Vorwerg et al.
Energy, Sustainability and Society (2025) 15:4
https://doi.org/10.1186/s13705-024-00498-5

Energy, Sustainability and Society

RESEARCH

Open Access

From fossil fuels to alternative fuels: strategy development for a sustainable transport sector in Germany

Franz Christian Vorwerg[1], Ali Ebadi Torkayesh[1] and Sandra Venghaus[1,2*]

Abstract

Background Many countries agreed to reduce CO_2 emissions to limit global warming under the terms of the Paris Agreement. In Europe, this agreement is supported by the climate targets introduced under the European Green Deal and the Fit for 55 package. Although Germany has made substantial progress in reducing emissions across various sectors, the transport sector remains a notable exception, showing little improvement. It is therefore essential to reevaluate the transport sector to strengthen its contribution to achieving the emission reduction targets. The aim of this study is to identify and propose strategies for shifting from fossil fuel-based transport to a more sustainable mode centred on alternative fuels. To investigate the potential pathways, an integrated approach is developed using a SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis and multi-criteria decision analysis (MCDA).

Results A two-step survey was used to collect data from different stakeholders in order to derive the key factors for the implementation of alternative fuels and devise transition strategies. The findings show that reducing GHG emissions, resource competition, and the impacts of environmental regulations are the most important factors for evaluating the transition strategies. On the other hand, reducing the competitiveness of fossil fuels through increased prices, as well as technical and infrastructural support, are the most promising strategies.

Conclusions The sustainable transition in the transport sector is fundamentally driven by the use of renewable fuel alternatives as sustainable energy carriers to replace fossil fuels. The use and deployment of renewable fuel alternatives will play the most significant role in the defossilization of the transport sector, on course to achieve a 55% reduction by 2030 and reaching climate-neutrality by 2050. However, identification of the proper transition strategies in the phase-out of fossil fuels and their replacement with renewable fuel alternatives necessitates a comprehensive evaluation framework. This work contributes to this by developing a holistic evaluation framework, enabling the incorporation of multiple stakeholders within the identification and evaluation of the transition strategies. While several strategies are identified, stakeholders agree that reducing the competitiveness of fossil fuels through increased prices and lower subsidies would be the best strategy.

Keywords Transport, Climate-neutrality, Alternative fuels, Greenhouse gases, Sustainable strategies, Germany

*Correspondence:
Sandra Venghaus
venghaus@socecon.rwth-aachen.de
[1] Decision Analysis and Socio-Economic Assessment, School of Business and Economics, RWTH Aachen University, 52072 Aachen, Germany
[2] Institute of Climate and Energy Systems – Jülich Systems Analysis, Forschungszentrum Jülich, Wilhelm-Johnen-Straße, 52428 Jülich, Germany

Background

Sustainable transport in Germany and the EU

With the recent advancements in transport and the reduction in time and cost for travelling, the rate of travel has increased noticeably [1–3]. This is reflected in various developments, such as an increase in the number of businesses in the European Union's (EU's) transport sector from 1.15 million in 2013 to 1.32 million in 2018 [4]. Another example is the growing number of registered cars in Germany, which rose from 41.738 million in 2001 to 48.249 million in 2021 [5]. In addition to the exponential growth in travel rates, combustion engines powered by fossil fuels represent the primary obstacle to reducing greenhouse gas (GHG) emissions in Germany. To achieve net-zero emissions in German transport, the number of combustion engines powered by fossil fuels must be significantly reduced. Such a reduction can be achieved through various means, including the increased market diffusion of electric vehicles (EVs), as well as other alternative fuels-based technologies. At present, however, most modes of transport lack competitive alternative fuel alternatives. Although EVs are regarded as a major alternative for road passenger transport, they have not yet gained a sufficient market share, thus mandating the implementation of strategies and policies that further promote alternative fuels in Germany and the EU [6].

For several decades, Germany has seen continuous innovation and policy development on the path to sustainable transport. The commitment to sustainable transport was originally part of the coalition agreement between the Social Democratic Party (SPD) and the Greens in 1998 [7]. In a chapter of the agreement entitled, "Efficient and Environmentally Sound Transport Policy", the proposed modifications to the German transport sector were delineated. These included an objective to enhance the competitiveness of railways and public transport, as well as to develop an environmentally sustainable individual transport system. Subsequently, each new coalition agreement has pledged to achieve climate protection and promote sustainable transport through the use of alternative fuels [8–11].

After signing the Paris Agreement in 2015, the coalition of the Christian Democratic Union (CDU) and SPD set forth new climate change targets in 2019. Regarding emissions reduction in the transport sector, the goal was to decrease total emissions by one-third by 2030 [12]. However, the highest court in Germany determined the law to be unconstitutional and explained that future generations would have their freedom greatly reduced due to the regulation not being strong enough to ensure a liveable future [13]. Following this verdict, emissions were required to be reduced by 65% to a total of 438 million tonnes of CO_2 equivalent by 2030 [14]. In the period commencing in 2020, there was a notable decline in GHG emissions within the transport sector, with figures reaching 146 million tonnes. This decline can be attributed primarily to the impact of the COVID pandemic [15]. Nevertheless, the federal government's 2021 projection report asserts that if the prevailing trends persist, CO_2 emissions would reach 126 million tonnes by 2030; a figure that is considerably higher than the target of 85 million tonnes [15].

In 2021, Germany made a commitment to placing a greater emphasis on climate change. This was reflected in the coalition agreement as a promise to rework law pertaining to it [16]. The government set forth ambitious objectives in their coalition agreement, with the goal of achieving 10–15 million EVs and 1 million public charging ports by 2030. Additionally, it agreed to increase funding for rail infrastructure and achieve 75% electrified rails by 2030. Following the modification of the emission reduction target to 65% by 2030, the German government set an even more ambitious goal of achieving climate-neutrality by 2045.

