Case Studies on Transport Policy 21 (2025) 101502

Contents lists available at ScienceDirect

Case Studies on Transport Policy

journal homepage: www.elsevier.com/locate/cstp

An expert-based evaluation of fuel alternatives for green road passenger transport in Germany

Javier Perez Vera [a], Ali E. Torkayesh [a,*], Sandra Venghaus [a,b]

[a] Decision Analysis and Socio-economic Assessment, School of Business and Economics, RWTHAachen University, 52072, Aachen, Germany
[b] Institute of Energy and Climate Research – Systems Analysis and Technology Evaluation (IEKSTE), Forschungszentrum Jülich, Wilhelm-Johnen-Straße, 52428 Jülich, Germany

ARTICLE INFO

Keywords:
Green road transport
Renewable fuels
Electric vehicles
Multi-criteria decision analysis
climate-neutrality

ABSTRACT

To achieve climate-neutrality in Germany by 2045, a profound transformation across all sectors is necessary. The transport sector is responsible for a significant proportion of greenhouse gas (GHG) emissions in Germany and the European Union more widely. With low reductions in GHG emissions, the fossil fuel-dependent German road passenger sector is regarded as one of the primary challenges to achieving the climate-neutrality target. Thus, replacing current fossil fuels with sustainable alternatives is of high importance for defossilizing the road passenger transport sector and moving towards climate-neutrality. However, the identification of promising fuel alternatives and their prioritization for implementation is a complex and multi-dimensional decision-making problem that requires robust tools to generate reliable solutions. For this purpose, a holistic approach was developed using an entropy-based consolidated multi-criteria decision analysis (MCDA) for fuel evaluation under technical and sustainability frameworks based on stakeholder opinions. Methodological and managerial sensitivity analyses are conducted to show the robustness of the results under different circumstances. The results indicate that GHG emissions with an importance of 22%, policy compliance with an importance of 13%, and ecotoxicity with an importance of 9% are the most important criteria for fuel evaluation. On the other hand, electric vehicles and green hydrogen demonstrate the most promising performance for shaping the future road transport sector, followed by advanced biofuels and Power-to-X fuels.

1. Introduction

Global emissions have reached record levels, and efforts to limit global warming to 1.5 °C, as called for in the 2015 Paris Agreement, seem unattainable with existing policy measures (Geden, 2016; Sun et al., 2022). As one of the top ten carbon-emitting countries in the world, Germany bears a significant responsibility for addressing emissions (European Commission et al., 2020). The government has pledged to reduce emissions by 65% by 2030 (compared to 1990 levels) and achieve climate-neutrality by 2045 (BMU, 2016, 2021; Federal Government of Germany, 2021). Currently, the transport sector accounts for 20% of overall greenhouse gas (GHG) emissions in Germany (UBA, 2022b). The sector has struggled to meet reduction targets, having only achieved modest progress over the years (UBA, 2022b). The need for action is emphasized in the projection report released by the Federal Government in 2021, indicating that existing policies are expected not to meet the targets for 2030 (UBA and BMU, 2021). Considering the sector's current emission level of 148.63 million tons CO_2 equivalent, without implementing further measures, the sector is projected to exceed its 2030 emissions target (90 million tons CO_2 equivalent) by 40 million tons CO_2 equivalent (UBA and BMU, 2021; UBA, 2022,b).

In the transport sector, road passenger transport has played a significant role in shaping current emissions levels (144,033 kilotons CO_2 equivalent in 2020) (DLR and DIW, 2020). Currently, the high carbon emissions level in the road passenger transport sector is primarily due to fossil fuel consumption (Kraftfahrtbundesamt, 2022). The extensive reliance on fossil-based transport fuels has further entrenched in Germany's oil dependence, with 98% of its crude oil being imported (BVEG, 2022). The evolving geopolitical landscape in Europe has heightened the necessity to reconsider fuel choices within the transport sector. Thus, in aligning with environmental objectives, the need to transition from fossil fuels to alternative fuels in Germany's road passenger sector should be actively pursued (Schnuelle et al., 2019).

Beyond diesel and gasoline, liquefied petroleum gas (LPG) and compressed natural gas (CNG) are currently two alternative fuels used in the German road transport sector (DLR, 2013; UBA, 2023). According

* Corresponding author.
E-mail address: ali.torkayesh@socecon.rwth-aachen.de (A. E. Torkayesh).

https://doi.org/10.1016/j.cstp.2025.101502
Received 25 January 2024; Received in revised form 13 March 2025; Accepted 26 May 2025
Available online 18 June 2025

to the latest data by FNR (2022), LPG and CNG accounted for 0.4% and 0.3% of the total fuel consumption in 2021. In the early 2000s, the blending of biofuels was proposed as another alternative to improve the ecology of the transport sector (Navas-Anguita et al., 2019). Nevertheless, the sustainability of first-generation biofuels has been significantly challenged due to concerns surrounding food-versus-fuel debates as well as indirect land use change. Consequently, advanced biofuels have emerged as a solution aiming to avoid these issues and are known as second- and third-generation biofuels (Navas-Anguita et al., 2019). Furthermore, alternative fuels, using electricity as an input, present diverse opportunities for defossilizing the transport sector. Apart from direct electrification via battery electric vehicles (BEVs), hydrogen-powered fuel cells also offer an opportunity to prevent carbon and air pollutant emissions during the usage phase (Frontier Economics and ifeu, 2021). Finally, the potential of Power-to-X (PtX) fuels, also referred to as e-fuels, has emerged as a significant topic of discussion in recent decades. By utilizing a sustainable carbon source in the production process as well as renewable electricity for hydrogen production and other processes, this technology has the capability of decreasing emissions compared to conventional diesel and gasoline fuels. Nevertheless, high costs, the inefficiency of the process, and its energy requirement currently hinder the widespread adoption of PtX fuels for road transport (NPM, 2020; Frontier Economics and ifeu, 2021). These limitations highlight the need for comprehensive policy frameworks and strategic initiatives to support the defossilization of the transport sector, particularly through long-term emission reduction goals and sector-wide transformation efforts.

In 2013, both the European Union (EU) and the German government initiated strategies aimed at addressing the transformation of the transport sector (BMVBS, 2013; European Commission, 2013). The crucial role of the sector was underscored in Germany's Climate Action Plan, which established a minimum carbon emission reduction target of 48% by 2030, which has recently been modified to 65% (proposed by The German Climate Protection Act) (BMU, 2016, 2021). The proposal suggested the introduction of a carbon price and the expansion of alternative fuel infrastructures as measures to promote the adoption of clean technologies (Bundesregierung Deutschland, 2019). An integral regulation relevant to the road passenger transport sector was established as part of the EU Green Deal, which specified that only zero-emission cars would be permitted for registration by 2035 (European Commission, 2021b).

Despite the general preference for electric vehicles (EVs) in road transport, Germany and the EU have highlighted their technology-open approach. Therefore, it is important to identify potential alternatives that are likely to be adopted to achieve climate-neutral road passenger transport. Establishing suitable frameworks for various fuel alternatives stands as a fundamental task to formulate proper policy measures for achieving climate-neutrality. On the other hand, following the identification of the relevant fuel alternatives, their evaluation under specific indicators is an important step to facilitate the development of supporting policy frameworks. The multi-dimensional nature of the problem, conflicting interests among various stakeholder groups, and the unpredictability of future developments amplify the complexity of the assessment process. Consequently, a multi-dimensional approach becomes essential for comprehensively analyzing the challenge and aiding in its resolution. In this context, using multi-criteria decision analysis (MCDA) methods is essential, as they can capture the various dimensions of sustainability (Govindan et al., 2022; Ozdagoglu et al., 2022; Pratap et al., 2022; Saxena and Yadav, 2023; Vorwerg et al., 2025).

Moreover, the increasing risk of not meeting the climate goals highlights the significant environmental and economic costs of unsustainable practices in the transport sector. The need to transition to cleaner fuels has thus become increasingly pressing (Bicer and Dincer, 2018; Gray et al., 2021; Ozdagoglu et al., 2022; Breuer et al., 2022; Louen et al., 2023; Johansson et al., 2024). Hence, this study aims to assess various fuel alternatives regarding sustainability and technical aspects for the German road passenger transport sector, with the goal of supporting policy-makers in understanding their performance within a multi-dimensional framework. A fuel evaluation framework is introduced in this study that enables a multi-dimensional perspective in identifying key potential fuel alternatives for German road passenger transport based on the measures introduced in the EU Green Deal and Fit for 55 package. Next, in order to ensure a comprehensive evaluation of the fuel alternatives, an evaluation framework is proposed that covers technical and sustainability pillars, including economic, environmental, and social aspects, along with regulatory and political factors. Evaluating various fuel alternatives against multiple criteria can be approached as an MCDA problem. To achieve this objective, an approach based on Shannon's Entropy is developed for the multi-criteria evaluation of fuel alternatives. This approach integrates four MCDA ranking techniques, namely: Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), Weighted Aggregated Sum Product Assessment (WASPAS), Combined Compromise Solution (CoCoSo), and Measurement of Alternatives and Ranking According to Compromise Solution (MARCOS). The Shannon's Entropy method is commonly used to objectively derive weight coefficients, effectively minimizing subjectivity among experts. Applying an objective technique rather than a subjective one mitigates discrepancies among stakeholders with diverse backgrounds and areas of expertise. This helps to achieve a more neutral and impartial evaluation process. Furthermore, the motivation for developing a consolidated MCDA approach is to reduce the dependence on a single MCDA method, recognizing the inherent soft computing characteristics of these quantitative techniques. A diverse panel of experts spanning relevant sectors is curated to integrate various stakeholder perspectives. In order to accommodate potential uncertainties within the expert perspectives, the proposed approach operates within a fuzzy environment (Zadeh, 1965). Employing fuzzy set theory allows experts to articulate their evaluations of different fuel alternatives against various criteria using human-mode linguistic terms, which serves to capture the nuanced nature of their assessments.

The main contributions of this study can be summarized as follows:

- Proposing a multi-dimensional framework based on technical, social, environmental, economic, and regulatory aspects for evaluating fuel alternatives in road passenger transport.
- Developing a multi-criteria evaluation approach based on Shannon's Entropy and a consolidated MCDA ranking method to evaluate fuel alternatives for road passenger transport in Germany.
- Conducting sensitivity analyses based on weight coefficient scenarios for the decision criteria and corresponding changes in the ranking order of fuel alternatives, as well as on the importance of experts' opinions considering their backgrounds and experience.
- Deriving managerial and policy implications to promote potential fuel alternatives for defossilizing road passenger transport in Germany.

The remainder of the paper is organized as follows. In Section 2, we review the literature on transport and fuel policies, as well as the available MCDA methods used for similar problems. The developed approach and its preliminaries are presented in Section 3. A definition of the problem, including descriptions of the fuel alternatives and proposed evaluation framework, are presented in Section 4. The results and extensive sensitivity analyses are provided in Section 5 and Section 6. Managerial and policy implications are presented in Section 7. Finally, Section 8 presents concluding remarks.

2. Literature review

2.1. Relevant regulatory frameworks

Global energy consumption and transport emissions are influenced by policies that govern both the transport and energy sectors. Emission reduction in the transport sector demands a holistic strategy encompassing consistent legislation that promotes renewable energy adoption, enhances fuel efficiency, and restructures transport networks (Axsen et al., 2020; Shah et al., 2021). This section provides an overview of important policies aimed at facilitating the transition of the transport sector towards sustainability.

In the 2010s, Germany implemented key transport policies to address challenges in meeting the 2030 emissions reduction targets. The National Electromobility Development Plan, introduced in 2009, was a foundational policy emphasizing the role of EVs in advancing sustainable transport by reducing oil dependency, lowering GHG emissions, and supporting EV integration. The plan prioritized R&D in BEVs and promoted market adoption, with the aim of achieving one million EVs by 2020. Meanwhile, in the EU, the Renewable Energy Directive (RED) was proposed in 2009 to regulate the transition from fossil fuels to renewable alternatives. Building on these foundational policies, the 2010s saw numerous initiatives aimed at reinforcing Germany's commitment to sustainable transport and emission reduction. Later, Germany also signed to the Paris Agreement, part of the United Nations Framework Convention on Climate Change (UNFCCC), committing to reduce its emission level. These endeavors finally were intensified following the release of two key policy packages, known as the EU Green Deal and Fit for 55, which heralded a cohesive push towards ambitious climate goals.

To present an overview of the legislation in Germany and the EU, the relevant regulatory frameworks are identified and summarized in Table 1. The identified regulatory frameworks show a direct or indirect influence on the transition in the transport sector. This overview thus provides the basis for formulating a resilient future fuel plan to foster a sustainable transport sector by identifying the relevant targets and regulatory instruments, as well as supported fuel alternatives.

Interested readers are referred to a comprehensive review and analysis of the regulatory frameworks guiding transition of Germany's transport sector by Torkayesh and Venghaus (2024a). After reviewing the relevant policies, it is essential to understand the applicability of MCDA methods to addressing the fuel evaluation problem.

2.2. Applications of MCDA for fuel evaluation and planning

Responsible decision-makers require appropriate and justified information, as well as supportive tools and models (Nuriyev, 2020). MCDA methods enable the ranking (sorting or prioritization) of several alternatives under multiple performance criteria (Lootsma, 1999). For this reason, MCDA methods have had a high relevance in the field of energy economics, transport planning, and policy-making (Kaya et al., 2019; Nuriyev, 2020; Yannis et al., 2020).

The first type of studies in the MCDA literature on fuel planning encompasses those that evaluate various pathways (technologies), strategies and barriers, focusing on optimizing sustainable directions within the transport sector. These studies primarily aim to identify the most effective approaches for reducing emissions, enhancing energy efficiency, and promoting the adoption of cleaner fuels. Heo et al. (2012) discussed different hydrogen production pathways using a fuzzy AHP. The six alternatives are assessed under 12 factors for the case of South Korea, concluding that steam methane reforming is the most suitable option for the country. This outcome is primarily driven by the dominance of economic feasibility factors, which accounted for more than 67% of the total influence. Next, Ren et al. (2021) examined strategies for EVs combining sentiment analysis and MCDA methods. They considered ten alternatives that were subsequently ranked using the VIseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) based on the type of technology, safety, comfort, and cost indicators. Torkayesh et al. (2024) investigated the market development barriers of renewable fuels in the transport sector of Germany. An integrated MCDA-based approach was developed using the decision-making trial and evaluation laboratory (DEMATEL), interpretive structural modeling (ISM), clustering algorithms, and additive ratio assessment (ARAS) in a Type-2 Neutrosophic environment. For the case of Germany, ten major barriers were identified, representing environmental, technical, social, economic, and regulatory challenges. The results highlighted the key role of insufficient policies supporting renewable energy sources as a major barrier for the market development of renewable fuels. Based on stakeholder input, road transport was identified as the sector most impacted by the identified barriers, particularly due to insufficient policies supporting renewable energy sources, which exert an overall influence of 10%.

