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Comparative Life Cycle Assessment of Alternative Fuels for Transport Sector Decarbonisation

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ABSTRACT

Decarbonising the transport sector is crucial, yet selecting the most suitable alternative fuels remains challenging. This study applies life cycle assessment to evaluate six alternative fuels, such as hydrogen, compressed natural gas, methanol, ethanol, Fischer-Tropsch gasoline, and diesel, against conventional gasoline, diesel, and grid electricity, focusing on global warming potential and acidification potential. Emissions were analysed using the Greenhouse gases, Regulated Emissions, and Energy use in Technologies model under two scenarios: current technologies (2025) and projected advancements (2050). The results indicate that, compared to gasoline, compressed natural gas reduces global warming potential and acidification potential by 27% and 23% in the short term, while gaseous hydrogen achieves reductions of 63% and 46% in the long term, respectively. These findings reinforce the theoretical foundation for transport sector decarbonisation and contribute to its sustainable development. Future research will broaden the assessment framework by incorporating complete vehicle life cycle analysis, evaluating additional alternative fuels, and integrating a wider set of indicators.

KEYWORDS

Transport sector, Decarbonisation, Life cycle assessment (LCA), Alternative fuels, Hydrogen, Electrofuels, Global warming potential (GWP), Acidification potential (AP).

INTRODUCTION

With the continuous advancement of the global economy, the transport industry has undergone significant expansion, playing a crucial role in facilitating trade, connectivity, and socio-economic development. However, this growth has been accompanied by increasing fossil energy consumption. The transport sector accounted for 27.0% of final energy consumption in 2023 [1], making it one of the primary contributors to greenhouse gas emissions and resource depletion. As concerns over environmental sustainability intensify, there is a growing need for strategies that balance economic development with energy efficiency and emission reduction in the transport sector. The imbalance in energy use within the transport sector remains a critical issue. In 2022, fossil fuels dominated global road

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transport energy consumption, with crude oil and natural gas accounting for 95%, while renewable energy sources remained marginal [2]. This heavy reliance on fossil fuels underscores the urgent need for sustainable energy transitions in the transport sector. However, the transition requires a thorough evaluation of various alternatives to conventional fossil energy, particularly concerning resource consumption and environmental impacts.

Various emerging energy alternatives to conventional fossil fuels, such as bioenergy, hydrogen, and hydrogen-based fuels, are playing an increasingly prominent role in this transition [1]. As these alternatives continue to gain attention, understanding their relative effectiveness in reducing emissions becomes crucial. However, most studies remain focused on individual fuels or specific regional contexts, with insufficient emphasis on comprehensive, globally comparative life cycle assessment that evaluates the decarbonisation potential of multiple alternative fuels under unified scenarios. For instance, while some studies have compared three hydrogen production technologies, such as steam methane reforming, biomass gasification, and wind power electrolysis, using Global Warming Potential (GWP), Cumulative Non-renewable Energy Demand, and Acidification Potential (AP), their results are not always directly comparable due to inconsistent methodologies and the omission of the end-of-life (EoL) stage [3]. Even when using a broad scope that includes the full life cycle of fuel cell electric vehicles, all hydrogen types exhibited identical impacts during the vehicle cycle. However, the study remains limited in scope, as it focuses exclusively on hydrogen and considers only two renewable production technologies, potentially overlooking broader environmental trade-offs. Seven distinct renewable power-to-methane technologies, including wind- and solar-powered electrolysis, methanation with direct air-captured CO_2 and anaerobic digestion of sewage sludge, pig manure, dairy manure, food waste, and landfill gas upgrading, were evaluated alongside compression technology using a comprehensive set of human and environmental impact indicators [4], suggesting that the pig manure system outperforms the conventional system in 6 of the 11 indicators, with the majority of the renewable systems have a lower GWP than natural gas compression. While the approach provides valuable insights, its scope is limited by the exclusion of the EoL stage, which may hinder the comprehensiveness of the sustainability assessment.