The German transport sector is currently at a crucial juncture, influenced by the interplay of global, EU, and national policies, and aiming for a significant shift towards sustainability and GHG-neutrality [17]. Germany's commitment to international agreements demonstrates the profound decision to address climate change and promote sustainable transport practices on a global scale. Germany took part in many EU projects to promote alternative fuels in the 2010s. These included the "Clean Power for Transport: A European Alternative Fuels Strategy", the Directive on Deployment of Alternative Fuels Infrastructure (AFIR), and Renewable Energy Directive II (RED II). These endeavours exemplified Germany's dedication to the establishment of a comprehensive and interlinked framework for sustainable transport within the EU. Furthermore, domestic policies in Germany, such as the Federal Transport Infrastructure Plan (FTIP) 2030, the Mobility and Fuels Strategy (MFS), the National Electromobility Development Plan, as well as the biofuels policies (quota act and sustainability ordinance) were crucial for outlining a pathway to phasing out fossil fuels and promoting the use of alternative fuels. Most importantly, the Federal Immission Control Act (BImSchG) introduced new regulations to manage the transition to alternative fuels by setting quotas for various alternative fuels, with a particular focus on biofuels and e-fuels. These regulations were further strengthened by the introduction of the EU Green Deal and the subsequent Fit for 55.

Since the unveiling of the EU Green Deal in 2019, the EU has been pursuing several targets, including a reduction of GHG emissions in the transport sector, with the intention to reduce these by 90% by 2050. This effort was followed by the Sustainable and Smart Mobility Strategy in 2020, according to which, by 2030, there should be 10–15 million EVs, and travelling less than 500 km should become carbon–neutral. By 2050, nearly all road transport should be carbon–neutral. To achieve these goals, carbon pricing and taxation are intended to support the use of carbon–neutral vehicles, as well as subsides for sustainable/alternative fuels [18]. To intensify efforts to defossilize the EU, the Fit for 55 package provided revisions to existing policies and introduced new initiatives to enable a sustainable transition in a regulated manner (Fig. 1).

Considering the necessity to achieve the defined reduction targets in the transport sector and the availability of various alternative fuels, it is clear that these goals cannot be met without strategic decisions at higher institutional levels. To support achieving the targets, the transport sector aims to primarily use alternative fuels such as renewable electricity and hydrogen for EVs other than light and heavy-duty vehicles, advanced biofuels, and power-to-x (PtX) fuels, also known as e-fuels, for aviation and maritime applications. To achieve these targets, new regulations are discussed to increase the competitiveness of alternative fuels. In order to create new regulatory frameworks or update existing paradigms, efficient strategies must be developed by identifying the key challenges in the sector. However, identifying challenges in the sector and developing effective strategies are complex and multi-dimensional tasks that require reliable and accurate tools.

Multi-criteria analysis for transport and fuel planning

The strategic planning and evaluation of the transport sector frequently entails the resolution of complex problems, which can only be effectively addressed through the use of reliable and sophisticated tools. Multi-criteria decision analysis (MCDA) methodologies have already been successfully employed in diverse multi-dimensional transport and fuel planning problems [20]. MCDA enables stakeholders to address complex and multi-dimensional problems via straightforward and reliable procedures [21–23]. MCDA methods mainly focus on two important tasks in the decision-making process, namely the weighting of decision criteria and the ranking of decision alternatives. For these tasks, several MCDA methods exist in the literature, such as analytical hierarchical process (AHP) [24], analytic network process (ANP) [25], COmplex PRoportional Assessment (COPRAS) [26], technique for ordering performance by similarity to ideal solution (TOPSIS) [27], and multi-objective optimization based on ratio analysis (MOORA) [28].

Recently, Yannis (2020) reviewed state-of-the-art MCDA methods in transport for over 50 papers between 1982 and 2019. The collected papers were reviewed for their specific use cases where MCDA methods were applied. These investigations revealed that MCDA methods are generally employed because they are highly

Fig. 1 The fit for 55 package [19]

suitable for addressing issues related to transport modes, transport policies, and transport projects. Table 1 presents a broader view of previous relevant studies on transport and fuels using MCDA methods both inside and outside of the EU.

Objectives and contributions

This study aims to address strategy development for the sustainable transition in the German transport sector towards GHG-neutrality by 2045. Due to the high priority of mitigating GHG emissions in the transport sector and previous failures to meet reduction targets in the sector, this study addresses an important sustainability concern within Germany.

By employing a SWOT (strengths, weaknesses, opportunities, threats) analysis, this study systematically identifies the significant and critical factors affecting the sustainable transition in the transport sector considering the roles of fossil and alternative fuels and proposes sustainable strategies to facilitate this transition. The prioritization of sustainable transition strategies is an important and challenging task for policymakers and other stakeholders. While all suggested strategies may contribute to the transition, their prioritization is essential given the limited resources and time to achieve the 2030 and 2045 targets. To prioritize the developed strategies, it is essential to determine the weight coefficients of the identified factors, which represent their relative importance. This will facilitate the prioritization of the proposed strategies, which ensures that the most critical aspects are given appropriate emphasis, leading to more effective and targeted decision-making. For this purpose, this study applies an integrated approach using a SWOT analysis, the best worst method (BWM), and TOPSIS in a Type-2 Neutrosophic Numbers (T2NN) environment. The T2NN is an advanced uncertainty modelling set, developed recently as an extension of the traditional Neutrosophic set (NS) that enables stakeholders to express their opinions with more reliability through the use of three functions: truth-membership, indeterminacy-membership, and falsity-membership. In this way, the decision-making environment relies on a more solid and accurate structure to reflect decision-makers' opinions using human linguistic terms.

The remainder of the paper is structured as follows. The next section presents the developed approach and its preliminaries. The problem is then defined, a case study outlined, which is followed by the sensitivity and comparative analysis. Building on these results, managerial and regulatory insights will be discussed. Finally, the last section concludes by summarizing the paper's main results, contributions, and future research directions.