Another type of study within the MCDA literature addresses sustainability assessments, examining fuel alternatives through a comprehensive lens that integrates environmental, economic, and social criteria to ensure balanced and sustainable decision-making. Osorio-Tejada et al. (2017) investigated the sustainability of liquefied natural gas (LNG), hydro-treated biodiesel, and diesel oil by an MCDA approach based on AHP for the case of Spain. Economic (initial and maintenance costs by 43%, reliability by 43% and legislation by 14%), environmental (GHG by 63%, noise pollution by 26% and air pollution by 11%), and social (employment by 63%, social benefits by 11% and social acceptability by 26%) criteria were explored in terms of vehicles, infrastructure, and fuels. The results show that LNG is considered by stakeholders to be the most sustainable fuel alternative. Mukherjee (2017) evaluated eight different fuel alternatives, namely: diesel, CNG, LPG, methanol, fuel cells, electric buses, hybrid buses with diesel engines, and hybrid buses with CNG engines — with regard to economic, environmental, social and technical criteria using TOPSIS with intuitionistic fuzzy sets. Among the identified criteria categories, technical factors play the most significant role, with an overall influence of 40%. Their results show that LPG and methanol are considered to be the most and least preferred fuel alternatives. Kügemann and Polatidis (2019) conducted an extensive review of road fuel alternatives and vehicle types using an MCDA, highlighting that the outcome is highly dependent on the reviewed context and region. Key identified fuel alternatives, include diesel, gasoline, CNG and LNG, LPG, biodiesel, ethanol, electricity, and hydrogen. In general, electricity for EVs and ethanol show better performance for light vehicles, whereas gaseous fuels are often favored for heavy vehicles.

Brainy et al. (2024) developed a unified fuzzy decision to evaluate potential sustainable fuel alternatives for the transport sector of India. An evaluation framework was built based on the principles of technical reliability, affordability, availability, environmental compatibility, and social acceptance to investigate the performance of biofuels, CNG, LPG, EVs, and hydrogen. Findings for the case study of India indicate that hydrogen and EVs are viewed as promising fuel alternatives to replace current fossil fuels. Most recently, Borghetti et al. (2024) suggested an integrated MCDA approach based on AHP, the ELimination Et Choix Traduisant la REalitè I (ELECTRE I) and a simple Weighted Sum Model (WSM) to evaluate alternative fuels for urban and interurban bus services in Italy. For this case study, BEVs, fuel cell EVs (FCEVs), diesel, CNG, LNG, and hybrid EVS (HEVs) were considered according to the European directives and policies under the Green Deal. On the other hand, the evaluation framework take into account environmental, vehicle life cycle, and economic costs. Building their data on the basis of stakeholders' perceptions, the results show that BEVs and HEVs are the most suitable alternatives for urban and interurban transport.

The fuel planning problem has also been addressed for other transport modes, such as maritime and aviation. For maritime transport, Hansson et al. (2019) evaluated multiple fuel alternatives by including the insights of Swedish stakeholders. Their goal was to analyze the competitiveness of different alternative fuels against conventional heavy fuel oil. The results conclude that the prioritization of fuel alternatives varies significantly depending on the interests of stakeholders and illustrates the need for policy incentives for the introduction of renewable marine fuels. For aviation, Chai and Zhou (2022) suggested a multi-phase MCDA approach based on AHP and TOPSIS using interval valued triangle fuzzy numbers under the prospect theory. Algal-based fuels,

Table 1
A summary of the relevant policies on sustainable road transport.

Policy	First release date (updates)	Target fuels	Summary of relevant targets & measures
Biofuel Quota Act	2006	Biofuels	- Applying tax exemptions on both, pure biofuels and biofuel blends, - Defining quotas, - Setting an annually increasing minimum share of biofuels in conventional diesel and gasoline, - Replacing the quotas with GHG quotas in 2009 (Deutscher Bundestag, 2002, 2006).
German Federal Government's National Electromobility Development Plan	2008	EVs	- Supporting the production of EVs to replace fossil fuel vehicles, - Introducing measures for market entry and diffusion of EVs, - Setting the target of 1 Million EVs by 2020 (BMVI, 2009).
Renewable Energy Directive (RED, RED II, RED III)	2009 (2018, 2021)	Biofuels, hydrogen, synthetic fuels (RFNBOs)	- Increasing its previous targets in the RED I & II to ensure a minimum share of 42.5% renewable energy in 2030, - Achieving at least 14% renewable energy in transport by 2030, - Supporting the use of advanced biofuels and synthetic fuels. European Commission (2023).
National Transport and Fuels Strategy (MFS)	2013	EVs, renewable fuels	- Diversifying the energy sources for decarbonizing the transport sector, - Supporting the National Electromobility Plan, - Supporting alternative fuels for different transport modes, - Promoting measures to expand the infrastructures for EVs and alternative fuels (BMVBS, 2013).
European Alternative Fuels Strategy	2013	EVs, hydrogen, Ammonia, LPG, LNG, Biofuels, CNG, GtL	- Supporting electrification in all transport modes with a major focus on road transport, - Using hydrogen in road transport via fuel cells, - Fostering advanced biofuels in liquid form, - Developing required infrastructures for liquid fuels produced using synthetic gas, hydrogen, and carbon (European Commission, 2013).
European Alternative Fuels Infrastructure Regulation (AFIR)	2014 (2023)	EVs, hydrogen, biofuels, LPG, LNG, CNG	- Installing electric recharging infrastructure for light- and heavy-duty EVs, - Installing hydrogen refueling stations for road vehicles (max 200 km in between), - Opening LNG infrastructures for road transport vehicles, - Setting mandatory national fleet based targets for minimum power output, and distance-based targets on the TEN-T core, - Including provisions for ensuring the user-friendliness of recharging infrastructures (European Commission, 2014).
National Climate Action Plan 2050	2016 (2022)	EVs, renewable fuels	- Setting climate-neutrality target by 2050, - Presenting measures to achieve climate-neutrality, - Supporting the electrification of the road and rail transport, - Introducing required carbon pricing mechanisms, as well as subsidies to foster EVs and alternative fuels, - Increasing the share of electricity generated from renewable sources to at least 80%, - Reducing final energy consumption in transport by 40% (BMU, 2016).
European Strategy for Low-Emission Transport	2016	EVs, renewable fuels	- Optimizing the transport sector through digitalization, fair pricing, and multiple modalities, - Supporting low-emission transport by using renewable fuels, and electric-transport, - Connecting the transport and energy systems, promoting R&D, economic investments, improving human labor skills (European Commission, 2016).
The 2030 Federal Transport Infrastructure Plan (FTIP 2030)	2016	EVs & hydrogen	- Facilitating mobility in road and rail passenger transport, - Enhancing transport safety, - Reducing emissions through the adoption of EVs and hydrogen, - Limiting the impact on nature and the landscape (BMVI, 2016).
Effort Sharing Regulation (ESR)	2018 (2023)	Fossil fuels, CNG, LNG, biofuels, EVs, hydrogen	- Reducing 30% of GHG emissions in non-ETS sectors by 2030, - Improving the average annual energy efficiency for new fossil and hybrid heavy-duty vehicles, - Supporting the use of biofuels, EVs, hydrogen, LNG, and CNG for road transport (European Commission, 2021c).
CO_2 emission performance standards for cars and vans	2019	Alternative fuels. CNG, LPG, fossil fuels	- Reducing emissions for the reporting periods of the year 2025 onward by 15%, - Achieving a 30% reduction in emissions from 2030 onward (European Commission, 2019).
National Platform Future of Mobility (NPM)	2018	EVs, renewable fuels	- Providing a platform to support the electrification of the transport sector as well as renewable fuels, - Supporting the digitalization in transport (NPM, 2020, 2021).
National Hydrogen Strategy	2020 (2023)	Hydrogen	- Developing necessary legal frameworks to produce hydrogen, given a major focus on green hydrogen, - Supporting the use of green hydrogen to produce fuels for transport, - Producing e-aviation (jet) fuels using green hydrogen, - Construction of required infrastructures for the production and transport of hydrogen, - Activating the market to boost investments in hydrogen-powered vehicles (e.g., light and heavy-duty vehicles, and buses), - Aiming for an electrolysis capacity of at least 10 GW by 2030 (Bundesregierung Deutschland, 2020).
Sustainable and Smart Mobility Strategy (SSMS)	2020	EVs, fossil fuels, CNG, LNG, LPG, biofuels, hydrogen, synthetic fuels	- Targeting a 90% reduction in transport emissions by 2050, - Boosting EV adoption and infrastructure development (European Commission, 2020).

petroleum refining, soybean-based fuels, and Fischer–Tropsch synthesis based on natural gas were considered the main fuel alternatives to be evaluated against technical, social, economic, and environmental indicators. The perceived sustainability performance of the identified fuel alternatives based on a panel of experts indicate a promising role of algal-based fuels for sustainable aviation.

Life cycle assessment (LCA) is one of the well-known approaches for determining the environmental characteristics of different processes. For fuel planning challenges, LCAs can be integrated with MCDA methods in order to address the problem in a comprehensive manner by consolidating their results. From this perspective, Onat et al. (2016) developed a decision model using an input–output based LCA and a fuzzy TOPSIS for assessing various vehicle technologies, including internal combustion EVs, HEVs, plug-in-hybrid electric vehicles (PHEVs), and BEVs- in the United States. Two scenarios were considered to address the problem with no additional power infrastructure requirements, as well as an extreme scenario utilizing solar power. In both of these scenarios, plug-in and hybrid EVs exhibited promising performances, ranking as the dominant alternatives. Another example of an integrated LCA-MCDA methodology can be found in a study by Macioł and Rębiasz (2018), in which various passenger vehicles were evaluated. The decision model was built based on AHP and TOPSIS, with the results showing that BEVs perform better than other alternatives for private passenger transport. Onat (2022) analyzed a case study in Qatar by comparing different vehicle types. Fourteen criteria were identified to assess the performance of different vehicles types taking into account economic, environmental, and social aspects. Following an LCA analysis, AHP and combinative distance-based assessment (CODAS) were used to prioritize the vehicle types. The final results indicate that solar-powered BEVs constitute the best solution for sustainable transport.

While the existing literature on fuel and energy policies in the transport sector has addressed the complexities associated with sustainable road passenger transport, recent studies underscore the significance of employing both quantitative and qualitative methodologies to effectively address these multi-dimensional challenges. There exists a notable gap in the adoption of methodologies that solely focus on specific sustainability dimensions, neglecting the need for a holistic framework that encompasses social, environmental, and economic aspects. Furthermore, although numerous studies have concentrated on individual fuel alternatives, only a limited number of studies simultaneously address multiple alternatives. Therefore, it is crucial to encompass all potential fuel alternatives within an evaluative framework. This approach proves essential in facilitating strategic decision-making, particularly in the formulation of policies for road transport. By encompassing a wider range of fuel alternatives, it becomes possible to identify the most viable ones based on the identified regulatory frameworks. In this way, it facilitates the creation of well-informed, sustainable, and efficient supporting strategies based on stakeholders' opinions for the road transport sector. As a method, MCDA can be used to solve transport-related problems. It is capable of managing diverse goals and criteria and offers an effective method for evaluating the applicability of different fuel alternatives. This evaluation aids in enhancing transport efficiency and promoting environmental sustainability.

3. Methodology

3.1. Fuzzy theory

Real-world problems are often linked to a certain degree of uncertainty, vagueness or incomplete information where the input data are obtained based on expert' opinions. This may lead to imprecise results and consequently, imperfect decisions (Nuriyev, 2020). The absence of considering uncertainty in modeling was already addressed in 1965 by Zadeh, who introduced fuzzy sets, as an approach to incorporating the dispersion of information (Zadeh, 1965). The idea of fuzzy numbers is to express the inaccuracy of values by membership functions (Zadeh, 1965), as is shown in Eq. (1) for a triangular FN.

$$\mu_{\tilde{A}}(y) = \begin{cases} 0, & y \in (-\infty, a) \\ \frac{y-a}{b-a}, & y \in [a, b] \\ \frac{c-y}{c-b}, & y \in [b, c] \\ 0, & y \in (c, +\infty) \end{cases} \tag{1}$$

Based on the definition of two triangular fuzzy numbers $\tilde{A}_1 = (a_1, b_1, c_1)$ and $\tilde{A}_2 = (a_2, b_2, c_2)$, the basic operations are described in the following Sun (2010), Stanković et al. (2020).

1. Addition:

$$\tilde{A}_1 \oplus \tilde{A}_2 = (a_1 + a_2, b_1 + b_2, c_1 + c_2) \tag{2}$$

2. Multiplication:

$$\tilde{A}_1 \otimes \tilde{A}_2 = (a_1 \cdot a_2, b_1 \cdot b_2, c_1 \cdot c_2) \tag{3}$$

3. Subtraction:

$$\tilde{A}_1 - \tilde{A}_2 = (a_1 - c_2, b_1 - b_2, c_1 - a_2) \tag{4}$$

4. Division:

$$\frac{\tilde{A}_1}{\tilde{A}_2} = \left(\frac{a_1}{c_2}, \frac{b_1}{b_2}, \frac{c_1}{a_2}\right) \tag{5}$$

3.2. Shannon's entropy

The weighting of criteria is a decisive step in the decision-making process and can be performed with subjective or objective models. Subjective weighting relies on the opinion of a group of experts or stakeholders. Objective approaches, on the other hand, are based on probability theories and use the information given in the decision matrix (Mukhametzyanov, 2021). According to Suh et al. (2019), subjective weighting can bias the outcome of the decision-making process. In contrast, objective approaches enable the elimination of human-made instabilities and thus lead to more realistic results. The steps of Shannon's Entropy are summarized in Appendix A.1.

3.3. Fuzzy TOPSIS

TOPSIS is a well-known MCDA method that was introduced by Hwang and Yoon (1981). The classic version is extended to incorporate fuzzy theory leading to the following adapted TOPSIS version with triangular fuzzy numbers (Chen, 2000). TOPSIS determines the alternative that is the furthest from the negative solution and the closest to the ideal one, making it useful for handling MCDA problems. It provides a clear method for ranking alternatives by taking into account both positive and negative ideal solutions. A brief description of Fuzzy TOPSIS is presented in Appendix A.2.

3.4. Fuzzy WASPAS

WASPAS, introduced by Zavadskas et al. (2012), combines two well-known approaches, namely the weighted sum model and weighted product model, and was motivated by the higher accuracy of aggregated methods compared to single ones (Zavadskas et al., 2012). By taking into account the importance of criteria and how well alternatives perform in relation to those, WASPAS aims to aggregate the weighted scores of alternatives and makes it possible to place a strong emphasis on the function of weight coefficients in ranking alternatives. A general procedure for fuzzy WASPAS was proposed by Turskis et al. (2015) and is outlined in Appendix A.3.

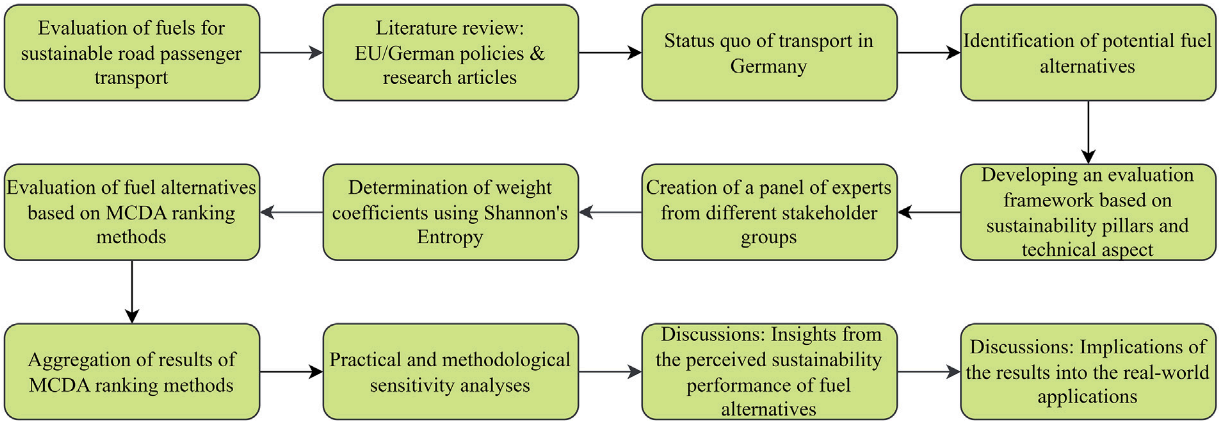


Fig. 1. Flowchart of the study.

