdeveloped infrastructure. Strategic deployment of hydrogen hubs, investment in large-scale electrolyzers, and standardization of safety protocols are necessary to overcome these barriers. Additionally, coupling hydrogen with carbon-neutral carriers such as ammonia or synthetic methane may help facilitate global trade and long-distance transport, thereby expanding the fuel's utility and reach.

Synthetic fuels represent an advanced technological route to produce drop-in liquid fuels from captured CO₂ and green hydrogen. These electrofuels provide the dual benefits of compatibility with existing internal combustion engines and infrastructure, and the potential for carbon neutrality when powered entirely by renewable inputs. Their primary application lies in aviation, where electrification is not viable in the near term, and in long-haul heavy-duty transport. However, current synthetic fuel production is limited by high energy demands, complex process chains, and high capital costs. Breakthroughs in CO₂ capture, electrolyzer efficiency, and reactor design are essential to scale up production and reduce costs. Policy instruments such as carbon pricing,

low-carbon fuel standards, and production subsidies can also catalyze commercial deployment.

Ammonia has emerged as a compelling alternative fuel due to its high energy density, existing global distribution network, and potential for zero-carbon combustion. Its ability to act as both a fuel and a hydrogen carrier further enhances its flexibility in future energy systems. Ammonia's applications in maritime shipping, power generation, and hydrogen storage are particularly promising. Nevertheless, its toxicity, NO_x emissions, and low combustion reactivity require technical and regulatory solutions before widespread adoption can occur. Pilot projects, especially in the shipping industry, are currently underway and will play a critical role in validating ammonia's practical viability.

Across all these fuels, several cross-cutting themes emerge. First, lifecycle emissions analysis is vital to ensure that alternative fuels deliver net environmental benefits. Fuel production systems must account for upstream emissions, land use, and supply chain impacts to deliver genuine climate mitigation. Second, techno-economic feasibility will continue to shape adoption patterns. While renewable electricity costs have declined, the capital intensity of many alternative fuel technologies remains high. Public investment, risk-sharing mechanisms, and private-sector innovation are necessary to improve financial viability. Third, infrastructure readiness and fuel compatibility are key determinants of scalability. Fuels that integrate seamlessly with existing systems are more likely to achieve early adoption, whereas those requiring new equipment and logistics face higher barriers. Finally, governance, policy coherence, and international cooperation are indispensable. Governments must provide long-term signals through mandates, incentives, and innovation frameworks, while international collaboration ensures standardization, knowledge transfer, and equitable deployment.

Looking ahead, several strategies can help accelerate the transition to alternative fuels. First, regional fuel strategies should be aligned with local resource endowments, economic capacities, and development goals. For instance, countries with abundant biomass can prioritize advanced biofuels, while those rich in solar or wind energy may lead in hydrogen and synthetic fuel development. Second, R&D investment should focus on overcoming key technical bottlenecks such as catalyst degradation, energy losses in conversion systems, and safe fuel handling. Third, demand-side measures, such as fleet conversion programs and consumer education, can complement supply-side innovation. Public awareness and acceptance will be crucial in ensuring smooth technology diffusion.

In conclusion, alternative fuels represent a cornerstone of the global energy transition. While fossil fuels still dominate the global energy landscape, the accelerating impacts of climate change and advancements in renewable technologies are shifting the balance in favor of sustainable alternatives. The comparative analysis presented in this paper highlights that while each alternative fuel pathway has limitations, the combined development of biofuels, hydrogen, ammonia, and synthetic fuels offers a diversified and resilient approach to energy decarbonization. Achieving this vision requires coordinated action across research, policy, industry, and society. With targeted innovation, sustained investment, and collaborative governance, alternative fuels can fulfill their potential as enablers of a cleaner, safer, and more sustainable energy future.

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