Methods

The following section presents the proposed approach and the essential preliminary steps.

SWOT

SWOT analysis is a strategic planning tool, introduced in the 1960s by Albert S. Humphrey at Harvard Business School. Strengths and Weaknesses refer to internal factors, whereas opportunities and threats refer to external factors that could affect a business, an organization, or an advocacy group to determine success. These four factors describe four different aspects of strategic planning and help to formulate strategies more clearly. Following a two-step process, a SWOT matrix enables decision-makers and policymakers to identify important factors regarding a decision and propose appropriate strategies. Although SWOT was first mostly applied to business problems, its applications have extended to different sectors including, e.g., the satellite industry [54], healthcare management [55], energy management [56], transport planning [57], and education systems [58].

For the implementation of SWOT, a questionnaire was prepared to collect data from experts in the field of transport. For each part of the matrix, experts were asked to provide their answers on factors representing strengths, weaknesses, opportunities, and threats. In the next step and based on the collected data, experts' opinions were integrated to identify the factors that contribute to the transition from fossil fuels to alternative fuels under the SWOT theme. Then, relevant strategies were developed based on the experts' factors to facilitate the transition and address the existing challenges. However, in order to prioritize the developed strategies, determining the importance of the identified factors is required.

BWM

BWM is one of the well-known MCDA methods for determining the weight of decision criteria/factors complex multi-criteria problems faster and with a higher consistency than the older AHP method [59]. Several examples of successfully using BWM can be found in a wide range of use cases, such as R&D performance evaluation [60], supply chain management [61–63], transport planning [64], healthcare management [65], fuel planning [66, 67], and waste management [68].

To determine the optimal importance of the identified factors from the SWOT analysis, the following steps were taken:

Table 1 A summary of previous studies on transport using decision-making techniques

Author(s)	Focus	Methodology	Case study	Implications
Nassereddine and Eskandari [29]	Evaluation of customer satisfaction level in public transport systems	AHP, PROMETHEE	Iran	Results indicate that taxis are the best option for the transport system of Tehran considering social and technical criteria.
Erdogan and Sayin [30]	Fuel selection	ANP, SWARA, MULTIMOORA	–	Evaluating various biodiesel-based alternative fuel options based on fuel quality and price.
Trinh and Le [31]	Analysing biofuel potential in the transport sector	SWOT	Vietnam	Vietnam could produce biofuels for domestic use but the support and incentives of the government are necessary to maximize the utility of biofuels.
de Aquino et al. [32]	Evaluation of the quality of public transport services—Bus Rapid Transit (BRT) system	Fuzzy TOPSIS	Brazil	Five quality dimensions such as reliability, comfort, convenience, information systems, technical security, accessibility, and empathy were used to evaluate the BRT system. Technical security was the best-performing dimension.
Kheybari et al. [33]	Anaylsing decision criteria for biofuel production technology selection	BWM	–	21 criteria were identified under social, economic and environmental categories. The results indicate that air pollution, land use change, and an expert workforce are the three criteria with the highest effectiveness regarding biofuel production technology selection.
D'Adamo et al. [34]	Development of biomethane for sustainable transport in Europe	SWOT, AHP	Europe	As a viable alternative to natural gas as a fuel for sustainable vehicles, biomethane's development absolutely depends on the implementation of government support programs to spur market expansion.
Kowalska-Pyzalska et al. [35]	Analysing markets of alternative fuel vehicles	SWOT	Poland	Identification of the weaknesses and opportunities of current policies and regulations around alternative fuels.
Bouraima et al. [36]	Developing a railway system	SWOT, AHP	West Africa	Identification of 14 factors in the SWOT matrix and proposal of appropriate strategies.
Elavarasan et al. [37]	Evaluation of drivers and barriers for renewable energy development	SWOT	India, China, Iceland, Sweden, and the US	Identification of weaknesses and threats as barriers, as well as strengths and opportunities as drivers for the development of renewable resources in each country.
Ul-Haq et al. [38]	Investigating technical, financial, and policy requirements for electric mobility	SWOT	Pakistan	Allocating a noticeable financial budget to supporting electric transport through improving the charging station network.
Uhunamure and Shale [39]	Exploring viability of renewable energy development	SWOT	South Africa	Wind and solar energy are the most favoured renewable energy sources in South Africa.
Mostafaeipour et al. [40]	Green hydrogen projects development	BWM, EDAS	Uzbekistan	Evaluation of various stations for the production of green hydrogen from wind energy sources in order to produce 71.752 tons of hydrogen annually through an estimated 2000 kW turbines in Nukus.
Almutairi et al. [41]	Prioritizing stations for hydrogen production using wind energy	SWARA, EDAS	Afghanistan	Eastern and northeastern parts of Badakhshan province considering technical, economic, and carbon footprint criteria.

Table 1 (continued)