3.5. Fuzzy CoCoSo

A recently devised MCDA methodology is CoCoSo, as introduced by Yazdani et al. (2018). This method demonstrates increased robustness against rank reversal and is considered an adaptive model with high stability and reliability. The procedure was adapted in the following for a fuzzy variant based on Yazdani et al. (2018). CoCoSo emphasizes the proportionality of relationships between criteria and alternatives and accounts for the relative importance and interdependence among criteria, making it suitable for complex decision problems in which criteria are interrelated. Appendix A.4 presents steps to implement Fuzzy CoCoSo.

3.6. Fuzzy MARCOS

In recent years, a series of novel MCDA methods was introduced with the aim of overcoming the drawbacks of classical approaches. One of these recent approaches is MARCOS, which was introduced by Stević et al. (2020). MARCOS offers reliability in dynamic environments and stability with large data sets, while maintaining its simplicity (Stević et al., 2020). In the following, the procedure for triangular fuzzy numbers is described (Stanković et al., 2020). MARCOS seeks to find a solution that balances trade-offs among conflicting criteria, allowing for a more nuanced evaluation. Fuzzy MARCOS is further summarized in Appendix A.5.

Fig. 1 represents a flowchart of the study, including its main steps. Two important tasks for defining the problem properly are to identify potential fuels for the future market and structure the evaluation framework.

4. Problem definition

In a holistic approach, the assessment of fuel alternatives for German road passenger transport considers economic, environmental, social/political (sustainability pillars), and technical aspects.

4.1. Road transport in Germany

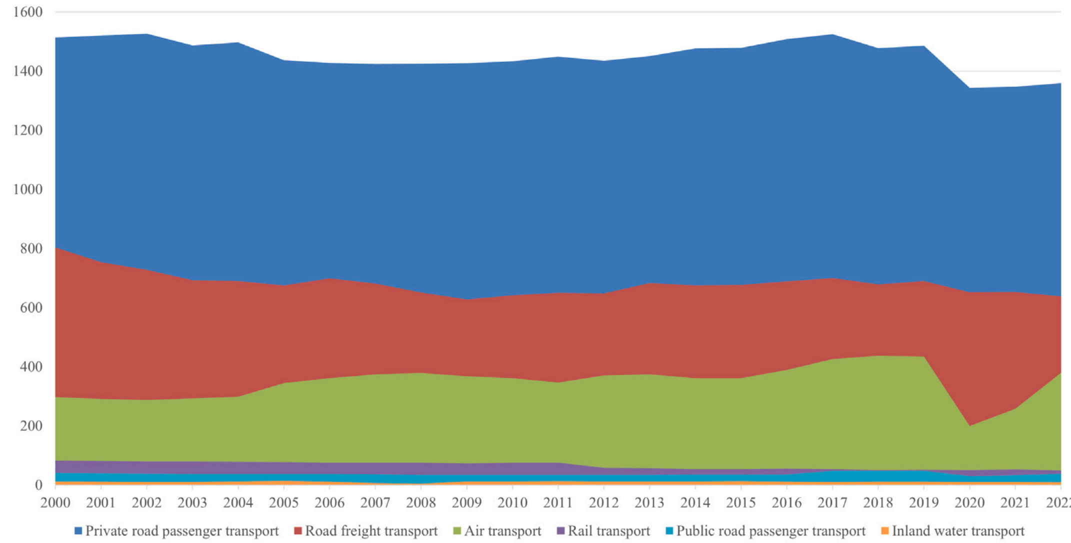
As a crucial part of one of EU's leading economies, the transport sector in Germany, plays a key role in industrial and social infrastructure. Multifaceted road, rail, air, and water transport carries millions of people and supports the country's export-oriented. However, transport is sill one of the major contributors to GHG emissions, and there is a pressing call for sustainable transformation (EEA, 2023). Fig. 2 presents an overview of energy consumption in the German transport sector.

Private road passenger transport in Germany is the backbone of mobility for most individuals, making it the largest contributor to the transport sector's activity and emissions (EEA, 2023). This mode primarily consists of personal cars, which are preferred due to their convenience, flexibility, and extensive road infrastructure across urban and rural areas. According to Fig. 2(a), energy consumption in private road passenger transport has remained remarkably stable, accounting for the highest share of energy consumption amongst all transport modes. In this regard, energy consumption in the private road passenger transport experienced a modest drop from 1514 petajoules in 2000 (over 55% of the total energy consumption) to 1359 petajoules in 2022 (approximately 55% of the total energy consumption). Despite the introduction of improved public transport systems, such as the S-Bahn and U-Bahn networks, and government incentives, such as the Deutschlandticket and tax-free company bicycles, to encourage the use of sustainable modes, such as cycling and car-sharing, reliance on private cars remains high (Jochem et al., 2020; Loder et al., 2024a,b). This is also visible in the low share of public road passenger transport, which accounted for 41 petajoules in 2000 and eventually decreased to 39 petajoules in 2022.

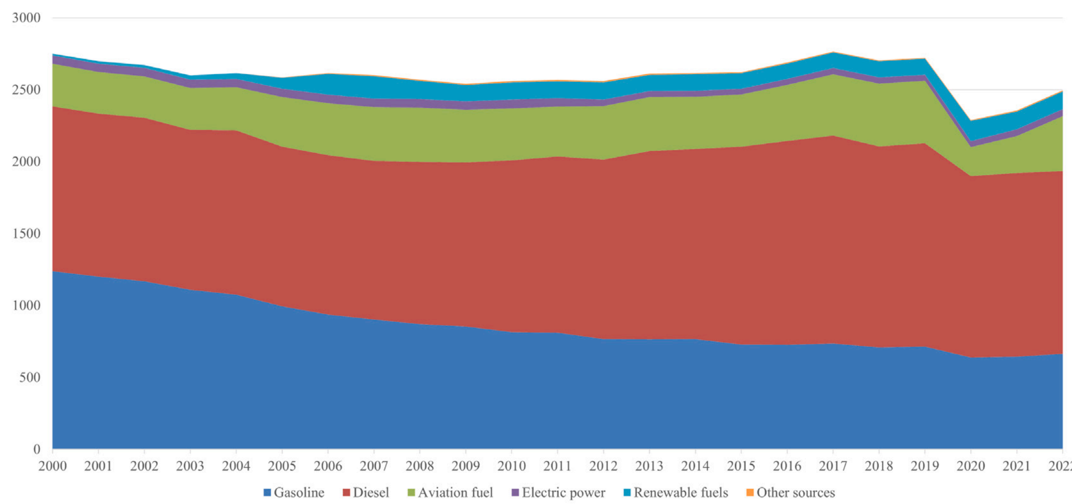
Fig. 2(b) illustrates the energy sources powering Germany's transport sector. Diesel and gasoline predominate, with diesel accounting for the largest share, particularly due to its use in road freight transport. However, both fuels exhibit a gradual decline over the years, reflecting increasing awareness and policies aimed at reducing fossil fuel dependency. In this regard, gasoline and diesel consumption in transport accounted for over 45% (1239 petajoules) and 41% (1145 petajoules) in 2000. Over the last two decades, the share of gasoline significantly reduced to 26% of the total energy consumption, which accounts for 664 petajoules in 2022. On the other hand, diesel followed a totally different trend, as its share of the total energy consumption increased to roughly 51% in 2020, accounting for 1272 petajoules. Both gasoline and diesel experienced sharp drops during the COVID-19 pandemic in 2020.

Renewable fuels and electric power exhibit a slow yet steady growth, driven by governmental incentives and technological advancements. Electric power, in particular, hints at the rising adoption of EVs, a positive indicator for defossilization efforts. Renewable fuels, such as biofuels, hydrogen, and synthetic fuels (e.g., PtX), are increasingly being integrated into the transport sector. These fuels offer a lower-carbon alternative to traditional diesel and gasoline, particularly for sectors where electrification is less feasible, such as aviation, maritime transport, and heavy road freight. Nevertheless, biofuels, such as biodiesel and bioethanol, have been considered for combustion engines in road transport in recent decades, but their growth has been tempered by concerns over competition with food crops and land use changes. Similar to diesel and gasoline, renewable fuels, electric power, and aviation fuels experienced dramatic drops in their consumption due to the COVID-19 pandemic in 2020.

Fig. 3 presents an overview of GHG emissions in the road transport sector of Germany over the last three decades. Total GHG emissions



(a) Energy consumption of the German transport sector by mode (in petajoules).



(b) Energy consumption of the German transport sector by source (in petajoules).

Fig. 2. Overview of energy consumption in the German transport sector (BMDV, 2022).

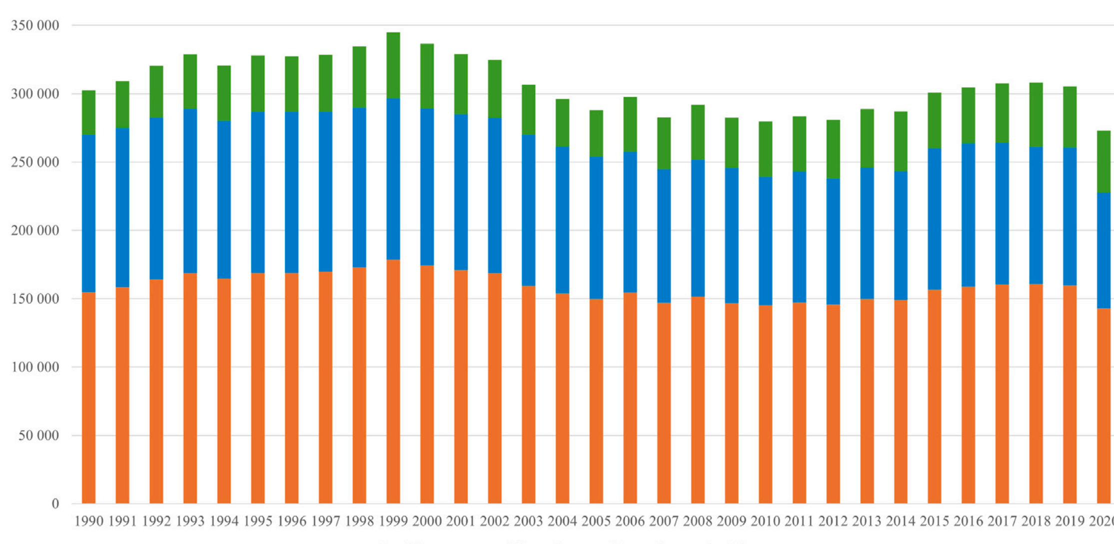
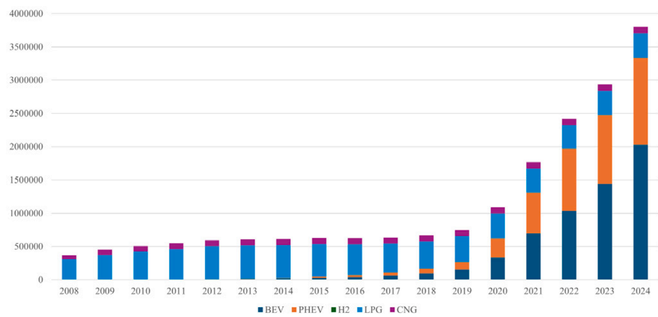
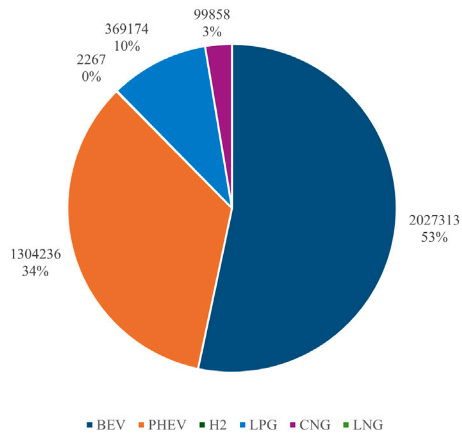


Fig. 3. GHG emissions in road transport (EEA, 2023).



(a) Total number of alternative fueled passenger cars and vans.



(b) Total number of alternative fueled passenger cars and vans by type.

Fig. 4. Overview of alternative fueled vehicles in Germany (European Alternative Fuels Observatory, 2024).

in the sector accounted for 154,826 and 144,033 kilotons of CO_2 equivalent in 1990 and 2020. Private cars were responsible for a large share of these emissions, by emitting 115,367 and 101,037 kilotons CO_2 equivalent in 1990 and 2019 (before the COVID-19 pandemic). On the other hand, the rest of the emissions in the sector were produced by heavy duty trucks and buses, which remained steady over 30 years.

Considering the need to reduce current GHG emissions level in Germany based on the recent climate change targets set out for the EU under the Green Deal and Fit for 55 Package, specific attention has been directed towards alternative fuels and vehicles. According to the European Alternative Fuels Observatory, 52,446,510 passenger cars and vans were registered in Germany at the end of 2023, which accounts for 5.6% of the total fleet (European Alternative Fuels Observatory, 2024).

Fig. 4 presents an overview of recent developments related to alternative fuels and vehicles in Germany. BEVs have shown exponential growth, rising from just 1300 units in 2008 to over two million by 2024, driven by advancements in battery technology, government subsidies, and expanded charging infrastructure. PHEVs have followed a similar trajectory, reaching over 1.3 million by 2024, as consumers embrace them as a transitional technology combining conventional fuel and electric power. In contrast, hydrogen-powered vehicles (H2) have exhibited much slower adoption, with numbers increasing from single digits in 2013 to only 2267 by 2024, reflecting challenges such as high costs and limited infrastructure, despite their potential for heavy-duty and long-distance transport. LPG and CNG vehicles have experienced a steady decline, with LPG dropping from a peak of over 500,000 in 2013 to 369,174 in 2024, and CNG declining from 60,744 in 2008 to under 100,000 over the same period. According to the Federal Motor Transport Authority (KBA), the share of alternative fueled vehicles has gradually increased while, the share of gasoline- and diesel-based vehicles have dropped notably. Nevertheless, gasoline- and diesel-based vehicles were still dominant in the market accounting for 35.2% and 17.20% of the total registered vehicles in 2024 (Kraftfahrtbundesamt, 2022).

Similarly, Fig. 4(b) illustrates the share of different fuels based on the total number of registered passenger cars and vans through 2024. BEVs dominate the sector, accounting for 53% of the total share with 2,027,313 units, highlighting their role as the primary driver of the transition towards electrification. PHEVs represent the second-largest share at 34%, with 1,304,236 units, further reinforcing the prominence of electrified transport solutions. LPG vehicles make up 10%, with 369,174 units, reflecting their diminishing importance as a transitional fuel amidst the shift towards renewable energy. CNG vehicles make up a modest 3%, with 99,858 units, whereas hydrogen-powered vehicles remain low, constituting less than 1% of the total, with only 2267 units. The graph underscores the overwhelming dominance of electric power – BEVs and PHEVs combined constitute 87% of the market – whereas fossil-based alternatives like LPG and CNG continue to decline. Hydrogen's minimal share emphasizes its nascent stage, despite its long-term potential for decarbonizing transport.