Building on these evaluations, a broader perspective is needed to compare alternative fuel systems. A more extensive approach is evident in the comparison of the whole life cycles of battery electric, hydrogen, and methanol-powered internal combustion engine vehicles [5]. However, only one production pathway for hydrogen and methanol was considered, highlighting the need for a more inclusive life cycle assessment to facilitate sustainability in the transport sector. The fossil, nuclear, and renewable (wind/solar) hydrogen production pathways for Fischer-Tropsch (FT) and ethanol e-fuels were assessed by evaluating both standalone and integrated systems (within ethanol production) [6]. These findings underscore the importance of defining system boundaries carefully, as systems with standalone assessment scope exhibited significantly lower GHG emissions. While hydrogen may seem to be the sole viable option for decarbonising transportation due to its versatility and clean-burning properties, addressing the challenge of carbon-intensive transportation requires a systematic approach, including sociological considerations such as public acceptance and local employment impacts [7]. A variety of fuels and propulsion systems are essential for achieving long-term sustainability, as no single solution can solve such a complex issue.

Life Cycle Assessment (LCA) is a valuable method for evaluating the environmental impacts of various energy pathways across their entire life cycle, from raw material extraction to EoL disposal [8]. Unlike studies focused on specific technologies or fuel pathways, LCA enables the comparison of a wide range of alternative fuels under unified criteria, providing a clearer understanding of their environmental impacts. By covering all life cycle stages, LCA identifies potential trade-offs and environmental hotspots often overlooked in narrower studies. This comprehensive approach ensures reliable and consistent comparisons between fuel systems, especially when assessing the long-term sustainability of alternative fuels and technologies. While the studies mentioned above provide valuable insights into LCA methodology, they were limited by their focus on a small number of production technologies and alternative fuel types.

This study adopts a systematic LCA approach to assess the environmental impacts of six different alternative fuels alongside conventional fossil fuels and grid electricity in the transport sector. Taking a global perspective, it evaluates key indicators such as GWP and AP to identify trade-offs and environmental hotspots.

The novelty of this work lies in its comprehensive comparison of multiple alternative fuels within a global, life cycle framework, accounting for various production pathways and real-world production shares. This approach ensures a more practical, inclusive, and accurate assessment compared to previous studies focused on individual fuels or production pathways and relying on unrealistic scopes and scenarios. The findings offer valuable insights for policymakers and the development of sustainable fuel strategies in the transport sector.

The remainder of this work is structured as follows: the methods section describes the approach and data sources used in the study, the results and discussion section presents and interprets the findings, and the conclusion offers final remarks and recommendations for future research.

METHODS

To effectively evaluate the viability of alternative fuels and technologies, critically assessing their potential in different global contexts is crucial. Fuel diversity is essential to accommodate regional variations in resource availability, infrastructure, and policy incentives. For example, compressed natural gas (CNG) is widely adopted in regions such as India **[9]**, Pakistan **[10]**, and Iran **[11]** due to local natural gas availability and supportive policies. At the same time, Italy has led the adoption of CNG in Europe **[12]**. Methanol is a strategic alternative in China to reduce oil dependency **[13]**, whereas Iceland explores its renewable methanol production using geothermal energy **[14]**. Strong government initiatives in Japan drive hydrogen fuel adoption **[15]**, South Korea **[16]**, and Germany **[17]**, while Brazil dominates sugarcane-based bioethanol production, primarily for E100 and flex-fuel vehicles **[18]**. The U.S. relies on corn-based ethanol blends like E15 and E85 **[19]**, like most of Europe, with the E10 gasoline blend being the norm **[20]**. Synthetic fuels (e-fuels) are emerging in Saudi Arabia, leveraging renewable hydrogen for sustainable fuel production **[21]**. These regional variations underscore the importance of regionally tailored policies and infrastructure investments to align fuel production with local resource availability and emission reduction targets, which will be considered in this work when comparing various fuel solutions for the transport sector.

The main goal of this study is to assess and identify the optimal short- and long-term alternative fuel options for the transport sector using a comprehensive LCA approach. The fuels evaluated include gaseous hydrogen, CNG, methanol, ethanol, and FT gasoline and diesel, representing gaseous, alcohol-based, and synthetic fuel types with distinct but occasionally interconnected production pathways. Conventional gasoline, diesel, and grid electricity serve as benchmark fuels to contextualise their competitiveness. This comparative framework enables an in-depth evaluation of the relative performance and viability of alternative fuels in both present and future contexts. The subsequent sections detail the methodology, including data sources and specific evaluation criteria.