Author(s)	Focus	Methodology	Case study	Implications
Al-Haidous et al. [42]	Evaluating LNG supply chain resilience	SWOT	Qatar	Improving strategic alliances to minimize LNG shipping through supporting clean transport modes.
Ecer [43]	Performance assessment of battery EVs	SECA, MARCOS, MAIRCA, COCOSO, ARAS, and COPRAS	–	Tesla Model S selected as the best option among 10 battery EVs.
Narwane et al. [44]	Development challenges of the biofuel industry	ISM-DEMATEL	India	Identification of 38 barriers to the sustainable development of biofuels where a lack of governmental support for sustainable supply chain solutions is the most important barrier.
Abdel-Basset et al. [45]	Evaluation of sustainable hydrogen production options	AHP, EDAS	–	The process of wind electrolysis, according to the results, is the secret to sustainably producing hydrogen.
Chai and Zhou [46]	Alternative aviation fuels selection	Fuzzy AHP, TOPSIS	–	Algal-based fuels, petroleum refining, soybean-based fuel, and Fischer–Tropsch synthesis based on natural gas.
Mehta and Mehta [47]	Algae biodiesel for power generation	TOPSIS	–	Algae biodiesel is the best option among eight biodiesels from different feedstocks.
Simic et al. [48]	Evaluation of environmental policies for mitigating climate change effect of urban transport system	MEREC, MARCOS		Four policies: a) informative actions; b) subsidies for micromobility modes; c) land use planning, i.e., limited traffic zones; and d) optimization and planning of public transport modes are considered. The results show that land use planning is the best policy.
Jusakulvijit et al. [49]	Sustainability analysis of 2nd generation biofuels production	Delphi, AHP	Thailand	Evaluation by 20 experts of the four dimensions ranked economic feasibility as the most important (32.7%), followed by environmental impacts (25.1%), technical feasibility (24.9%), and social impacts (17.3%).
Wang et al. [50]	Optimized location analysis of bioethanol supply chain for biorefinery sites	GIS, MCDM, MILP	China	Effective subsidies, mandatory energy substitution policies, and other environmental regulatory measures are essential to promoting the development of the bioethanol industry.
Rahimirad and Sadabadi [51]	Technology development and policymaking for green hydrogen	SWOT, TOPSIS, AHP, VIKOR	Iran	The top priority is determining the role of green hydrogen technology in energy policymaking, followed by carrying out experimental projects and promoting hydrogen as an energy source through public acceptance.
Sun et al. [52]	Risk analysis for hydrogen storage and transport in urban areas	DEMATEL, ANP	China	The skills of the personnel were identified as the most significant risk-related factor, whereas environmental volatility and the effectiveness of feedback were recognized as root factors.
Olabi et al. [53]	Sustainability assessment of hydrogen production pathways	WASPAS, TOPSIS, CRITIC, Shannon's entropy	–	Biomass gasification and steam methane reforming outperform other pathways. Hydrogen's primary impact on the SDGs arises from its potential to offer a clean energy source (SDG 7: Affordable and Clean Energy) and reduce greenhouse gas emissions (SDG 13: Climate Action).

- **Step 1.** Experts determined the decision criteria/factors via the SWOT analysis. Then, they identified the most and least valuable desirable criteria.
- **Step 2.** Experts determined pairwise comparisons between the best criterion and other criteria, using a scale of 1–9, which constructs a best-to-others vector. In this scale, 1 represents the least and 9 the highest levels of importance.
- **Step 3.** Experts made pairwise comparisons between other criteria and the worst criterion, using a scale of 1–9, which constructs an others-to-worst vector.
- **Step 4.** The optimal weights $(w_1^*, w_2^*, \ldots, w_{n)}^*$ can be calculated by solving the following optimization model (Eqs. 1–5):

$$\text{minimize}\, \xi \tag{1}$$

subject to

$$\left| \frac{w_{Best}}{w_j} - a_{Bj} \right| \leq \xi \forall j \tag{2}$$

$$\left| \frac{w_j}{w_{Worst}} - a_{jW} \right| \leq \xi \forall j \tag{3}$$

$$\sum_j w_j = 1 \forall j \tag{4}$$

$$w_j \geq 0 \quad \forall j \tag{5}$$

Step 5. Consistency ratio of results from the optimization model can be determined based on Eq. (6) and Table 2.

$$\text{Consistency ratio} = \frac{\xi^*}{\text{Consistency index}}. \tag{6}$$

T2NN–TOPSIS

After using BWM to determine the importance of the identified factors, experts could express their opinions to prioritize the developed strategies. For better and more accurate consideration of their opinions, the concept of T2NN was employed.

Preliminaries of T2NN

This section presents basic concepts, requirements, and operations of T2NN, which were initially introduced by Abdel-Basset, Saleh [69]. Smarandache [70] introduced NS as a generalization of the intuitionistic fuzzy set. In the last decade, NS has attracted considerable interest from researchers in various domains seeking reliable tools for handling ambiguous and uncertain information in problem-solving situations. The basics of T2NN are presented below.

Definition 1 [69] Consider Ω as the limited universe of discourse and $E[0, 1]$ in the form of triangular NS on $E[0, 1]$. A T2NN denoted by $\widetilde{H}$ can be defined in ω as follows:

$$\widetilde{T} = \left\{ \langle \omega,\ \widetilde{T}_{\widetilde{H}}(\omega),\ \widetilde{I}_{\widetilde{H}}(\omega),\ \widetilde{F}_{\widetilde{H}}(\omega) \mid \omega \in \Omega \rangle \right\}, \tag{7}$$

where $\widetilde{T}_{\widetilde{H}}(\omega) : \Omega \rightarrow E[0,\ 1]$, $\widetilde{I}_{\widetilde{H}}(\omega) : \Omega \rightarrow E[0,\ 1]$, and $\widetilde{F}_{\widetilde{H}}(\omega) : \Omega \rightarrow E[0,\ 1]$. A T2NNS $\widetilde{T}_{\widetilde{H}}(\omega) = \left(T_{T_{\widetilde{H}}}(\omega),\ T_{I_{\widetilde{H}}}(\omega),\ T_{F_{\widetilde{H}}}(\omega) \right)$, $\widetilde{I}_{\widetilde{H}}(\omega) = \left(I_{T_{\widetilde{H}}}(\omega),\ I_{I_{\widetilde{H}}}(\omega),\ I_{F_{\widetilde{H}}}(\omega) \right)$, and $\widetilde{F}_{\widetilde{H}}(\omega) = \left(F_{T_{\widetilde{H}}}(\omega),\ F_{I_{\widetilde{H}}}(\omega),\ F_{F_{\widetilde{H}}}(\omega) \right)$, defines the truth, indeterminacy, and falsity memberships of ω in $\widetilde{H}$, respectively. The membership parameters must satisfy the constraint in Eq. (8):

$$0 \leq \widetilde{T}_{\widetilde{H}}(\omega)^3 + \widetilde{I}_{\widetilde{H}}(\omega)^3 + \widetilde{F}_{\widetilde{H}}(\omega)^3 \leq 3, \quad \forall \omega \in \Omega. \tag{8}$$