4.2. Fuel alternatives

According to the European Commission, potential fuel alternatives are divided into seven categories (European Commission, 2013, 2016). This categorization forms the foundation of our analysis and is outlined below.

(a) **Diesel and gasoline**
The road passenger transport sector currently relies heavily on fossil fuels, primarily diesel. Both fuels consist of diverse hydrocarbon molecules and are utilized in internal combustion engines (ICE), resulting in the emission of numerous pollutants. These emissions comprise GHGs, causing severe environmental harm and contributing substantial air pollutants such as nitrogen oxides, non-methane volatile organic compounds, and particulates, directly impacting human health (Navas-Anguita et al., 2019).

(b) **LPG**
LPG, often referred as 'autogas' in Germany, represents a technically advanced substitute for fossil fuels, consisting of light hydrocarbons such as propane, propene, and butane (BMVBS, 2013; Navas-Anguita et al., 2019). The composition of German autogas is 50% propane and 50% butane (Navas-Anguita et al., 2019). Due to its similarities, LPG can be utilized in modified gasoline engines (DLR, 2013; UBA, 2023). LPG vehicles were previously associated with lower carbon emissions, which leant them to tax benefits compared to diesel and gasoline. However, these incentives have gradually been reduced and ended completely by the end of 2022 (Deutscher Bundestag, 2021).

(c) **Natural gas**
There are two types based on temperature and pressure conditions, namely CNG and LNG. The suitability of these alternatives varies based on the required range and vehicle size. CNG is generally more commonly used for cars and smaller vans, whereas LNG is preferred for heavier, long-haul vehicles (Navas-Anguita et al., 2019). The use of CNG and LNG in the road transport sector remains very limited (UBA, 2023). However, despite its low adoption rate, the German government views CNG as a more environmentally friendly option compared to other conventional fossil fuels and has chosen to extend its tax incentives until 2026 (DLR, 2013; Deutscher Bundestag, 2021).

(d) **Biofuels**
Biofuels refer to liquid or gaseous fuels derived from biomass feedstock that can be utilized in combustion engines by either blending them with traditional fossil fuels or by direct utilization (Navas-Anguita et al., 2019). Biofuels can be categorized into three types based on the nature of their feedstock:

- **First-generation** (1st gen) biofuels are made from the edible part of the plant and include feedstocks such as corn, wheat, sugarcane, sugar beet, oil crops, or soybean. They are regarded as a mature technology, with sugar- and starch- based bioethanol and oil crop-based biodiesel being the most well-known examples (IEA, 2011).
- **Second-generation** (2nd gen) biofuels are made from non-edible biomass, such as lignocellulosic feedstocks from plants, organic waste, and agricultural and forestry wastes (Navas-Anguita et al., 2019). Often referred to as advanced biofuels, this category contains cellulosic ethanol, biomass-to-liquid (BtL) diesel and bio-synthetic gas, amongst others (IEA, 2011).
- **Third-generation** (3rd gen) biofuels describe, e.g., algae-based fuels, which are currently neither commercially viable nor technologically mature (Navas-Anguita et al., 2019).

First-generation biofuels have faced growing criticism due to their competition with the food sector (Navas-Anguita et al., 2019). In this context, their ecological impact has also been called into question, as the use of these biofuels was determined to lead to indirect land use changes (ILUC) (Di Lucia et al., 2012; Maia and Bozelli, 2022). This phenomenon arises when biofuel feedstock is cultivated on land that was previously used for conventional agriculture. As the demand for agricultural goods remains constant, their cultivation shifts to other regions, potentially causing deforestation, threatening biodiversity, and escalating GHG emissions (BMVBS, 2013). According to the Federal Environmental Agency, biofuels accounted for 6.4% of the total fuel consumption in the German transport sector in 2020 (UBA, 2022a). Around three-quarters are attributed to biodiesel, while the rest is almost fully made up of bioethanol. Although the effects of ILUC have been politically acknowledged, first-generation biofuels dominated the biofuel market with a share of 72% (BMVBS, 2013; NPM, 2020).

Due to the distinctions between first- and second-generation biofuels, they are treated as distinct fuel alternatives in this study. Third-generation biofuels are excluded from consideration due to their limited and ambiguous degrees of commercialization and the challenges associated with their market diffusion.

(e) **Renewable electricity**

EVs constitute other key alternatives for the road transport sector, and are classified into three main types (Navas-Anguita et al., 2019):

- **BEVs** rely exclusively on electrical power stored in their batteries, which can be charged by plugging them into the electrical grid.
- **HEVs** are equipped with combustion engines that are complemented by electric motors. The battery of an HEV is charged by an ICE and through regenerative braking, which captures energy lost during the braking process.
- **PHEVs** are equipped with batteries that can either be charged by being plugged into an external power source, through regenerative braking, or by its on-board ICE. If the battery is empty or during times of high load, the combustion engine takes over.

With enhanced sector integration, EVs could serve as short-term energy storage, utilizing surplus electricity for charging. However, their full potential can only be realized if the electricity used is generated from renewable sources (BMVBS, 2013; European Commission, 2016; Zirganos et al., 2022).

(f) **Green hydrogen**

Hydrogen is a versatile element and is attributed a key role in the German energy transition across all sectors (Bundesregierung Deutschland, 2020). Depending on the process by which it is produced, hydrogen is categorized into four types (Bundesregierung Deutschland, 2020):

- **Gray hydrogen** is based on the use of fossil hydrocarbons and is produced via the steam reforming of natural gas.
- **Turqoise hydrogen** is derived from methane, which is decomposed in a pyrolysis process into hydrogen and carbon.
- **Blue hydrogen** refers to hydrogen produced from natural gas using a carbon capture and storage (CCS) system, and which therefore does not allow the generated CO_2 to enter the atmosphere.
- **Green hydrogen** is based on the electrolysis of water, whereby the electricity required for the process is exclusively supplied by renewable sources.

In the passenger road transport context, hydrogen can be employed in FCEVs. These utilize a hydrogen tank, fuel cell, and an electric engine, which is powered by an electrochemical process. In this way, FCEVs, as well as BEVs, do not produce any direct GHG emissions (Navas-Anguita et al., 2019; Frontier Economics and ifeu, 2021). Green hydrogen is considered a sustainable option in the long-term, which is why our study focuses on this type (Bundesregierung Deutschland, 2020). The lack of charging infrastructure and high costs are seen as the current barriers to green hydrogen, according to the EU and German government (European Commission, 2021a; Bundesregierung Deutschland, 2020).

(g) **Synthetic fuels**

Synthetic fuels, often termed e-fuels, electricity-based fuels, or PtX, share similar properties to conventional fuels such as gasoline, diesel, kerosene, or methane (Frontier Economics and ifeu, 2021; Torkayesh and Venghaus, 2024b). Depending on the resulting fuel, the process is known as Power-to-Liquid (PtL) and Power-to-Gas (PtG) (NPM, 2020). Unlike their fossil counterparts, PtX fuels are produced through a synthesis process using green hydrogen, electricity and a carbon source (from either industry, a point source, or direct air capture) (Liebich et al., 2020). The Fischer–Tropsch process initially produces a mixture of various hydrocarbons, which are then refined into the final fuel product. An alternative pathway is provided by the methanol synthesis (NPM, 2020).

PtX fuels present a promising pathway for defossilizing the transport sector, a prospect likely to attract greater political focus in light of the 2045 climate targets. Considering their challenges, such as low energy efficiency, high production costs, and high resource use, German and EU strategies prioritize PtX applications in aviation and shipping, where direct electrification remains less practical (European Commission, 2016; Bundesregierung Deutschland, 2020).

4.3. Evaluation framework

Fuel planning involves multiple dimensions, as various factors play a role in this decision-making process. Political decision-makers face the challenge of crafting a comprehensive fuel policy that addresses various dimensions to ensure a sustainable solution for the German road passenger transport sector. Hence, four overarching categories have been pinpointed to assess fuel alternatives, aligning with the overarching objective of establishing a sustainable fuel policy. The decision-making problem encompasses economic, environmental, social/political, and technical aspects. These categories are then subdivided into various criteria, ensuring a comprehensive approach to the evaluation process.

In order to streamline the overview, certain criteria have been consolidated and synthesized to incorporate findings from additional

Table 2
Brief description of the evaluation criteria for fuel planning.

Category	Criterion	Description	References
Economic	Fuel Price (C1)	Fuel price based on production costs , raw material costs, and fuel production efficiency.	Hansson et al. (2019), Osorio-Tejada et al. (2017), Kügemann and Polatidis (2019) Tsita and Pilavachi (2013)
	Vehicle cost (C2)	Investment and maintenance costs of the vehicle (excluding fuel price).	Osorio-Tejada et al. (2017), Kügemann and Polatidis (2019), Büyüközkan et al. (2018) Ren et al. (2021)
	Infrastructure costs (C3)	Costs for developing infrastructures for the transport system, e.g., costs for distribution, storage and refueling infrastructures.	Osorio-Tejada et al. (2017), Kügemann and Polatidis (2019), Tsita and Pilavachi (2013)
	Transition costs (C4)	Investment costs in refineries and fuel/vehicle production by switching to alternative fuel.	Kügemann and Polatidis (2019), Tsita and Pilavachi (2013), Ren et al. (2013)
Environmental	GHG emissions(E1)	Life-cycle CO_2 equivalent emissions (including ILUC effects).	Osorio-Tejada et al. (2017), Kügemann and Polatidis (2019), Macioł and Rębiasz (2018) Büyüközkan et al. (2018)
	Air pollutantemissions (E2)	NOx and SOx emissions with acidification potential.	Hansson et al. (2019), Osorio-Tejada et al. (2017), Kügemann and Polatidis (2019) Macioł and Rębiasz (2018)
	Eco-toxicity (E3)	Effects on ecosystems during the production process, e.g., biodiversity reduction due to deforestation.	Kügemann and Polatidis (2019), Macioł and Rębiasz (2018), Onat et al. (2016)
	Resource consumption(E4)	Amount of consumed resources (e.g., water, food, finite fossil resources, rare materials).	Kügemann and Polatidis (2019), Tsita and Pilavachi (2013), Onat et al. (2016) Fazeli et al. (2011)
Social/political	Health impacts (S1)	Particulate matter formation potential refers to the impact of air pollutants on human health.	Hansson et al. (2019), Kügemann and Polatidis (2019), Macioł and Rębiasz (2018) Onat (2022)
	Public acceptance (S2)	Public opinion, trust and support for a fuel alternative.	Osorio-Tejada et al. (2017), Kügemann and Polatidis (2019), Tsita and Pilavachi (2013)
	Energy security (S3)	Availability, affordability, reliability and dependency on energy sources that can be affected by global market prices, political instability, and land availability.	Hansson et al. (2019), Osorio-Tejada et al. (2017), Kügemann and Polatidis (2019) Tsita and Pilavachi (2013), Mukherjee (2017)
	Policy compliance (S4)	Consistency with existing regulation targets (e.g., emission & energy reduction) and legislation benefits (e.g., subsidies & tax exemptions).	Hansson et al. (2019), Osorio-Tejada et al. (2017), Kügemann and Polatidis (2019) Ren et al. (2021)
	Job creation (S5)	Employment potential, including direct & indirect jobs.	Tsita and Pilavachi (2013), Kügemann and Polatidis (2019), Onat (2022)
	Market adoption potential (S6)	Diffusion potential based on national market size and demand.	Kügemann and Polatidis (2019), Heo et al. (2012), Chang et al. (2011)
Technical	Technology maturity (T1)	Status of research, development, demonstration and deployment necessary for the commercialization of a fuel.	Kügemann and Polatidis (2019), Tsita and Pilavachi (2013), Fazeli et al. (2011)
	Infrastructure availability (T2)	Compatibility with the current infrastructures.	Hansson et al. (2019), Osorio-Tejada et al. (2017), Kügemann and Polatidis (2019)
	Efficiency (T3)	Energy conversion efficiency in feedstock production, fuel production, motor use, ratio of system output and energy consumption.	Kügemann and Polatidis (2019), Büyüközkan et al. (2018), Mukherjee (2017) Aydın and Kahraman (2014)
	Fuel range (T4)	Distance that can be traveled without the need for refueling or recharging.	Kügemann and Polatidis (2019), Ren et al. (2021), Fazeli et al. (2011) Aydın and Kahraman (2014)
	Safety (T5)	Depending on fuel characteristics, such as auto-ignition point, flashpoint, and toxicity, the risk of fire, explosion, and health risks.	Hansson et al. (2019), Kügemann and Polatidis (2019), Aydın and Kahraman (2014)

sources, categorizing them into the four primary categories. In this way, a final list of 19 criteria were identified and are elaborated in Table 2, which includes a description of each criterion and corresponding sources.

Finally, the hierarchical decision structure is shown in Fig. 5.

4.4. Data collection

In order to conduct the assessment, a panel of ten experts was assembled, comprising stakeholders from diverse backgrounds, including academia, industry, politics, and environmental institutions (Fig. B.1). Appendix B presents further information on how the questionnaire was conducted. The intention was to ensure well-rounded and varied perspectives within the evaluation panel. The study involved ten experts with diverse backgrounds to ensure a comprehensive evaluation (see Table 3). The participants represented key sectors, including the automotive industry, academia, politics, and environmental organizations. Their areas of expertise covered fields such as vehicle engineering, fuel design, energy policy and economics, and transport. The experts brought a broad range of professional experience, from 3 to 40 years, contributing valuable insights from both practical and academic perspectives. This balanced mix of sectors and experience levels strengthened the study by incorporating technical knowledge, policy understanding, and environmental considerations into the decision-making process.

5. Results

Table 5 presents a part of the collected data based on a pairwise comparison of the performance of the eight alternatives regarding the identified criteria in each category using linguistic terms (Table 4). Tables C.1–C.7 in Appendix C present evaluation matrices of rest of the participants. Then, the collected data was transformed into numerical values based on fuzzy numbers. Later, the individual evaluations were aggregated to construct the initial decision matrix (Table 6), in accordance with Eq. (10). At this stage, all stakeholders were considered equally important.

In the next step, the weights of the criteria were determined using Shannon's entropy method. Following the procedure outlined in

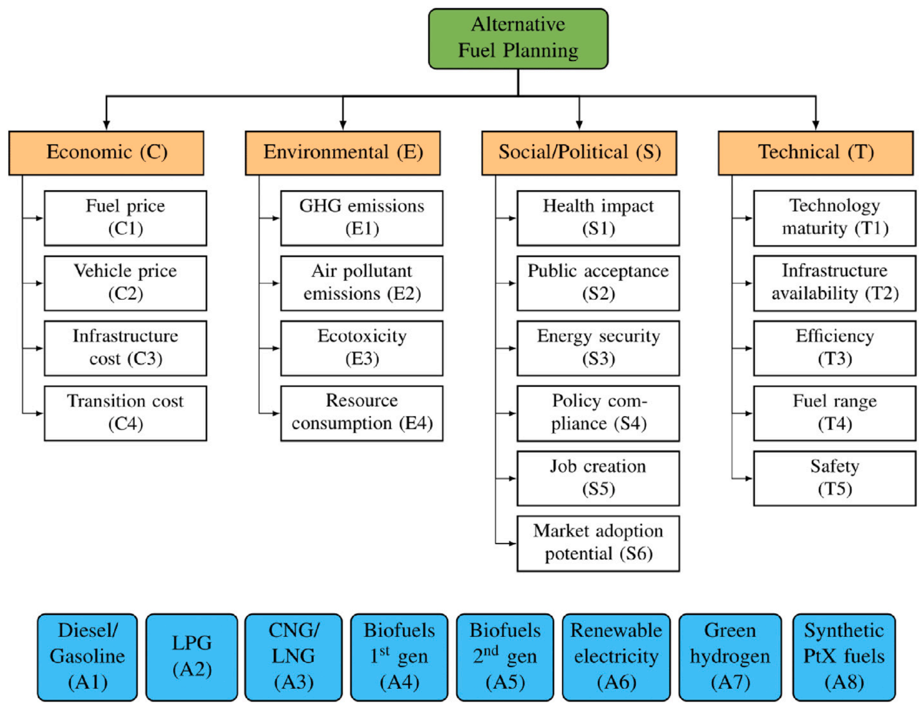


Fig. 5. Hierarchical decision structure.