Life cycle assessment

LCA is a widely used method for evaluating the environmental impacts of products and processes across their entire life cycle **[22]**. In this study, LCA is applied to assess the environmental performance of conventional fossil fuels and their alternative fuels for the transport sector. The LCA methodology comprises four primary interconnected stages: goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation. Each stage systematically identifies, quantifies, and evaluates the environmental impacts associated with different fuel pathways.

Stage 1 – Goal and scope definition. This stage establishes the foundational aspects of the study, including the system boundaries and the functional unit, which ensures a harmonised basis for comparison [23]. The system boundaries for this study encompass the full life cycle of the assessed fuels, commonly known as a fuel-cycle or well-to-wheel (WTW) analysis in the literature. This approach consists of three phases: the "feedstock" phase, which includes the acquisition, processing and transportation of the primary raw material used for the fuel production; the "fuel production" phase, which accounts for the technological processes, efficiencies, and associated impacts involved in converting feedstock into the final fuel product; and lastly "operation" phase, also referred to as "tailpipe emissions" which contains the usage of the fuel inside a vehicle. This structured approach ensures a systematic evaluation of the environmental impacts associated with the fuels' life cycle, which is particularly well-suited for the study. The functional unit of this work is 1 megajoule (MJ) of energy contained in the fuel product.

Stage 2 – Life cycle inventory analysis. This stage involves the collection and compilation of data pertaining to the input and output flows associated with the life cycle of the assessed product [24]. Life cycle inventory data have been sourced from Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) model [25], developed by Argonne National Laboratory. This model has been widely used in numerous studies for comparative analysis and interpretations in this field, making it a suitable reference for this research. For the grid electricity mixture, the basis is derived from [26]. The hydrogen production ratio was derived from the International Energy Agency's 2024 Global Hydrogen Report [27]; the future ratio was based on the IEA's Hydrogen Production and Infrastructure Projects Database [28] and the Det Norske Veritas' (DNV) Hydrogen forecast to 2050 [29]. It is anticipated that, by 2050, the efficiency of all engine types will improve due to technological advancements, stricter emission regulations, and global efforts to reduce emissions [30]. For the 2025 scenario, ethanol production ratios were derived from studies on historical costs [31] and second generational advancements [32], methanol from renewable sources – a feasibility study [33] and a production overview [34], and CNG – an overview [35] and renewable technologies' potential assessments [36, 37]. Future projections were based on supportable development curves from the referenced studies.

Three alternative fuel blends are considered in the examined products: M85 (85% methanol mixed with 15% conventional gasoline), E85 (85% ethanol mixed with 15% conventional gasoline), and E10 FT gasoline, which is blended with 10% bioethanol (ethanol derived from the same production techniques in both scenarios). For FT diesel, blending is unnecessary due to its excellent ignition properties. Most of the fuels examined in this study involve multiple production pathways, with ethanol being an exception.

Table 1. Examined fuels' production ratios (2025 scenario)

Fuel	Natural Gas	Coal	Fossil + CCS	Byproduct	Synthetic (Electrolysis)
Hydrogen	62.5%	21%	0.6%	16%	0.1%
CNG	100%	—	—	—	—
Methanol	65%	35%	—	—	—
FT Gasoline	62.5%	21%	0.6%	16%	0.1%
FT Diesel	62.5%	21%	0.6%	16%	0.1%

Table 2. Electricity production ratio (2025)

Energy Source	Percentage
Oil	1.6%
Natural Gas	19.6%
Coal	15.8%
Nuclear	21.9%
Biomass	4.4%
Renewable	36.7%

For synthetic methane, methanol, and FT fuels (which are assumed to follow a synthetic electrofuel production pathway), the production processes involve the usage of hydrogen and captured CO_2. The hydrogen production ratios align with those used in standalone hydrogen production scenarios, ensuring methodological coherence throughout the study. Ethanol is derived exclusively from biological feedstocks, incorporating both first-generation (food crops) and second-generation (non-food biomass) technologies, as outlined in **Table 3**.

The pathways data for all examined fuels in the 2025 scenario are presented in **Table 1**,**Table 2**, and **Table 3**, and those in the 2050 scenario are presented in **Table 3**, **Table 4**, and **Table 5**.