Based on Definition 1, T2NN is considered in the following form:

$$\widetilde{H} = \langle \left(T_{T_{\widetilde{H}}}(\omega),\ T_{I_{\widetilde{H}}}(\omega),\ T_{F_{\widetilde{H}}}(\omega) \right), \left(I_{T_{\widetilde{H}}}(\omega),\ I_{I_{\widetilde{H}}}(\omega),\ I_{F_{\widetilde{H}}}(\omega) \right), \left(F_{T_{\widetilde{H}}}(\omega),\ F_{I_{\widetilde{H}}}(\omega),\ F_{F_{\widetilde{H}}}(\omega) \right) \rangle,$$

in the rest of the paper.

Definition 2 [69]. Let us consider two T2NNs as:

$$\widetilde{H}_1 = \langle \left(T_{T_{\widetilde{H}_1}}(\omega),\ T_{I_{\widetilde{H}_1}}(\omega),\ T_{F_{\widetilde{H}_1}}(\omega) \right), \left(I_{T_{\widetilde{H}_1}}(\omega),\ I_{I_{\widetilde{H}_1}}(\omega),\ I_{F_{\widetilde{H}_1}}(\omega) \right), \left(F_{T_{\widetilde{H}_1}}(\omega),\ F_{I_{\widetilde{H}_1}}(\omega),\ F_{F_{\widetilde{H}_1}}(\omega) \right) \rangle,$$

$$\widetilde{H}_2 = \langle \left(T_{T_{\widetilde{H}_2}}(\omega),\ T_{I_{\widetilde{H}_2}}(\omega),\ T_{F_{\widetilde{H}_2}}(\omega) \right), \left(I_{T_{\widetilde{H}_2}}(\omega),\ I_{I_{\widetilde{H}_2}}(\omega),\ I_{F_{\widetilde{H}_2}}(\omega) \right), \left(F_{T_{\widetilde{H}_2}}(\omega),\ F_{I_{\widetilde{H}_2}}(\omega),\ F_{F_{\widetilde{H}_2}}(\omega) \right) \rangle \ and\ \lambda > 0.$$

The basic arithmetic operations for these two numbers can be defined as follows:

$$\begin{aligned}\widetilde{H}_1 \oplus \widetilde{H}_2 = \langle &\left(T_{T_{\widetilde{H}_1}}(\omega) + T_{T_{\widetilde{H}_2}}(\omega) - T_{T_{\widetilde{H}_1}}(\omega) \times T_{T_{\widetilde{H}_2}}(\omega),\ T_{I_{\widetilde{H}_1}}(\omega) + T_{I_{\widetilde{H}_2}}(\omega) \right. \\ &\left. - T_{I_{\widetilde{H}_1}}(\omega) \times T_{I_{\widetilde{H}_2}}(\omega),\ T_{F_{\widetilde{H}_1}}(\omega) + T_{F_{\widetilde{H}_2}}(\omega) - T_{F_{\widetilde{H}_1}}(\omega) \times T_{F_{\widetilde{H}_2}}(\omega) \right), \\ &\left(I_{T_{\widetilde{H}_1}}(\omega) \times I_{T_{\widetilde{H}_2}}(\omega),\ I_{I_{\widetilde{H}_1}}(\omega) \times I_{I_{\widetilde{H}_2}}(\omega),\ I_{F_{\widetilde{H}_1}}(\omega) \times I_{F_{\widetilde{H}_2}}(\omega) \right), \\ &\left(F_{T_{\widetilde{H}_1}}(\omega) \times F_{T_{\widetilde{H}_2}}(\omega),\ F_{I_{\widetilde{H}_1}}(\omega) \times F_{I_{\widetilde{H}_2}}(\omega),\ F_{F_{\widetilde{H}_1}}(\omega) \times F_{F_{\widetilde{H}_2}}(\omega) \right) \rangle,\end{aligned} \tag{9}$$

$$\begin{aligned}\widetilde{H}_1 \otimes \widetilde{H}_2 = \langle &\left(T_{T_{\widetilde{H}_1}}(\omega) \times T_{T_{\widetilde{H}_2}}(\omega),\ T_{I_{\widetilde{H}_1}}(\omega) \times T_{I_{\widetilde{H}_2}}(\omega),\ T_{F_{\widetilde{H}_1}}(\omega) \times T_{F_{\widetilde{H}_2}}(\omega) \right), \\ &\left(T_{T_{\widetilde{H}_1}}(\omega) + T_{T_{\widetilde{H}_2}}(\omega) - T_{T_{\widetilde{H}_1}}(\omega) \times T_{T_{\widetilde{H}_2}}(\omega),\ T_{I_{\widetilde{H}_1}}(\omega) + T_{I_{\widetilde{H}_2}}(\omega) \right. \\ &\left. - T_{I_{\widetilde{H}_1}}(\omega) \times T_{I_{\widetilde{H}_2}}(\omega),\ T_{F_{\widetilde{H}_1}}(\omega) + T_{F_{\widetilde{H}_2}}(\omega) - T_{F_{\widetilde{H}_1}}(\omega) \times T_{F_{\widetilde{H}_2}}(\omega) \right), \\ &\left(T_{T_{\widetilde{H}_1}}(\omega) + T_{T_{\widetilde{H}_2}}(\omega) - T_{T_{\widetilde{H}_1}}(\omega) \times T_{T_{\widetilde{H}_2}}(\omega),\ T_{I_{\widetilde{H}_1}}(\omega) + T_{I_{\widetilde{H}_2}}(\omega) \right. \\ &\left. - T_{I_{\widetilde{H}_1}}(\omega) \times T_{I_{\widetilde{H}_2}}(\omega),\ T_{F_{\widetilde{H}_1}}(\omega) + T_{F_{\widetilde{H}_2}}(\omega) - T_{F_{\widetilde{H}_1}}(\omega) \times T_{F_{\widetilde{H}_2}}(\omega) \right) \rangle,\end{aligned} \tag{10}$$