Table 3
Expert profiles.

Expert	Working fields	Years of experience
K_1	Automotive industry	12
K_2	Automotive industry	35
K_3	Academia - Vehicle engineering	10
K_4	Academia - Fuel design	3
K_5	Academia - Energy Policy & Economics	3
K_6	Politics - Energy & Transport	30
K_7	Politics - Energy & Transport	40
K_8	Environmentalism - Transport	25
K_9	Environmentalism/Academia	32
K_{10}	Environmentalism/Academia	28

Table 4
Linguistic terms for the performance evaluation (Chen, 2000).

Linguistic term	Code	TFN
Very poor	VP	(0,0,1)
Poor	P	(0,1,3)
Medium poor	MP	(1,3,5)
Medium	M	(3,5,7)
Medium good	MG	(5,7,9)
Good	G	(7,9,9)
Very good	VG	(9,9,10)

Eqs. (6)–(9), the weight coefficients are shown in Fig. 6. The environmental and social/political categories were the most decisive ones, receiving over 30%, followed by economic and technical, which makes up 11% of the total weights. Amongst the individual values, two criteria emerged as particularly significant, with GHG emissions (E1) standing out as the highest-weighted criterion, accounting for 22%, with policy compliance (S4) ranking second, at a weight of 13%. Following these two, six criteria were identified as having above-average weights: infrastructure costs (C3), transition costs (C4), air pollutant emissions (E2), eco-toxicity (E3), health impacts (S1), and infrastructure availability (T2). The remaining eleven criteria only made up about 24% of the total. Within such a complex system, market adoption potential (S6), safety (T5) and fuel range (T4) seemed to be the less relevant impact factors, with each accounting for less than 1%.

Next, the consolidated MCDA approach consisting of four MCDA methods was used to rank the alternatives. Using the initial decision matrix (Table 6) and the previously determined criteria weights (Fig. 6), the consolidated MCDA approach was carried out. Table 7 presents the results for all four methods, which generate the same ranking order in every method. Direct electrification using renewable power (A6) was identified as being the most suitable alternative for the German road passenger transport sector, followed by green hydrogen (A7), second-generation biofuels (A5), and synthetic PtX fuels (A8). With a considerable margin, first-generation biofuels (A4) ended up in the next place, whereas the three fossil options CNG/LNG (A3), LPG (A2) and conventional diesel/gasoline (A1) finalized the ranking.

6. Sensitivity analysis

Understanding the underlying factors influencing the outcomes is crucial for comprehensively evaluating the reliability and robustness of the applied approach. The relative importance attributed to criteria weights is a decisive aspect of the ranking process of alternative fuels (Kügemann and Polatidis, 2019). The prioritization of fuel alternatives could significantly vary based on the interests of stakeholders. For instance, politicians might emphasize social aspects, whereas car manufacturers could prioritize economic considerations. Additionally, external factors such as ongoing geopolitical changes, societal discussions, or evolving policies could immediately impact how all actors and decision-makers prioritize criteria. A sensitivity analysis was conducted to assess how changes in criterion weights could influence the results. To this end, the original data from the initial decision matrix was briefly reviewed to understand how weight modifications could impact the outcomes. Subsequently, six scenarios with different weight prioritizations were introduced, and the resulting ranking orders were analyzed. Fig. 7 illustrates the defuzzified performance scores for the criteria category of each alternative based on Table 6.

From an economic perspective, the prevailing conventional diesel/gasoline (A1) was clearly superior in terms of infrastructure (C3) and transition costs (C4), as expected. Renewable alternatives for electrification (A6), green hydrogen (A7), and PtX fuels (A8) received significantly lower scores for these criteria. PtX fuels were an exception

Table 5
Individual expert decision matrices.

	K_1								K_2							
	A1	A2	A3	A4	A5	A6	A7	A8	A1	A2	A3	A4	A5	A6	A7	A8
C1	MG	M	MP	MP	MG	VG	MP	VP	G	VG	VG	G	G	G	M	MP
C2	MP	MP	P	MP	MP	G	MP	MP	VG	G	G	VG	VG	P	P	VG
C3	G	MP	MP	G	G	MG	MP	P	VG	M	M	VG	VG	VP	P	VG
C4	VG	MG	MP	M	MP	MG	P	P	VG	MG	MG	VG	VG	VP	P	VG
E1	VP	P	P	MP	MG	VG	G	G	VP	P	P	M	G	G	G	G
E2	MP	MP	G	MP	MG	VG	VG	MP	MG	MG	MG	MG	MG	VG	VG	MG
E3	M	MP	M	M	MG	VG	VG	G	MP	MG	MG	MP	MP	MG	G	M
E4	VP	P	MP	M	MG	MG	MG	M	G	G	G	M	G	M	MG	G
S1	MP	MP	M	M	G	VG	VG	MP	MG	MG	MG	MG	MG	G	G	MG
S2	M	M	M	MP	G	VG	VG	MG	M	MP	MP	M	M	G	MG	MG
S3	MP	M	MP	M	G	VG	M	M	MG	MG	MG	MG	MG	M	M	MG
S4	VP	P	MP	G	G	VG	VG	MP	VP	P	P	VP	M	VG	VG	MG
S5	VP	P	MP	M	G	M	VG	MG	M	M	M	M	M	M P	M	M
S6	MP	MP	MP	M	G	VG	M	MG	VG	G	G	VG	VG	MG	M	VG
T1	VG	VG	G	G	G	VG	G	M	VG	G	VG	VG	VG	MG	M	VG
T2	VG	MG	M	G	MG	MG	M	MP	VG	G	G	VG	VG	VP	VP	G
T3	VP	VP	P	MP	MG	VG	MP	VP	MG	MG	MG	MG	MG	G	G	MG
T4	VG	G	G	MG	MG	MG	G	VG	VG	VG	VG	VG	VG	M P	G	VG
T5	MG	G	G	G	G	VG	MG	MG	MG	MG	MG	MG	MG	M	M	MG
	K_3	K_4	K_5	K_6	K_7	K_8	K_9		K_{10}							
	...								A1	A2	A3	A4	A5	A6	A7	A8
C1	...								G	G	M	M	G	M	MP	MP
C2	...								M	M	M	M	M	MP	P	G
C3	...								M	MP	MP	MP	MP	MP	MP	M
C4	...								M	MP	MP	MP	MP	P	P	P
E1	...								VP	P	P	MP	M	G	G	MG
E2	...								VP	P	P	P	P	VG	VG	P
E3	...								VP	P	P	P	P	G	G	P
E4	...								VP	VP	VP	VP	MP	M	MP	P
S1	...								VP	P	P	P	P	G	G	MP
S2	...								M	M	M	MP	MG	G	M	MG
S3	...								MP	MP	P	MP	MP	M	M	M
S4	...								P	P	P	P	M	MG	MG	MP
S5	...								MP	MP	MP	MP	MP	MG	MG	M
S6	...								M	M	M	MP	M	G	MG	M
T1	...								VG	VG	VG	G	MG	M	M	M
T2	...								VG	G	G	M	G	P	P	G
T3	...								MP	MP	MP	MP	MP	G	M	P
T4	...								G	G	G	G	G	M	M	VG
T5	...								MG	MG	MG	MG	MG	MG	MP	MG

A1. Diesel/Gasoline; A2. LPG; A3. CNG/LNG; A4. first-generation biofuels; A5. second-generation biofuels; A6. renewable electricity; A7. green hydrogen; A8. PtX.

Table 6
Aggregated initial decision matrix.

	A1	A2	A3	A4	A5	A6	A7	A8
C1	(4.0, 5.7, 7.0)	(5.1, 6.8, 7.9)	(4.5, 6.2, 7.5)	(2.6, 4.4, 6.0)	(3.7, 5.4, 6.8)	(6.0, 7.8, 8.7)	(2.0, 3.8, 5.8)	(1.7, 2.8, 4.2)
C2	(4.1, 5.8, 7.1)	(3.6, 5.6, 7.2)	(3.9, 5.8, 7.2)	(3.4, 5.0, 6.5)	(3.4, 4.9, 6.3)	(4.3, 6.2, 7.4)	(1.8, 3.4, 5.4)	(4.8, 6.6, 7.7)
C3	(6.8, 8.0, 9.0)	(4.0, 6.0, 7.4)	(3.4, 5.4, 7.2)	(5.2, 6.8, 8.2)	(5.1, 6.5, 7.8)	(1.5, 2.9, 4.8)	(0.4, 1.7, 3.6)	(4.6, 6.2, 7.5)
C4	(6.8, 7.4, 8.7)	(4.6, 6.6, 8.0)	(4.2, 6.2, 7.8)	(3.8, 5.6, 7.1)	(3.5, 5.2, 6.7)	(2.4, 3.9, 5.8)	(0.6, 2.0, 4.0)	(2.0, 3.3, 5.1)
E1	(0.0, 0.1, 1.2)	(0.3, 1.6, 3.6)	(1.0, 2.4, 4.4)	(3.2, 5.2, 6.8)	(5.0, 7.0, 8.0)	(8.0, 8.8, 9.6)	(7.6, 8.8, 9.4)	(6.4, 7.8, 8.7)
E2	(1.6, 2.6, 4.0)	(2.5, 4.1, 5.6)	(4.1, 6.0, 7.2)	(3.5, 5.1, 6.4)	(4.1, 5.7, 6.8)	(8.8, 9.0, 9.9)	(9.0, 9.0, 10.0)	(3.9, 5.0, 6.2)
E3	(0.8, 1.8, 3.4)	(1.4, 3.0, 5.0)	(2.5, 4.2, 6.0)	(2.5, 4.2, 5.8)	(3.5, 5.4, 7.0)	(7.0, 8.2, 9.2)	(7.2, 8.4, 9.2)	(5.1, 6.6, 7.8)
E4	(2.1, 3.2, 4.6)	(1.9, 3.2, 4.8)	(2.0, 3.2, 4.7)	(2.1, 3.7, 5.4)	(4.4, 6.2, 7.7)	(4.1, 6.0, 7.8)	(3.8, 5.8, 7.6)	(3.9, 5.8, 7.2)
S1	(1.4, 2.4, 4.0)	(2.2, 4.0, 6.0)	(2.2, 3.8, 5.8)	(3.3, 4.9, 6.4)	(3.7, 5.3, 6.6)	(8.0, 9.0, 9.5)	(8.2, 9.0, 9.6)	(4.0, 5.5, 6.9)
S2	(3.0, 4.8, 6.4)	(2.8, 4.8, 6.6)	(3.2, 5.2, 7.2)	(2.2, 4.2, 6.2)	(5.0, 6.8, 8.3)	(6.8, 8.2, 9.1)	(6.2, 7.6, 8.9)	(5.3, 6.6, 8.3)
S3	(2.6, 4.2, 5.8)	(2.4, 4.0, 5.8)	(2.1, 3.6, 5.2)	(3.3, 5.2, 6.8)	(4.2, 6.0, 7.5)	(6.0, 7.6, 8.8)	(5.6, 7.2, 8.6)	(4.8, 6.6, 8.3)
S4	(0.4, 1.1, 2.6)	(1.3, 2.7, 4.6)	(1.6, 3.1, 5.0)	(2.0, 3.5, 5.2)	(5.2, 6.8, 8.4)	(8.0, 8.8, 9.6)	(7.0, 8.0, 9.1)	(3.5, 5.4, 7.2)
S5	(2.0, 3.5, 5.2)	(2.2, 4.0, 6.0)	(2.0, 3.8, 5.8)	(3.0, 5.0, 6.8)	(4.8, 6.8, 7.8)	(4.6, 6.4, 7.9)	(6.6, 8.2, 9.0)	(4.6, 6.6, 8.0)
S6	(4.0, 5.3, 6.6)	(3.7, 5.6, 7.2)	(4.2, 6.2, 7.8)	(4.6, 6.4, 7.9)	(5.2, 6.8, 8.2)	(7.2, 8.4, 9.4)	(4.6, 6.4, 7.9)	(4.8, 6.4, 8.0)
T1	(8.4, 8.8, 9.8)	(6.8, 8.2, 9.3)	(7.4, 8.4, 9.5)	(6.4, 8.0, 8.6)	(5.2, 7.0, 8.5)	(6.0, 7.6, 8.8)	(3.6, 5.6, 7.4)	(3.9, 5.6, 7.1)
T2	(8.6, 9.0, 9.8)	(5.1, 6.7, 7.9)	(5.2, 7.0, 8.3)	(5.6, 7.2, 8.4)	(5.3, 6.8, 8.0)	(2.3, 3.9, 5.6)	(0.9, 2.0, 3.8)	(4.2, 6.0, 7.3)
T3	(3.0, 4.3, 5.9)	(3.4, 5.1, 6.4)	(3.4, 5.2, 6.8)	(3.5, 5.1, 6.9)	(4.7, 6.3, 7.5)	(6.6, 8.2, 8.8)	(4.2, 6.2, 7.6)	(3.6, 4.7, 5.9)
T4	(8.2, 9.0, 9.6)	(7.0, 8.4, 9.1)	(7.0, 8.6, 9.0)	(7.0, 8.4, 9.3)	(7.2, 8.6, 9.3)	(3.4, 5.4, 7.4)	(5.6, 7.4, 8.5)	(8.2, 9.0, 9.6)
T5	(4.0, 6.0, 7.8)	(3.4, 5.2, 6.8)	(3.9, 5.8, 7.2)	(4.2, 6.2, 7.6)	(5.0, 7.0, 8.2)	(6.6, 8.2, 9.0)	(3.7, 5.6, 7.2)	(5.0, 7.0, 8.2)

A1. Diesel/Gasoline; A2. LPG; A3. CNG/LNG; A4. first-generation biofuels; A5. second-generation biofuels; A6. renewable electricity; A7. green hydrogen; A8. PtX.