Table 3. EtOH production mixes (2025 and 2050)

Feedstock	Ethanol (EtOH)	
	2025	2050
Corn	60%	20%
Sugarcane	40%	25%
Forest residue	—	15%
Cellulosic	—	40%

Table 4. Examined fuels' pathway ratios (2050 scenario)

Fuel	Natural Gas	Coal	Fossil + CCS	Biomass	Synthetic (Electrolysis)
Hydrogen	10%	5%	29%	3%	53%
CNG	60%	—	—	30%	10%
Methanol	15%	5%	40%	15%	25%
FT Gasoline	10%	5%	29%	3%	53%
FT Diesel	10%	5%	29%	3%	53%

Table 5. Electricity production ratio (2050)

Energy Source	Percentage
Oil	1%
Natural Gas	16%
Coal	1%
Nuclear	25%
Biomass	5%
Renewable	52%

Stage 3 – Life cycle impact assessment. This stage focuses on deriving life cycle impact indicators, with the selection of appropriate impact categories being critical to the study's relevance and aim [38]. In this study, two key impact indicators were considered:

- Global warming potential (GWP): This indicator quantifies carbon emissions and their contribution to climate change, providing a measure of the impact of each fuel option on global warming over a specified time horizon (typically 100 years) [39].
- Acidification potential (AP): This indicator evaluates the emissions of acidifying substances, such as sulphur dioxide (SO_2), nitrogen oxides (NO_x), and ammonia (NH_3, although it is a base, its atmospheric oxidation can form acidic compounds, contributing to acidification), and their potential to acidify soil and water ecosystems. The AP is used to assess the environmental impact of fuel options on ecosystem health [40].

These categories are most relevant in assessing the environmental sustainability of alternative fuels in the transport sector, due to their direct impact on emissions reductions and ecosystem protection in the context of climate change and pollution.

Stage 4 – Interpretation. This stage entails drawing conclusions from the resulting impact data and summarising these findings in alignment with the original goal and scope of the study [41]. The interpretation of the life cycle impact data includes evaluating the relative environmental performance of the different fuel options, identifying key trade-offs and hotspots that may influence policy decisions. The conclusions drawn from the impact assessment are linked back to the initial objectives of the study, ensuring that the findings are relevant and actionable for future fuel policy development and implementation.

The outcomes of the Life Cycle Impact Assessment and Interpretation stages are discussed in detail in the results and discussion section of this work.

RESULTS AND DISCUSSION

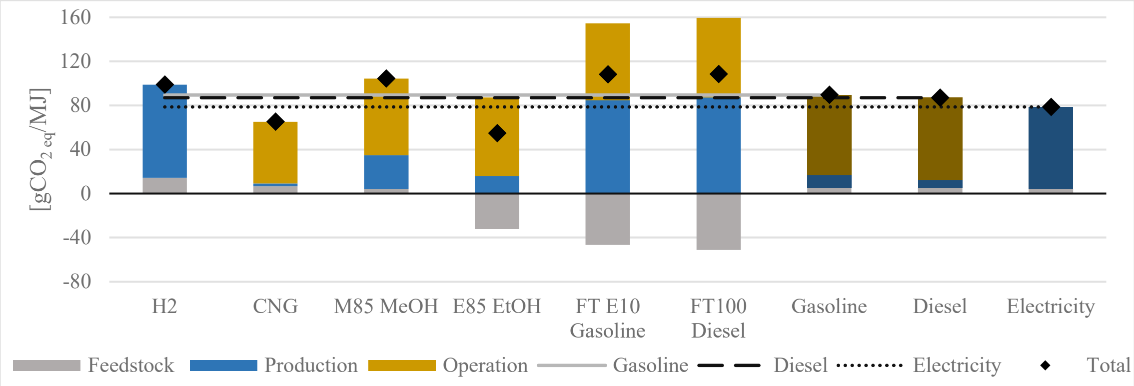
All emission data utilised for calculating the two indicators presented in this section are generated using the GREET 2024 Excel model. Subsequent calculations, including data conversion into indicators and determination of numerical results for additional analyses, are performed within the same Excel framework to maintain consistency in data processing. The results for the 2025 and 2050 scenarios, along with a comparative study of both, are provided in the following subsections.