$$\begin{aligned}\lambda\widetilde{H} = \langle &\left(1 - \left(1 - T_{T_{\widetilde{H}}}(\omega) \right)^{\lambda},\ 1 - \left(1 - T_{I_{\widetilde{H}}}(\omega) \right)^{\lambda},\ 1 - \left(1 - T_{F_{\widetilde{H}}}(\omega) \right)^{\lambda} \right), \\ &\left(\left(I_{T_{\widetilde{H}}}(\omega) \right)^{\lambda},\ \left(I_{I_{\widetilde{H}}}(\omega) \right)^{\lambda},\ \left(I_{F_{\widetilde{H}}}(\omega) \right)^{\lambda} \right), \\ &\left(\left(F_{T_{\widetilde{H}}}(\omega) \right)^{\lambda},\ \left(F_{I_{\widetilde{H}}}(\omega) \right)^{\lambda},\ \left(F_{F_{\widetilde{H}}}(\omega) \right)^{\lambda} \right) \rangle,\end{aligned} \tag{11}$$

$$\begin{aligned}\widetilde{H}^{\lambda} = \langle &\left(\left(T_{T_{\widetilde{H}}}(\omega) \right)^{\lambda},\ \left(T_{I_{\widetilde{H}}}(\omega) \right)^{\lambda},\ \left(T_{F_{\widetilde{H}}}(\omega) \right)^{\lambda} \right), \\ &\left(1 - \left(1 - I_{T_{\widetilde{H}}}(\omega) \right)^{\lambda}, 1 - \left(1 - I_{I_{\widetilde{H}}}(\omega) \right)^{\lambda},\ 1 - \left(1 - I_{F_{\widetilde{H}}}(\omega) \right)^{\lambda} \right), \\ &\left(1 - \left(1 - F_{T_{\widetilde{H}}}(\omega) \right)^{\lambda},\ 1 - \left(1 - F_{I_{\widetilde{H}}}(\omega) \right)^{\lambda},\ 1 - \left(1 - F_{F_{\widetilde{H}}}(\omega) \right)^{\lambda} \right) \rangle.\end{aligned} \tag{12}$$

Definition 3 [69]. Suppose that $\widetilde{H}_l = \langle \left(T_{T_{\widetilde{H}_l}}(\omega), T_{I_{\widetilde{H}_l}}(\omega), T_{F_{\widetilde{H}_l}}(\omega) \right), \left(I_{T_{\widetilde{H}_l}}(\omega), I_{I_{\widetilde{H}_l}}(\omega), I_{F_{\widetilde{H}_l}}(\omega) \right), \left(F_{T_{\widetilde{H}_l}}(\omega), F_{I_{\widetilde{H}_l}}(\omega), F_{F_{\widetilde{H}_l}}(\omega) \right) \rangle$ $(l = 1, \ldots, p)$ is a collection of T2NNs, and $\gamma = (\gamma_1, \ldots, \gamma_p)^T$ is their weight vector, with $\gamma_l \in [0, 1]$ and $\sum_{l=1}^{p} \gamma_l = 1$. A T2NN weighted averaging (T2NNWA) operator is defined as follows:

$$\begin{aligned}&T2NNWA_{\gamma}(\widetilde{H}_1,\ \ldots,\ \widetilde{H}_l,\ \ldots,\ \widetilde{H}_p) = \gamma_1\widetilde{H}_1 \oplus \cdots \oplus \gamma_l\widetilde{H}_l \oplus \cdots \oplus \gamma_p\widetilde{H}_p = \mathop{\oplus}_{l=1}^{p} \gamma_l\widetilde{H}_l \\ &= \langle \left(1 - \prod_{l=1}^{p} \left(1 - T_{T_{\widetilde{H}_l}}(\omega) \right)^{\gamma_l},\ 1 - \prod_{l=1}^{p} \left(1 - T_{I_{\widetilde{H}_l}}(\omega) \right)^{\gamma_l},\ 1 - \prod_{l=1}^{p} \left(1 - T_{F_{\widetilde{H}_l}}(\omega) \right)^{\gamma_l} \right), \\ &\left(\prod_{l=1}^{p} \left(I_{T_{\widetilde{H}_l}}(\omega) \right)^{\gamma_l},\ \prod_{l=1}^{p} \left(I_{I_{\widetilde{H}_l}}(\omega) \right)^{\gamma_l},\ \prod_{l=1}^{p} \left(I_{F_{\widetilde{H}_l}}(\omega) \right)^{\gamma_l} \right), \\ &\left(\prod_{l=1}^{p} \left(F_{T_{\widetilde{H}_l}}(\omega) \right)^{\gamma_l},\ \prod_{l=1}^{p} \left(F_{I_{\widetilde{H}_l}}(\omega) \right)^{\gamma_l},\ \prod_{l=1}^{p} \left(F_{F_{\widetilde{H}_l}}(\omega) \right)^{\gamma_l} \right) \rangle.\end{aligned} \tag{13}$$