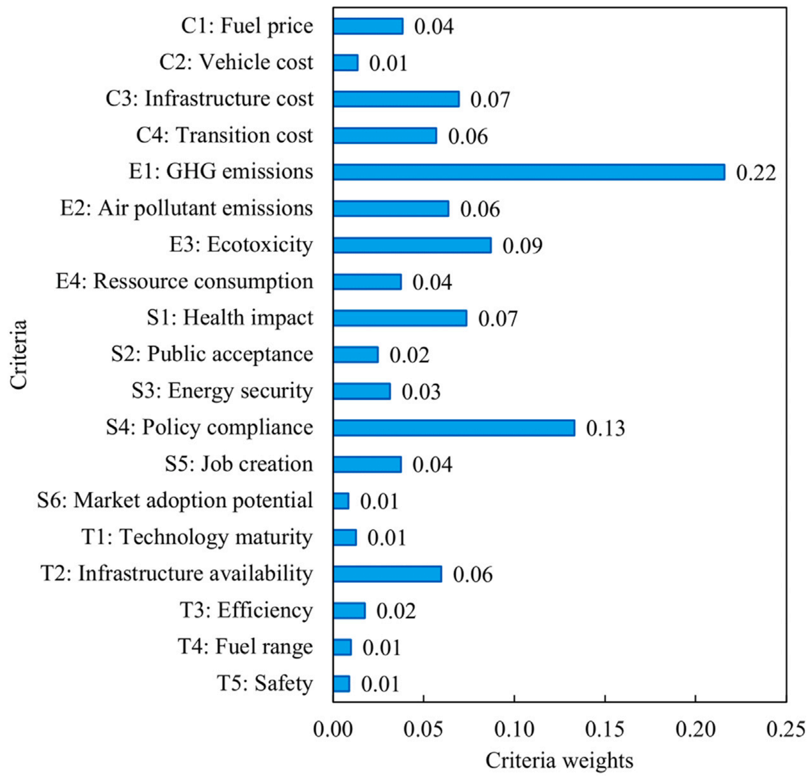


Fig. 6. Final weight coefficients.

Table 7
Ranking scores of different MCDA methods.

Alternative	TOPSIS CC	WASPAS Q	CoCoSo k_F	MARCOS $f(K)$	Ranking
A1 (Diesel/Gasoline)	0.328	0.273	1.532	0.185	8
A2 (LPG)	0.379	0.402	1.708	0.250	7
A3 (CNG/LNG)	0.415	0.451	1.807	0.296	6
A4 (1st generation biofuels)	0.485	0.536	1.974	0.398	5
A5 (2nd generation biofuels)	0.611	0.670	2.272	0.612	3
A6 (Renewable electricity)	0.745	0.772	2.524	0.856	1
A7 (Green hydrogen)	0.674	0.676	2.336	0.705	2
A8 (PtX fuels)	0.593	0.639	2.210	0.568	4

in relation to infrastructure costs, due to the fact that they could be used in existing combustion engines and benefit from the current refueling system. Moreover, renewable electricity was considered to perform very well with regard to both fuel price (C1) and vehicle costs (C2). In contrast, the fuel price was identified as being a significant obstacle for synthetic PtX fuels, while green hydrogen faced the greatest challenges in terms of overall economic competitiveness.

The environmental category revealed a completely different perspective, with renewable electricity (A6) and green hydrogen (A7) emerging as equally dominant due to their carbon-neutral and air pollutant-free nature during usage. PtX fuels (A8) demonstrated strong overall environmental performance but showed shortcomings in air pollutant emissions (E2). Furthermore, second-generation biofuels (A5) received high environmental evaluations, outperforming even PtX fuels in terms of air pollution and equaling the other renewable alternatives with respect to resource consumption (E4). The remaining alternatives did not appear to be competitive from an environmental point of view.

The social and political evaluation revealed notable insights, with renewable electricity (A6) and green hydrogen (A7) once again outperforming other alternatives across most criteria. Large differences were found, especially in relation to health impacts (S1) and policy compliance (S4), where the aforementioned alternatives received significantly higher scores. The top alternatives were followed by second-generation biofuels (A5) and PtX fuels (A8) with similar ratings for all criteria except for S4, whereas synthetic PtX fuels were not able to fully keep up. As for the environmental category, the alternatives diesel/gasoline A1 to A4 were not determined to effectively address social and political issues.

The technical dimension presented a more balanced perspective compared to the other categories. Significant differences were observed in infrastructure availability (T2), which remained a notable challenge for renewable electricity (A6) and an even greater issue for green hydrogen (A7). According to stakeholders, the fuel range (T4) of EVs was considered a challenge, while their efficiency (T3) was highlighted as a significant advantage over the other alternatives.

The previous observations regarding the performance evaluations outlined both the advantages and issues of the considered alternatives, which were contingent on the specific criteria being evaluated. This visualization illustrates that changes in prioritization directly impact the ranking scores and, consequently, the ranking order. For that purpose, a sensitivity analysis was performed that examined six different weight modification cases based on Table 8.

The sensitivity analysis involves several scenarios modifying weight coefficients to evaluate their impact on the outcomes. The baseline scenario, M0, applies standard entropy weights without adjustments. M1 increases the weight of economic criteria by 50%, emphasizing cost-related factors such as fuel price and infrastructure costs. M2 prioritizes

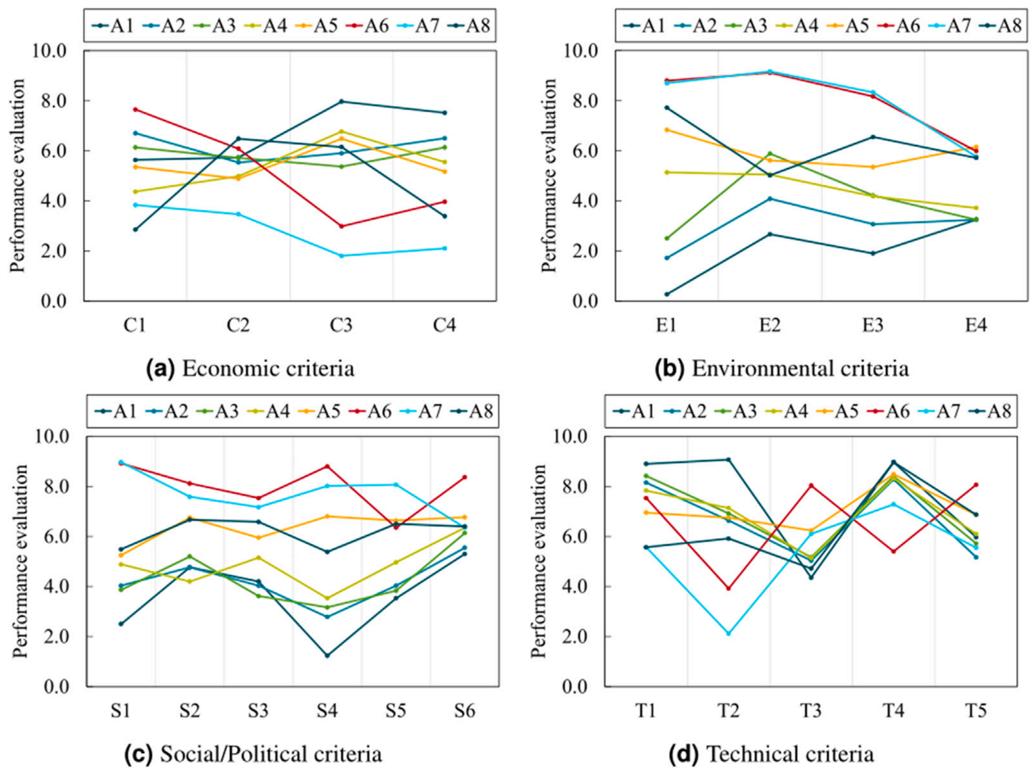


Fig. 7. Defuzzified performance evaluations for each category (A1. Diesel/Gasoline; A2. LPG; A3. CNG/LNG; A4. first-generation biofuels; A5. second-generation biofuels; A6. renewable electricity; A7. green hydrogen; A8. PtX).

Table 8
Weight modification cases.

Modification case	Description
M0	Standard entropy weights
M1	Economic weights ↑ 50%
M2	Environmental weights ↑ 50%
M3	Social/Political weights ↑ 50%
M4	Technical weights ↑ 50%
M5	Equal category weights
M6	Equal criterion weights

environmental criteria by raising their weight by 50%, focusing on issues such as GHG emissions and air pollutants. M3 amplifies the significance of social and political criteria by 50%, highlighting factors such as policy compliance and societal acceptance. In M4, technical criteria are given 50% more weight, emphasizing aspects such as technological efficiency. M5 assigns equal weights to each category, ensuring balanced consideration, while M6 equalizes the weights of all individual criteria, treating them with the same level of importance.

The resulting ranking orders were depicted in the form of the radar chart shown in Fig. 8, with the alternatives represented by the colored lines and each corner standing for one modification case. From this analysis, three key findings emerged. First, across all scenarios and methods, the direct use of renewable electricity consistently remained the leading alternative by a significant margin, highlighting the robustness and reliability of this solution. Second, in all cases and methods, Diesel/Gasoline (A1), LPG (A2), CNG/LNG (A3), and first-generation biofuels (A4) occupied the last places without any rank reversals between them. Third, depending on the prioritization, alterations were observed between the second-best options. An increase in economic, and to a lesser extent technical criteria weights, favored second-generation biofuels (A5) at the expense of green hydrogen (A7). From an environmental and social/ political perspective, green hydrogen (A7) remained the preferred alternative. Moreover, balanced

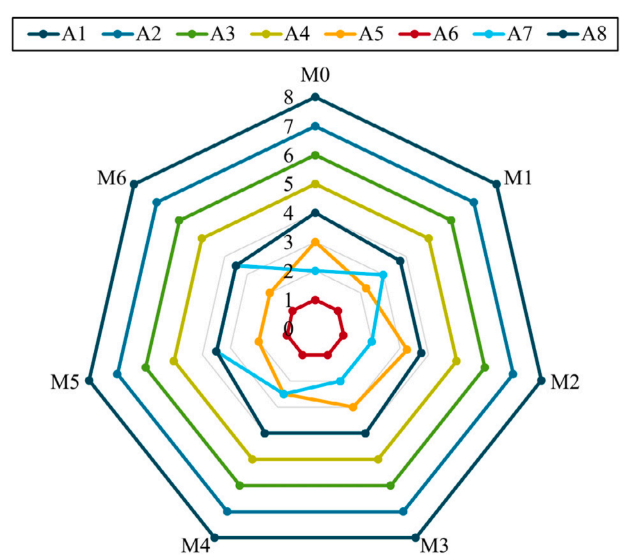


Fig. 8. Resulting ranking order for each weight modification case (A1. Diesel/Gasoline; A2. LPG; A3. CNG/LNG; A4. first-generation biofuels; A5. second-generation biofuels; A6. renewable electricity; A7. green hydrogen; A8. PtX).

weights (M5 and M6) improved the performance of PtX fuels (A8), which in these cases ended up in third place, together with green hydrogen (A7).

According to Table 3, the experts can be categorized into four groups based on their working fields: the automotive industry, academia, politics, and environmentalist. Considering the diverse fields of expertise and varying years of experience amongst the experts, assigning equal importance to all may introduce an element of subjectivity. To address this concern, a sensitivity test was conducted

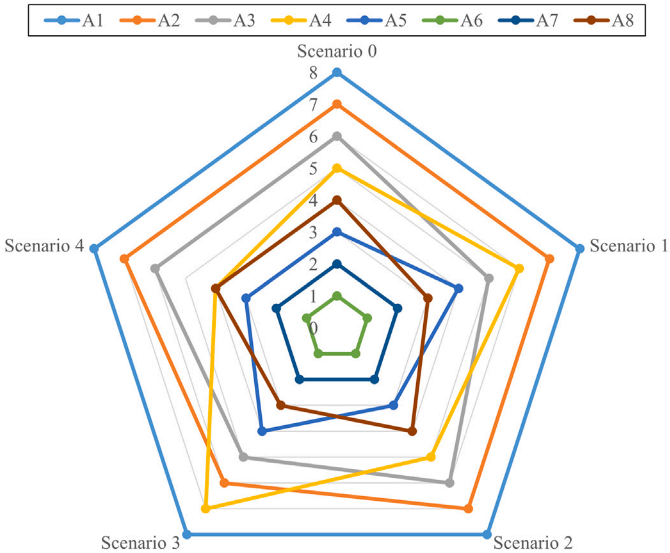


Fig. 9. Sensitivity analysis based on the expert scenarios (A1. Diesel/Gasoline; A2. LPG; A3. CNG/LNG; A4. first-generation biofuels; A5. second-generation biofuels; A6. renewable electricity; A7. green hydrogen; A8. PtX). Scenario 0 represents the original case.

across four scenarios, where in each scenario, a higher importance was attributed to a specific expert group while the importance of the other groups remained fixed. The scenarios were defined to assess the sensitivity of the results to the dominance of expert groups. In each scenario, one group was assigned a higher weight (40%) to simulate increased influence, while the remaining groups retained equal weights (20%), ensuring that no group was entirely disregarded. The 40%–20% distribution was chosen to reflect a moderate but noticeable shift in influence, allowing the exploration of how the dominance of specific expertise may affect the final results.

The scenarios were defined as follows:

- Scenario 1: Experts from the automotive industry were assigned 40% importance, while the others were fixed at 20%.
- Scenario 2: Experts from academia were assigned 40% importance, while the others were fixed at 20%.
- Scenario 3: Experts from politics were assigned 40% importance, while the others were fixed at 20%.
- Scenario 4: Experts from environmental agencies are assigned 40% importance, while the others were fixed at 20%.

The results, as illustrated in Fig. 9, reveal a consensus in the preference for renewable electricity (A6) for EVs as the most favored fuel alternative, whereas diesel and gasoline (A1) are consistently regarded as the least preferred options. Moreover, all expert groups stated that green hydrogen (A7) can be considered the second promising alternative. However, there exist different opinions among expert groups with regard to the remaining fuel alternatives. Experts from the automotive industry and politics exhibited greater alignment in their opinions, while a similar pattern was observed among experts from academia and environmental agencies and institutions. The experts from academia and environmental institutions preferred second-generation biofuels (A5) as the third promising alternative, whereas the other two expert groups chose PtX fuels (A8). Another difference relates to first-generation biofuels (A4), which was ranked fifth in the initial results. Although experts from academia and environmental institutions selected them as the fifth alternative, experts from automotive and politics ranked them as the sixth and seventh alternatives. All experts ranked LPG as the seventh alternative, except for those from politics, who placed it in sixth position.

After assessing the robustness of the results through a sensitivity analysis, it is essential to explore their potential policy and managerial implications. The sensitivity analysis revealed the implications arising from modifying a parameter in the evaluation framework and approach. These results can provide an essential bridge to support the formulation of robust, flexible, and progressive policies and strategies.

7. Implications

Section 1 illustrated the need for action in the German road passenger transport sector. Several policy measures and strategies have been developed for the road transport sector to contribute to the overall goal of climate-neutrality as described in Section 2. Using a holistic approach (Section 4), different fuel options for the German road passenger transport sector were evaluated. In this section, the political implications of the previously obtained results within the German and European policy frameworks are discussed.

7.1. Roll-out of electrification

The utilization of renewable electricity is recognized as the most favorable fuel alternative for German road passenger transport. This finding was confirmed by the sensitivity analysis presented in Section 6. In general, both the German fuel strategy displayed in the Climate Action Plan 2050, as well as the EU's ambitions proclaimed in the EU Green Deal, attribute an essential role to electric transport for the future transport sector. Nevertheless, at present EVs only account for a share of 5.6% of all German cars, which reveals the apparent adoption barriers (European Alternative Fuels Observatory, 2024). In order to attain the sector targets, particularly the 48% reduction in emissions by 2030, the transformation must be substantially accelerated.