Environmental impacts in the 2025 scenario

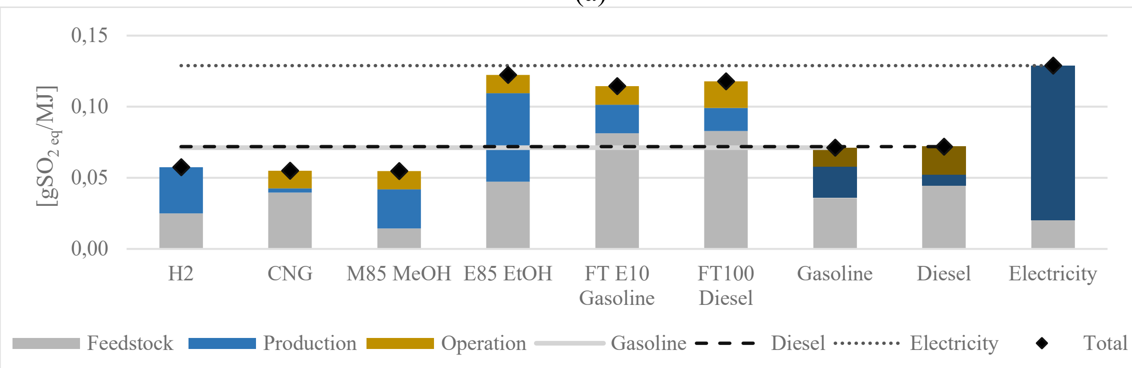
The environmental impacts of various fuel options in the 2025 scenario are evaluated and presented in this section, focusing on GWP and AP. The analysis compares six alternative fuels with conventional gasoline, diesel, and grid electricity to assess their relative environmental performance. The results, presented in Figure 1, illustrate the differences in emissions across fuel pathways, highlighting key trade-offs and potential benefits associated with each option.

In both Figure 1a and Figure 1b, the environmental impacts at the feedstock stage (acquisition, preparation and transportation) are represented by grey bars. In contrast, those at the fuel production stage are shown as blue bars. The impacts of the operation stage (EoL phase for the fuel product) are depicted using amber-coloured bars. Benchmark fuels are presented with darker colours. The benchmark values for comparison are represented by different line styles: a solid grey line for gasoline, a black dashed line for diesel, and a black dotted line for electricity. Black diamond markers indicate the total impact for each fuel.

Considering GWP, Figure 1a demonstrates that CNG (65.27 $gCO_{2\ eq}$) and E85 EtOH (54.81 $gCO_{2\ eq}$) emerge as the most sustainable options, exhibiting the lowest net and gross emissions, respectively. Notably, these are the only two alternative fuels with total GWP lower than those of the three benchmark fuels. CNG exhibits a particularly low carbon intensity, primarily due to its simple feedstock acquisition and production processes [42], resulting in a combined feedstock and production phase emission of only 9.04 $gCO_{2\ eq}$. In contrast, bioethanol (e.g., E85 EtOH, the fourth bar in Figure 1a) offsets a significant portion of its emissions through biological feedstocks, such as corn and sugarcane, which absorb substantial amounts of CO_2 during their growth cycles [43], leading to a carbon offset of −32.42 $gCO_{2\ eq}$ in the current scenario.



(a)



(b)