Table 2 BWM consistency index [59]

a_{BW}	1	2	3	4	5	6	7	8	9
CI	0	0.44	1.00	1.63	2.30	3.00	3.73	4.47	5.23

Definition 4 [69]. Let $\widetilde{H} = \langle \left(T_{T_{\widetilde{H}}}(\omega),\ T_{I_{\widetilde{H}}}(\omega),\ T_{F_{\widetilde{H}}}(\omega) \right), \left(I_{T_{\widetilde{H}}}(\omega),\ I_{I_{\widetilde{H}}}(\omega),\ I_{F_{\widetilde{H}}}(\omega) \right),\ \left(F_{T_{\widetilde{H}}}(\omega),\ F_{I_{\widetilde{H}}}(\omega),\ F_{F_{\widetilde{H}}}(\omega) \right) \rangle$ be a T2NN. The score function of $\widetilde{H}$ is defined as follows:

$$S(\widetilde{H}) = \frac{1}{12}\langle 8 + \left(T_{T_{\widetilde{H}}}(\omega) + 2\left(T_{I_{\widetilde{H}}}(\omega) \right) + T_{F_{\widetilde{H}}}(\omega) \right) - \left(I_{T_{\widetilde{H}}}(\omega) + 2\left(I_{I_{\widetilde{H}}}(\omega) \right) + I_{F_{\widetilde{H}}}(\omega) \right) - \left(F_{T_{\widetilde{H}}}(\omega) + 2\left(F_{I_{\widetilde{H}}}(\omega) \right) + F_{F_{\widetilde{H}}}(\omega) \right) \rangle. \tag{14}$$

T2NN–TOPSIS

TOPSIS is one of the very early MCDA methods, developed in 1981 by [27]. It ranks or prioritizes several alternatives against decision criteria using distance-based scores. TOPSIS has been used in many different fields and applications, such as public health [71], risk prioritization [72, 73], tourism management [74], transport [75], and energy planning [76, 77]. T2NN–TOPSIS is one of the most recent and advanced extension of TOPSIS [69].

To systematically prioritize the developed strategies against the identified factors, the following procedure of T2NN–TOPSIS can be used:

Step 1. A decision matrix is created with m alternatives, representing the developed strategies, and n criteria showing the identified factors using the T2NN scale shown in Table 3.

Step 2. The T2NNWA operator defined in Eq. (13) is used to aggregate all decision matrices by experts into a single decision matrix.

Step 3. Equation (14) is then used to determine the score value of the T2NN values.

Step 4. Subsequently, the decision matrix is normalized based on Eq. (15):

$$r_{ij} = \frac{x_{ij}}{\sqrt{\left(\sum x^2{}_{ij}\right)}} \text{ for } i = (1, 2, \ldots, m); j = (1, 2, \ldots, n), \tag{15}$$

where x_{ij} is the performance score of alternative i against criterion j and r_{ij} denotes the normalized value of the performance score.

Step 5. The weighted normalized decision matrix is constructed using Eq. (16):

$$v_{ij} = w_j * r_{ij} \text{ for } i = (1, 2, \ldots, m); j = (1, 2, \ldots, n), \tag{16}$$

where w_j is the weight coefficient of criterion j obtained by BWM.

Step 6. Positive and negative ideal solutions are determined accordingly.

$A^* = \left\{ v_1^*, v_2^*, \ldots, v_n^* \right\}$ Positive ideal solution,

$$\text{where } v_j{}^* = \left\{ max\left(v_{ij}\right) \text{if } j \epsilon B;\ min\left(v_{ij}\right) \text{if } j \epsilon C \right\}. \tag{17}$$

$A^* = \{ v_1\prime, v_2\prime, \ldots, v_n\prime \}$ Negative ideal solution,

$$\text{where } v_j{}' = \left\{ min\left(v_{ij}\right) \text{ if } j \epsilon B;\ max\left(v_{ij}\right) \text{ if} j \epsilon C \right\} \tag{18}$$

B denotes the benefit criteria and C represents the cost criteria.

Step 7. Distance from each alternative to positive and negative idea solutions are calculated as follows (eqs. 19–20):

$$S_i^* = \left[\sum \left(v_j^* - v_{ij}\right)^2 \right]^{1/2} \text{i} = (1, \ldots, \text{m}), \tag{19}$$

$$S_i' = \left[\sum \left(v_j{}' - v_{ij}\right)^2 \right]^{1/2} \text{i} = (1, \ldots, \text{m}). \tag{20}$$

Step 8. The relative closeness of the ideal solution CC_i is calculated as:

$$CC_i = S_i\prime / (S_i^* + S_i\prime). \tag{21}$$

The alternative with CC_i closest to 1 is considered the best alternative.

Results

Problem definition and case study

The EU and its member countries have been planning to reduce GHG emissions in all sectors, including transport. Since the mid-1950s, Germany, as one of the pioneers in moving towards sustainability and the transition to a low-carbon economy, has been addressing its GHG emission-based challenges through the well-known *Energiewende* (Energy Transition) framework.

Figure 2 illustrates an overview of GHG emissions in the main sectors of the EU, as well as the transport sector in Germany over the last three decades. According to the statistics, although the EU transport sector experienced an overall increase in GHG emissions during this period, the German transport sector managed to achieve a slight reduction in emissions. This reduction, however, falls short of the targets anticipated by policies introduced in the 1990s and 2000s. The failure to reduce emissions in all sectors, most importantly in transport sector, led to Climate Action Plan 2050. The Climate Action Plan was one of the most important steps of Germany for reducing GHG emissions in all sectors by 55%, 40–42% in the transport sector, 61–62% in the energy sector, 66–67% in the building sector, 49–51% in the heavy industry sector and 31–34% in agriculture by 2030 (compared to 1990), and almost near zero emissions (80–95% reduction) by 2050. Recently, Germany updated this plan and put stricter reduction targets by increasing the overall reduction target to 65% in 2030 and climate-neutrality in 2045, thus advancing beyond the EU's target of 2050. Special attention is given to the transport sector to tackle challenges and move towards meeting emission standards for 2030 and 2045.

In this regard, various German policies, including those related to biofuels, EVs and other alternative fuels, along with other EU policies, serve to achieve GHG reduction targets through different pathways. As fossil fuels and their derivatives account for a large share of GHG emissions in the EU, German and EU policies are prioritizing the adoption of sustainable alternative fuels to reduce these. However, the transition is affected by the complex supply chains of these sustainable alternative fuels. Thus, meeting the GHG reduction targets in the transport sector necessitates robust, carefully planned and well-designed strategies.