One of the primary obstacles remains the limited number of charging infrastructure. Although the EU has acknowledged this issue and established obligatory expansion targets, so far the efforts remain insufficient and require further investment. Presently, the German government provides subsidies for the purchase of new EVs, yet there are plans to notably reduce these. Achieving the goals for 2030, however, will require additional measures to establish EVs as an alternative to traditional combustion engines, particularly for lower-income segments. Another critical factor concerns the supply of renewable electricity, which is a necessary prerequisite for ensuring the sustainability of EVs. Achieving an eco-friendly transport sector requires a simultaneous transformation of the energy sector as well.

7.2. Potential of hydrogen

The results presented here provide another key finding attributing a high potential to hydrogen for the future German road transport sector, and are considered the second best alternative after renewable electricity. Green hydrogen is a clean transport fuel that neither produces carbon emission during the use phase nor any other air pollutants, while even offering advantages to renewable electricity in terms of fuel range. Today, the technology cannot be considered economically competitive, which also relates to the lack of basic infrastructure and the competition between BEVs and fuel cells. Nonetheless, Germany has presented an ambitious plan for the roll-out of the technology in its National Hydrogen Strategy. The planned major infrastructural investments could lead to significant price reductions in the coming years, potentially also making hydrogen a competitive alternative in road transport.

8. Conclusions

Ambitious targets have been introduced by Germany with the objective of achieving climate-neutrality by 2045, and the reduction of

GHG emissions, along with defossilization of all sectors, is considered critical for this purpose. The road passenger transport sector plays a noticeable role in the current level of GHG emissions, and Germany is in the process of developing a reliable plan for a sustainable transition by replacing fossil fuels with cleaner and sustainable fuel alternatives. The predominance of fossil fuels has led to a critical environmental situation and the effects of intensive oil dependency have become quite visible. However, policy-making for the future road passenger sector is highly complex given the various fuel alternatives, regulatory standards and their infrastructural requirements. For this purpose, we applied a holistic MCDA approach for fuel planning in the road passenger transport sector by considering eight potential fuel alternatives under a multi-dimensional evaluation framework.

MCDA is a useful tool in fuel planning for road passenger transport, facilitating strategic decision-making in complex environments with diverse goals and requirements. By applying MCDA, decision-makers can effectively assess and prioritize fuel alternatives, considering diverse criteria and objectives vital for promoting sustainability and efficiency in the transport sector. By systematically evaluating and ranking fuel alternatives, MCDA serves as a vital framework for helping stakeholders navigate the complex variables involved in identifying the most sustainable fuel options. This study has not only clarified the relative benefits of various fuel alternatives but it has also offered a structured framework for maintaining a balance between operational, environmental, and economic perspectives.

According to the results, electrification via renewable electricity is expected to play a fundamental role in the future road passenger transport sector, serving as a key enabler for BEVs and as the foundation for hydrogen and PtX fuels. The development of climate-friendly road transport should therefore be closely aligned with the establishment of a reliable green energy infrastructure. The analysis suggests the prioritization of direct electrification, as it appears to be the only possible short-term option capable of meeting the German reduction targets in 2030. During the transition phase, green hydrogen, advanced biofuels, and synthetic fuels (e.g., PtX fuels) could contribute to the overall goal of climate-neutrality by being used in fuel cells or as a blend in current combustion engines.

Although this study addresses an up-to-date challenge to mitigate emissions in the German road passenger transport sector, it is important to note several limitations. An objective weighting technique was utilized to reduce the subjectivity of experts' opinions; however, using a subjective technique might better reflect experts' or other stakeholders' viewpoints. Moreover, a combined weighting approach, merging results from an objective and a subjective technique, could be considered to ascertain the optimal weight coefficients. Increasing the number of experts in future studies could also enhance the reliability of the evaluations. Integration of the proposed approach with data mining and machine learning algorithms could further optimize the ranking of fuel alternatives, especially when dealing with a large number of decision criteria and diverse data. This could lead to more efficient and accurate decision-making processes. For this purpose, such tools can be used to determine weight coefficients, facilitate feature selection processes, and impute the incomplete data in case experts prefer not to express their opinions on specific pairwise comparisons.

Fuel planning for the future road passenger transport sector in Germany has been under investigation for a long time. At present, the quest to reduce emissions has become crucial due to the introduction of emissions reduction targets as part of the EU Green Deal and the Fit for 55 Package. Building on this work, future research could focus on evaluating the specific policy measures needed to accelerate the adoption of alternative fuels. Additionally, a more detailed examination of the potential for sustainable bio and synthetic fuels to reduce emissions from existing road passenger vehicles could be undertaken. In addition, the proposed approach could potentially extend its application to other transport modes, such as maritime, or aviation to drive the shift towards a climate-neutral transport sector. Clearly, however, extending the proposed approach to other transport modes would require tailored adjustments to the evaluation criteria to align with the specific needs of each.

CRediT authorship contribution statement

Javier Perez Vera: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ali E. Torkayesh:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Conceptualization. **Sandra Venghaus:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy – Cluster of Excellence 2186 "The Fuel Science Center" – ID: 390919832.

Appendix A

A.1. Shannon's entropy

1. *Normalization of the decision matrix.*
   In the first stage, each value of the decision matrix is normalized according to Eq. (6).
   $$p_{ij} = \frac{x_{ij}}{\sum_j x_{ij}} \tag{6}$$
2. *Computation of entropy measure.*
   After that, the entropy measure e_j is computed. The total number of alternatives is represented by m, while n refers to the number of criteria.
   $$e_j = -\kappa \sum_{i=1}^{m} p_{ij} \ln\left(p_{ij}\right), \qquad \kappa = \left(\ln\left(m\right)\right)^{-1} \tag{7}$$
3. *Calculation of divergence.*
   Subsequently, the divergence div_j is calculated according to Eq. (8).
   $$div_j = \left|1 - e_j\right| \tag{8}$$
4. *Determination of objective weights.*
   Finally, the objective entropy weights w_j are obtained for each criterion j as follows:
   $$w_j = \frac{div_j}{\sum_{k=1}^{n} div_k} \tag{9}$$

A.2. Fuzzy TOPSIS

1. Development of the initial decision matrix.
   It is assumed that the alternatives were evaluated by a group of K_E experts who provided individual fuzzy ratings $\tilde{x}_{ij}^k = (a_{ij}^k, b_{ij}^k, c_{ij}^k)$.
   First, the expert ratings were aggregated to form the fuzzy, aggregated decision matrix $\tilde{X}$. The averaged components $\tilde{x}_{ij} = (a_{ij}^k, b_{ij}^k, c_{ij}^k)$ of $\tilde{X}$ were calculated as follows (Chen and Tsao, 2008):

$$a_{ij} = \frac{1}{K_E}\sum_{k=1}^{K_E} a_{ij}^k, \quad b_{ij} = \frac{1}{K_E}\sum_{k=1}^{K_E} b_{ij}^k, \quad c_{ij} = \frac{1}{K_E}\sum_{k=1}^{K_E} c_{ij}^k \tag{10}$$

2. Normalization of the decision matrix.
   The components $\tilde{r}_{ij}$ of the normalized fuzzy decision matrix were obtained through Eqs. (11)–(12).

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^+}, \frac{b_{ij}}{c_j^+}, \frac{c_{ij}}{c_j^+}\right), \quad c_j^+ = \max_i\{c_{ij}\} \quad \text{(benefit criteria)} \tag{11}$$

$$\tilde{r}_{ij} = \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}}\right), \quad a_j^- = \min_i\{a_{ij}\} \quad \text{(cost criteria)} \tag{12}$$

3. Weighting of the normalized decision matrix.
   The components $\tilde{v}_{ij}$ of the fuzzy weighted normalized decision matrix can now be calculated using Eq. (13).

$$\tilde{v}_{ij} = \tilde{r}_{ij} \cdot w_j \tag{13}$$

4. Identification of the positive and negative ideal solutions.
   The positive ideal solution A^+ and the negative ideal solution A^- were calculated according to Eqs. (14) and (15), respectively.

$$A^+ = \{\tilde{v}_1^+, \tilde{v}_2^+, \dots, \tilde{v}_n^+\}, \quad \tilde{v}_j^+ = \max_i\{\tilde{v}_{ij,c}\} \tag{14}$$

$$A^- = \{\tilde{v}_1^-, \tilde{v}_2^-, \dots, \tilde{v}_n^-\}, \quad \tilde{v}_j^- = \min_i\{\tilde{v}_{ij,a}\} \tag{15}$$

5. Computation of the distances to the positive and negative ideal solution.
   Based on Eq. (16), the distance between two triangular fuzzy numbers $\tilde{A}_1 = (a_1, b_1, c_1)$ and $\tilde{A}_2 = (a_2, b_2, c_2)$ can be calculated (Chen, 2000).

$$d(\tilde{A}_1, \tilde{A}_2) = \sqrt{\frac{1}{3}\left[(a_1 - a_2)^2 + (b_1 - b_2)^2 + (c_1 - c_2)^2\right]} \tag{16}$$

   The distances from each alternative A_i to the fuzzy positive and negative ideal solutions were derived as follows:

$$d_i^+ = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^+) \tag{17}$$

$$d_i^- = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^-) \tag{18}$$

6. Calculation of the closeness coefficient.
   Finally, the closeness coefficient CC_i was obtained as follows:.

$$CC_i - = \frac{d_i^-}{d_i^- + d_i^+} \tag{19}$$

A.3. Fuzzy WASPAS

1. Development of the initial decision matrix.
   The generation of the initial matrix was analogous to the fuzzy TOPSIS method.
2. Normalization of the decision matrix.
   WASPAS uses a normalization procedure equivalent to Step 2 of fuzzy TOPSIS.
3. Calculation of the weighted normalized decision matrix.
   After that, the WSM and WPM approaches were applied, which resulted in the weighted normalized decision matrix for WSM whose values $\tilde{q}_{ij}^{(1)}$ were obtained as follows:

$$\tilde{q}_{ij}^{(1)} = \tilde{r}_{ij} \cdot w_j \tag{20}$$

   Analogously, the values of the weighted decision matrix for WPM were calculated using Eq. (21)

$$\tilde{q}_{ij}^{(2)} = \tilde{r}_{ij}^{w_j} \tag{21}$$

4. Calculation of the optimality measures.
   This allows computation of the fuzzy optimality measures $\tilde{Q}_i^{(1)}$ and $\tilde{Q}_i^{(2)}$ in this step.

$$\tilde{Q}_i^{(1)} = \sum_{j=1}^{n} \tilde{q}_{ij}^{(1)} \quad (WSM) \tag{22}$$

$$\tilde{Q}_i^{(2)} = \prod_{j=1}^{n} \tilde{q}_{ij}^{(2)} \quad (WPM) \tag{23}$$

5. Defuzzification of the optimality measures.
   To obtain a single value that enables the classification of alternatives, $\tilde{Q}_i^{(1)}$ and $\tilde{Q}_i^{(2)}$ were defuzzified following the Graded Mean Integration Representation (GMIR) method (Chen and Li, 2000).

$$Q_i^{(1)} = \frac{\tilde{Q}_{ia}^{(1)} + 4\tilde{Q}_{ib}^{(1)} + \tilde{Q}_{ic}^{(1)}}{6} \tag{24}$$

$$Q_i^{(2)} = \frac{\tilde{Q}_{ia}^{(2)} + 4\tilde{Q}_{ib}^{(2)} + \tilde{Q}_{ic}^{(2)}}{6} \tag{25}$$

6. Calculation of the total relative importance.
   Finally, the total relative importance Q_i can be calculated as follows:

$$Q_i = \lambda\, Q_i^{(1)} + (1 - \lambda)\, Q_i^{(2)} \tag{26}$$

   (Turskis et al., 2015) determine a specific value for λ based on the assumption that the total of all alternative WSM scores must be equal to the total of WPM (Eq. (27)).

$$\lambda = \frac{\sum_{i=1}^{m} Q_i^{(2)}}{\sum_{i=1}^{m} Q_i^{(1)} + \sum_{i=1}^{m} Q_i^{(2)}} \tag{27}$$

A.4. Fuzzy CoCoSo

1. Development of the initial decision matrix.
   The initial matrix was determined similarly to the other methods.
2. Normalization of the decision matrix.
   The fuzzy compromise normalization is represented by Eqs. (28)–(29).

$$\tilde{r}_{ij} = \frac{\tilde{x}_{ij} - \min_i \tilde{x}_{ij}}{\max_i \tilde{x}_{ij} - \min_i \tilde{x}_{ij}} \quad \text{(benefit criteria)} \tag{28}$$

$$\tilde{r}_{ij} = \frac{\max_i \tilde{x}_{ij} - \tilde{x}_{ij}}{\max_i \tilde{x}_{ij} - \min_i \tilde{x}_{ij}} \quad \text{(cost criteria)} \tag{29}$$

3. Calculation of the comparability sequences.
   In the third step, the fuzzy sum weighted comparability sequence $\tilde{S}_i$ and the fuzzy power-weighted comparability sequence $\tilde{P}_i$ were calculated as follows:

$$\tilde{S}_i = \sum_{j=1}^{n} \tilde{r}_{ij} w_j \tag{30}$$

$$\tilde{P}_i = \sum_{j=1}^{n} (\tilde{r}_{ij})^{w_j} \tag{31}$$

4. Calculation of alternative scores.
   Based on the S_i and P_i values, three different appraisal score strategies were applied.

$$\tilde{k}_{i,a}^{(1)} = \frac{\tilde{S}_i + \tilde{P}_i}{\sum_{i=1}^{m}(\tilde{S}_i + \tilde{P}_i)} \tag{32}$$

$$\tilde{k}_i^{(2)} = \frac{\tilde{S}_i}{\min_i \tilde{S}_i} + \frac{\tilde{P}_i}{\min_i \tilde{P}_i} \tag{33}$$

$$\tilde{k}_i^{(3)} = \frac{\lambda \tilde{S}_i + (1-\lambda)\tilde{P}_i}{\left(\lambda \max_i \tilde{S}_i + (1-\lambda)\max_i \tilde{P}_i\right)} \tag{34}$$

After defuzzifying the three scores with the GMIR method, the final ranking score k_F was obtained with Eq. (35).

$$k_{F,i} = (k_i^{(1)} k_i^{(2)} k_i^{(3)})^{\frac{1}{3}} + \frac{1}{3}(k_i^{(1)} + k_i^{(2)} + k_i^{(3)}) \tag{35}$$

A.5. Fuzzy MARCOS

1. Development of the initial decision matrix.
   The initial matrix is set up as in the other methods.
2. Formation of the extended initial fuzzy matrix.
   In the second stage, the anti-ideal solution (AI) and the ideal solution (ID) were calculated and added to the initial matrix. AI is an artificial alternative that was constructed by adopting the worst alternative values for each criteria (Eq. (36)). ID is the positive counterpart, representing the best possible alternative (Eq. (37)).

$$AI = \begin{cases} \min_i x_{ij}, & \text{(benefit criteria)} \\ \max_i x_{ij}, & \text{(cost criteria)} \end{cases} \tag{36}$$

$$ID = \begin{cases} \max_i x_{ij}, & \text{(benefit criteria)} \\ \min_i x_{ij}, & \text{(cost criteria)} \end{cases} \tag{37}$$

3. Normalization of the extended fuzzy matrix.
   In order to normalize the matrix with fuzzy components, Eq. (38) was used.

$$\tilde{r}_{ij} = \begin{cases} \left(\frac{x_{id,a}}{x_{ij,a}}, \frac{x_{id,a}}{x_{ij,b}}, \frac{x_{id,a}}{x_{ij,c}}\right), & \text{(benefit criteria)} \\ \left(\frac{x_{ij,a}}{x_{id,c}}, \frac{x_{ij,b}}{x_{id,c}}, \frac{x_{ij,c}}{x_{id,c}}\right), & \text{(cost criteria)} \end{cases} \tag{38}$$