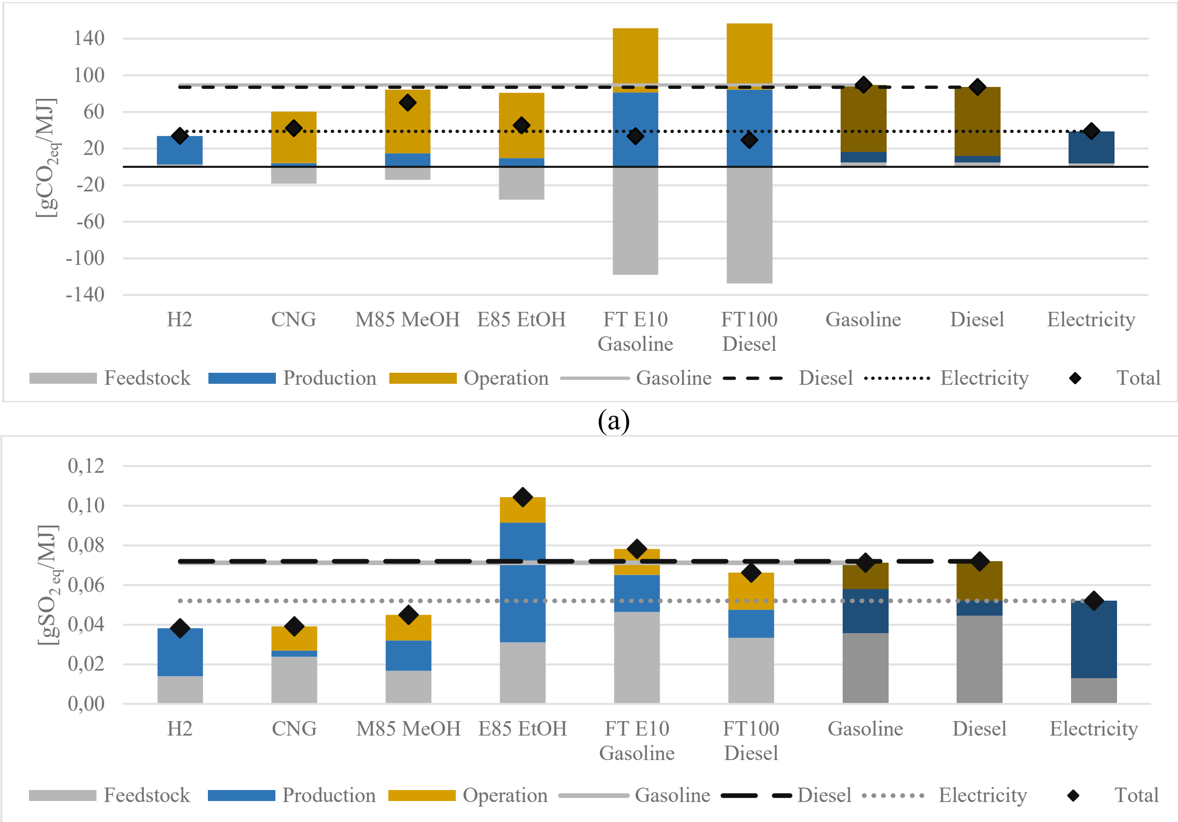
Figure 1. Environmental impacts of six alternative fuels and three conventional fuels in the 2025 scenario: Global Warming Potential – GWP (a) and Acidification Potential – AP (b)

Although FT fuels (the fifth and sixth bars in Figure 1a) also exhibit high negative offsets (i.e., −46.65 and −51.12 $gCO_{2\ eq}$, respectively), their pre-use phases, including a hydrogen production in the feedstock phase and fuel synthesis in the production phase, are highly carbon-intensive [44] resulting in total emissions that exceed those of the benchmark fuels. Methanol, while demonstrating relatively low pre-use CO_2 emissions (34.72 $gCO_{2\ eq}$ from both phases combined), remains more carbon-intensive than conventional fuels due to its comparable tailpipe emissions. The current hydrogen production mix is dominated by grey hydrogen, which significantly increases its carbon emissions, placing hydrogen at a disadvantage in terms of overall emissions [45].

Figure 1b shows that half of the alternative fuels have nearly double the AP compared to conventional fossil fuels. However, the AP levels of today's electricity far exceed those of all alternative fuels, primarily due to the emissions associated with battery production for energy storage [46], resulting in a total AP of 0.129 $gSO_{2\ eq}$. Hydrogen, CNG, and M85 MeOH demonstrate relatively minor differences in SO_2-equivalent emissions, with values of 0.0575, 0.0549 and 0.0548 $gSO_{2\ eq}$, respectively. These fuels have lower AP due to their relatively cleaner production processes. For instance, AP of the hydrogen is relatively low due to its production from low-emission sources like electrolysis, even though this is contingent on the electricity source [47]. CNG has a low AP because its feedstock acquisition and production processes are less polluting compared to other fuels [42], leading to reduced sulphur and nitrogen oxide emissions. At the same time, M85, being a blend of methanol and gasoline, also benefits from a cleaner production process compared to pure gasoline.

Environmental impacts in the 2050 scenario

This section evaluates the environmental impacts of various fuel options in the 2050 scenario. Figure 2a and Figure 2b present the emission differences across six alternative fuels and three conventional fuels, with a focus on GWP and AP.