4. Determination of the weighted fuzzy matrix.
   The weighted fuzzy values $\tilde{v}_{ij}$ were computed according to Eq. (39).

$$\tilde{v}_{ij} = \tilde{r}_{ij} \cdot w_j \tag{39}$$

5. Calculation of the fuzzy utility degrees.
   The fuzzy utility degrees $\tilde{K}_i$ denote the performance of each alternative in relation to the anti-ideal and ideal solution and were calculated as follows:

$$\tilde{K}_i^- = \frac{\tilde{Z}_i}{\tilde{Z}_{ai}} = \left(\frac{\tilde{Z}_{i,a}}{\tilde{Z}_{ai,c}}, \frac{\tilde{Z}_{i,b}}{\tilde{Z}_{ai,b}}, \frac{\tilde{Z}_{i,c}}{\tilde{Z}_{ai,a}}\right) \tag{40}$$

$$\tilde{K}_i^+ = \frac{\tilde{Z}_i}{\tilde{Z}_{id}} = \left(\frac{\tilde{Z}_{i,a}}{\tilde{Z}_{id,c}}, \frac{\tilde{Z}_{i,b}}{\tilde{Z}_{id,b}}, \frac{\tilde{Z}_{i,c}}{\tilde{Z}_{id,a}}\right) \tag{41}$$

   The fuzzy sum of the elements $\tilde{Z}_i$ was obtained using Eq. (42).

$$\tilde{Z}_i = (\tilde{Z}_{i,a}, \tilde{Z}_{i,b}, \tilde{Z}_{i,c}) = \sum_{j=1}^{n} \tilde{v}_{ij} \tag{42}$$

6. Determination of the fuzzy auxiliary number.
   The fuzzy nature of the variables demands an additional step compared to the original MARCOS procedure. First, the variable $\tilde{t}_i$ was computed as follows:

$$\tilde{t}_i = \tilde{K}_i^- \oplus \tilde{K}_i^+ \tag{43}$$

   Then, the auxiliary fuzzy number $\tilde{D}$ is calculated using Eq. (44).

$$\tilde{D} = (\tilde{D}_a, \tilde{D}_b, \tilde{D}_c) = \max_i \tilde{t}_i \tag{44}$$

   The fuzzy expression $\tilde{D}$ can now be defuzzified according to (45), obtaining the crisp value df.

$$df = \frac{\tilde{D}_a + 4\tilde{D}_b + \tilde{D}_c}{6} \tag{45}$$

7. Determination of the fuzzy utility function.
   The previous steps enabled the calculation of the utility functions in relation to the ideal $f(\tilde{K}_i^+)$ and the anti-ideal solution $f(\tilde{K}_i^-)$, as shown in Eqs. (46)–(47).

$$f(\tilde{K}_i^+) = \frac{\tilde{K}_i^-}{df} \tag{46}$$

$$f(\tilde{K}_i^-) = \frac{\tilde{K}_i^+}{df} \tag{47}$$

   In order to be able to calculate the utility function, the expressions $f(\tilde{K}_i^-)$, $f(\tilde{K}_i^+)$, $\tilde{K}_i^-$ and $\tilde{K}_i^+$ were defuzzified using the GMIR method. Finally, the utility function $f(K_i)$ could be computed using Eq. (48).

$$f(K_i) = \frac{K_i^+ + K_i^-}{1 + \frac{1-f(K_i^+)}{f(K_i^+)} + \frac{1-f(K_i^-)}{f(K_i^-)}} \tag{48}$$

Appendix B

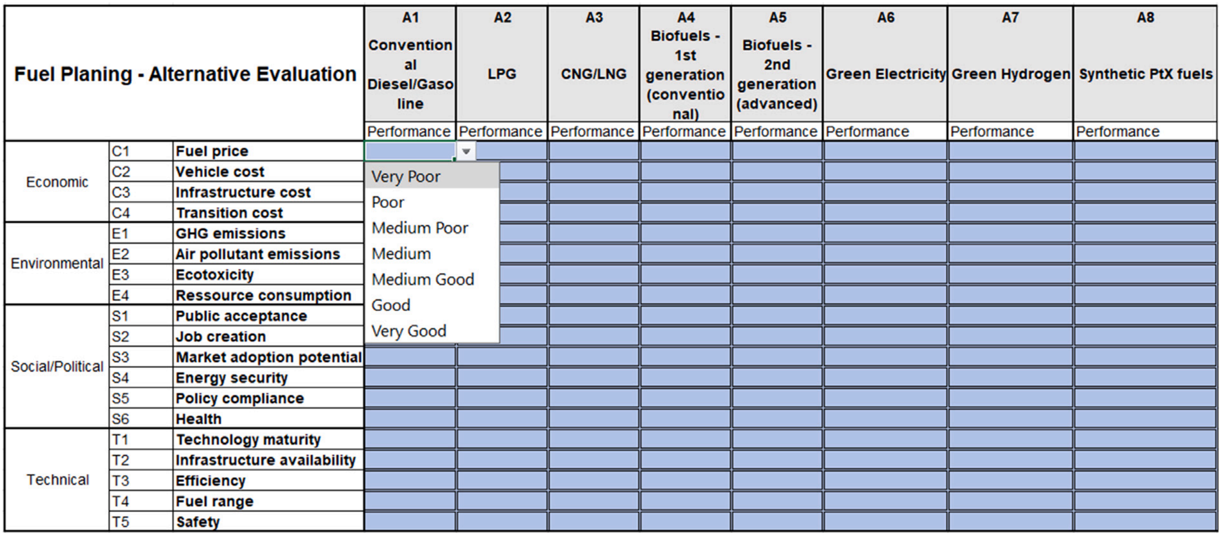
For data collection, potential experts were first identified and invited to participate via email. The questionnaire was provided as an Excel file consisting of two sheets. The first sheet included detailed instructions, outlining the study's objectives, the fuel alternatives under consideration, and the evaluation framework. The second sheet contained the evaluation matrix with drop-down options, allowing experts to express their opinions on each pairwise comparison (Fig. B.1).

Appendix C

See Tables C.1–C.7.

Table C.1
Decision matrix by expert K_3.

	A1	A2	A3	A4	A5	A6	A7	A8
C1	MP	M	M	MG	MG	MG	P	G
C2	G	M	G	G	G	M	P	G
C3	VG	MP	G	VG	VG	P	P	MG
C4	VG	MP	MG	G	G	P	P	MG
E1	P	MP	M	MG	G	G	G	G
E2	G	G	G	G	G	VG	VG	G
E3	MP	M	M	G	G	MG	VG	G
E4	M	MP	MP	M	VG	P	M	G
S1	MG	MG	MG	G	G	G	G	MG
S2	P	MP	M	MP	G	G	G	VG
S3	G	M	M	G	VG	MG	MG	G
S4	MP	M	MG	M	VG	G	G	G
S5	M	MP	MP	M	G	M	MG	MG
S6	G	P	MP	G	VG	VG	M	G
T1	VG	MG	VG	VG	G	MG	M	MG
T2	VG	VP	VG	VG	VG	MP	P	VG
T3	M	M	MG	M	G	G	MG	MG
T4	VG	G	G	VG	VG	M	G	VG
T5	MG	M	G	G	G	G	MG	G



Fuel Planing - Alternative Evaluation			A1 Conventional Diesel/Gasoline	A2 LPG	A3 CNG/LNG	A4 Biofuels - 1st generation (conventional)	A5 Biofuels - 2nd generation (advanced)	A6 Green Electricity	A7 Green Hydrogen	A8 Synthetic PtX fuels
			Performance	Performance	Performance	Performance	Performance	Performance	Performance	Performance
Economic	C1	Fuel price								
	C2	Vehicle cost								
	C3	Infrastructure cost								
	C4	Transition cost								
Environmental	E1	GHG emissions								
	E2	Air pollutant emissions								
	E3	Ecotoxicity								
	E4	Ressource consumption								
Social/Political	S1	Public acceptance								
	S2	Job creation								
	S3	Market adoption potential								
	S4	Energy security								
	S5	Policy compliance								
	S6	Health								
Technical	T1	Technology maturity								
	T2	Infrastructure availability								
	T3	Efficiency								
	T4	Fuel range								
	T5	Safety								

Fig. B.1. The evaluation matrix in the questionnaire.

Table C.2
Decision matrix by expert K_4.

	A1	A2	A3	A4	A5	A6	A7	A8
C1	P	M	M	P	P	G	MG	P
C2	MP	M	M	MP	MP	G	MG	MP
C3	G	M	M	G	G	P	MP	G
C4	VG	M	M	MP	MP	MG	MP	MP
E1	VP	P	P	G	G	VG	G	G
E2	M	G	G	G	G	VG	VG	G
E3	VP	P	P	MP	MP	G	G	MG
E4	VP	P	P	M	M	MG	M	MP
S1	M	MG	MG	MG	MG	VG	VG	G
S2	M	M	M	MP	MP	VG	G	MG
S3	VP	VP	VP	MP	MP	VG	G	MG
S4	VP	MP	MP	MP	MG	VG	G	M
S5	P	P	P	M	M	G	G	M
S6	VP	MG	MG	M	M	VG	MG	MG
T1	VG	G	G	MP	MP	VG	M	MP
T2	VG	M	M	MP	MP	G	MP	MP
T3	P	M	M	M	M	VG	MG	M
T4	VG	VG	VG	VG	VG	MG	MG	VG
T5	MP	M	M	MG	MG	G	M	MG

Table C.3
Decision matrix by expert K_5.

	A1	A2	A3	A4	A5	A6	A7	A8
C1	M	MG	MG	MP	M	MG	MP	VP
C2	M	MP	MP	M	M	MG	P	MG
C3	VG	MG	MG	MG	MG	M	P	G
C4	VG	G	M	G	G	M	P	VP
E1	VP	P	P	MP	MP	VG	VG	M
E2	VP	MP	MP	VP	VP	VG	VG	VP
E3	VP	MP	MP	P	M	VG	G	M
E4	P	P	P	P	MP	MG	MG	M
S1	VP	MP	MP	VP	VP	G	G	VP
S2	G	MG	MG	MP	MG	MG	M	P
S3	M	MP	MP	MP	MG	G	MG	M
S4	P	P	P	P	MG	G	MP	P
S5	M	M	M	M	M	G	G	G
S6	P	M	M	M	M	G	M	MP
T1	G	MG	MG	G	MG	MG	MG	G
T2	G	M	M	MG	MG	M	P	MP
T3	P	MP	MP	VP	VP	G	MP	VP
T4	G	MG	M	G	G	M	MG	G
T5	MP	P	MP	MP	MP	G	MP	MP

Table C.4
Decision matrix by expert K_6.

	A1	A2	A3	A4	A5	A6	A7	A8
C1	VP	P	P	MP	M	G	P	VP
C2	M	M	M	M	M	G	M	M
C3	G	MG	MG	MG	MG	P	MP	MG
C4	VG	MG	MG	M	M	MG	M	MP
E1	VP	P	P	MP	MG	MG	MG	MP
E2	P	P	MP	M	M	VG	VG	MP
E3	P	P	P	P	M	M	M	MP
E4	VP	VP	VP	P	M	MG	MG	MP
S1	P	P	P	P	P	VG	VG	P
S2	MP	M	M	MP	MG	MG	MG	M
S3	VP	VP	VP	P	M	G	MG	MG
S4	VP	VP	VP	P	MG	VG	VG	MG
S5	M	M	M	M	G	MP	G	M
S6	G	MG	MG	MG	MG	MG	MP	MP
T1	VG	VG	VG	G	MG	G	MP	P
T2	VG	G	MG	G	G	P	P	G
T3	P	P	P	M	G	M	MP	VP
T4	G	G	G	G	G	M	G	G
T5	MP	MP	P	MP	MP	MG	P	MP

Table C.5
Decision matrix by expert K_7.

	A1	A2	A3	A4	A5	A6	A7	A8
C1	MG	G	G	G	G	G	M	VP
C2	G	G	M	G	G	MG	MP	G
C3	VG	G	MG	MG	MG	M	VP	G
C4	VG	G	MG	M	M	MG	P	M
E1	VP	MP	MP	MP	MP	VG	VG	VG
E2	VP	M	G	P	P	VG	VG	VP
E3	M	M	G	MP	M	G	VG	G
E4	M	M	VG	MP	MG	MG	G	MG
S1	VP	MP	P	MP	MP	VG	VG	MG
S2	P	MP	MG	MG	MG	G	VG	M
S3	M	M	MP	G	M	MG	VG	M
S4	VP	M	MG	M	M	VG	VG	M
S5	P	M	MG	G	G	MG	G	M
S6	MP	M	MG	G	G	G	G	M
T1	VG	G	MG	G	MG	G	M	MP
T2	VG	VG	M	G	G	M	VP	MG
T3	VG	G	MG	VG	VG	G	G	G
T4	VG	VG	G	G	G	M	M	G
T5	G	G	G	G	G	G	G	G

Table C.6
Decision matrix by expert K_8.

	A1	A2	A3	A4	A5	A6	A7	A8
C1	G	G	G	MP	P	M	MP	M
C2	G	M	G	P	VP	MP	M	MP
C3	MG	G	M	MP	VP	M	P	M
C4	MP	MG	G	MP	P	MP	MP	MP
E1	VP	MP	M	MG	G	VG	VG	VG
E2	P	MP	M	MG	G	G	VG	VG
E3	P	MP	M	MG	MG	VG	MG	VG
E4	M	M	MP	MP	M	G	M	G
S1	P	M	M	MG	MG	G	VG	G
S2	M	G	MG	MG	VG	VG	VG	VG
S3	MG	MG	M	MG	G	G	G	VG
S4	P	MG	MP	MG	VG	VG	VG	MG
S5	P	MG	P	M	G	VG	VG	G
S6	VG	G	MG	MG	MG	VG	VG	VG
T1	VG	MG	VG	G	MG	G	MG	G
T2	VG	MG	MG	M	P	MP	P	M
T3	G	G	G	MG	G	G	G	VG
T4	VG	M	G	MG	G	MG	VG	VG
T5	MG	M	MP	M	G	VG	G	G

Table C.7
Decision matrix by expert K_9.

	A1	A2	A3	A4	A5	A6	A7	A8
C1	MG	G	G	P	P	G	MG	MG
C2	P	MG	MG	P	P	G	MG	G
C3	M	G	MP	M	M	P	P	P
C4	MP	G	G	M	M	P	MP	P
E1	VP	P	M	G	G	VG	VG	VG
E2	VP	VP	M	G	G	VG	VG	VG
E3	VP	P	M	G	G	VG	VG	VG
E4	MG	MG	MP	G	G	M	MP	MG
S1	VP	MP	P	G	G	VG	VG	VG
S2	G	MP	MP	M	M	M	MG	VG
S3	MP	M	G	M	MP	MG	VG	MG
S4	M	MP	M	MP	M	G	MG	MG
S5	G	M	M	MP	M	MG	G	G
S6	M	M	G	M	MP	MG	G	MG
T1	MG	MG	MG	M	M	M	M	M
T2	G	MG	G	MG	M	M	MG	MP
T3	MG	G	G	MG	M	M	MG	G
T4	G	G	G	MG	MG	M	M	G
T5	MG	P	M	MP	MG	G	MG	G

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