(a)

(b)

Figure 2. Environmental impacts of six alternative fuels and three conventional fuels in the 2050 scenario: Global Warming Potential – GWP (a) and Acidification Potential – AP (b)

In the 2050 scenario, M85 exhibits a carbon footprint comparable to conventional fossil fuels, with an emissions value of 70.16 $gCO_{2\ eq}$, making it the least favourable option among the alternatives. It is mainly due to the emissions from methanol production and combustion. Both CNG and E85 EtOH continue to exhibit lower carbon intensity, benefiting from carbon sequestration during feedstock growth [48]. Hydrogen (33.54 $gCO_{2\ eq}$) and FT e-fuels, including FT gasoline (33.24 $gCO_{2\ eq}$) and FT diesel (29.15 $gCO_{2\ eq}$), are predicted to have a lower carbon footprint than the projected electricity benchmark (38.74 $gCO_{2\ eq}$), as illustrated in Figure 2a, due to increased use of renewable energy in hydrogen production and carbon capture technologies in FT fuel synthesis [49].

In Figure 2b, the AP for these fuels remains similar to the 2025 scenario. EtOH and FT fuels show higher SO_2-equivalent emissions, mainly due to fertiliser use in ethanol production and emissions from the FT synthesis process [50]. The least acidifying options in the 2050 scenario are gaseous hydrogen (0.0381 $gSO_{2\ eq}$), CNG (0.0392 $gSO_{2\ eq}$) and M85 MeOH (0.0449 $gSO_{2\ eq}$). Overall, hydrogen demonstrates the best long-term potential among the alternatives, based on both impact indicators evaluated in this study.

Comparative environmental impacts: 2025 vs. 2050 scenarios

From 2025 to 2050, significant reductions in GWP are observed across most alternative fuels, driven by advancements in production technologies and decreased use of non-renewable energy carriers. Gaseous hydrogen and FT fuels experience the most significant decline, with emissions decreasing to one-third of their 2025 values, due to the scaling of green hydrogen production. CNG follows with a 36%, resulting in total carbon emissions of 41.88 $gCO_{2\ eq}$. Electricity also shows a substantial decrease, almost halving its emissions in the 2025 results, attributed to the decarbonisation of power grids, while M85 decreases by 30% but remains at 70.16 $gCO_{2\ eq}$. E85 exhibits the smallest reduction of 45.14 $gCO_{2\ eq}$, whereas conventional gasoline and diesel remain unchanged in this assessment, constrained by the similar carbon intensities of their feedstocks.

In terms of AP, the reductions vary: M85 and E85 decrease by 15–19%, H_2, CNG and FT gasoline by 29–33%, and FT diesel by 43.8%. Electricity shows the most significant improvement, with a 60% reduction in AP, though the environmental impact of unused energy's storage systems remains a challenge [51]. CNG stands out as the most environmentally favourable option in 2025, making it a promising short-term solution for sustainable transportation. However, in the long term, hydrogen emerges as the most viable alternative, offering the best balance between low carbon emissions and minimal acidification impacts, reinforcing its role as a key candidate for future sustainable fuel strategies.

CONCLUSION

The GWP and AP of six alternative fuels in the transport sector are evaluated and compared with three conventional fuels across both 2025 and 2050 scenarios to identify the optimal options for the short- and long-term decision-making. In the 2025 scenario, CNG comes as the most favourable choice due to its simple production technology and cleaner combustion properties with a GWP of 65.27 $gCO_{2\ eq}$ and an AP of 0.0549 $gSO_{2\ eq}$. By 2050, gaseous hydrogen appears to be the least polluting alternative fuel, achieving a significantly lower GWP of 33.54 $gCO_{2\ eq}$ and an AP of 0.0381 $gSO_{2\ eq}$. In both scenarios, bioethanol, particularly with the advancement of second-generation technologies, and synthetic e-fuels are strong contenders for the short- and long-term sustainability, respectively.

While this study identifies promising low-emission alternatives, it does not deeply analyse conventional fossil fuels in the future scenario or include the full life cycle of vehicles using these fuels. Future research should expand the scope by incorporating a broader range of alternative fuels (e.g. liquid petroleum gas, dimethyl-ether or biobutanol), assessing vehicle life cycles, and integrating additional environmental and economic indicators. Further investigation into the techno-economic feasibility of emerging fuel technologies and the development of comprehensive life cycle inventories would provide valuable insights for policymakers and industry stakeholders, supporting the transition to a more sustainable transportation sector.

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NOMENCLATURE

Abbreviations

AP	Acidification Potential
CCS	Carbon Capture and Storage

CNG	Compressed Natural Gas
EoL	End-of-Life
FT	Fischer-Tropsch
GHG	Greenhouse Gases
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Technologies
GWP	Global Warming Potential
LCA	Life Cycle Assessment
WTW	Well-to-Wheel

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