The identification of the strengths and challenges of the current system is of high significance for designing effective strategies for the transition to alternative fuels from the fossil fuels-based transport sector. Thus, the current study applies an expert-based tool to analyse the transition to alternative fuels in the German transport sector. For this purpose, a SWOT analysis was used to investigate the current developments in the transport sector. Identified factors related to strengths, opportunities, weaknesses, and threats can enable decision-makers, managers and politicians to propose strategies to facilitate the sustainable transition. Although all proposed strategies may be relevant and applicable, upper-level managers in related industries and politicians must make critical decisions by giving priority to some of the strategies due to resource constraints. Thus, this study tackles the prioritization of strategies using an MCDA approach.

Table 3 T2NN linguistic terms for weight assessment

Linguistic terms	T2NN
Absolutely low	< (0.1,0.1,0.1),(0.8,0.9,0.9),(0.85,0.7,0.6) >
Very low	< (0.2,0.2,0.1),(0.65,0.8,0.85),(0.75,0.8,0.7) >
Low	< (0.35,0.35,0.1),(0.5,0.75,0.8),(0.65,0.75,0.65) >
Medium low	< (0.5,0.3,0.5),(0.5,0.35,0.45),(0.55,0.3,0.6) >
Medium	< (0.4,0.45,0.5),(0.4,0.45,0.5),(0.45,0.4,0.45) >
Medium high	< (0.6,0.45,0.5),(0.25,0.15,0.25),(0.3,0.25,0.2) >
High	< (0.7,0.75,0.8),(0.2,0.2,0.25),(0.2,0.15,0.15) >
Very high	< (0.8,0.9,0.9),(0.15,0.15,0.2),(0.15,0.1,0.1) >
Absolutely high	< (0.95,0.9,0.95),(0.1,0.1,0.05),(0.05,0.05,0.05) >

Figure 3 presents a flowchart of the proposed approach for strategy development and evaluation in the transport sector.

Panel of experts

For the SWOT and MCDA analyses, a panel of experts was created consisting of five experts from the fields of transport, environmental and climate sciences, and energy. A brief profile of each of these is provided below:

- Expert 1 (E1): male with an M.Sc. degree and five years of experience in energy system modelling;
- Expert 2 (E2): male with an M.Sc. degree and two years of experience in fuel and transport planning;
- Expert 3 (E3): female with an M.Sc. degree and one year of experience in transport planning;
- Expert 4 (E4): male with a PhD and five years of experience in climate science and energy planning;
- Expert 5 (E5): male with an M.Sc. degree and three years of experience in technology assessment.

Key factors and strategies

In the first stage, a questionnaire was designed to evaluate the experts' opinions on the transition of Germany towards a sustainable transport sector with a focus on the role of alternative fuels. Experts were asked to fill out a SWOT matrix and provide their opinion regarding the four pillars of strengths, weaknesses, opportunities, and threats. Figure 4 shows the SWOT based on the data collected.

Based on the experts' opinions regarding the transition process, three key strengths of transitioning to a sustainable transport sector with alternative fuels in Germany

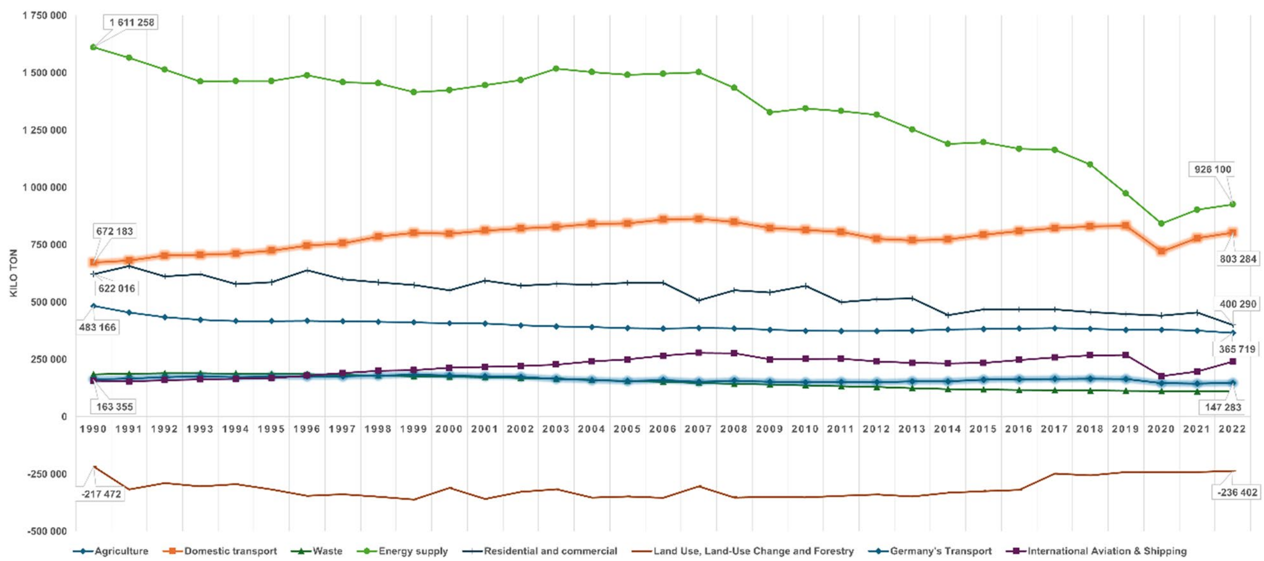

Fig. 2 GHG emissions (CO2 equivalent) in the EU and Germany over three decades [78]

were the high public acceptance of these fuels, the potential for significant job creation, and ongoing R&D in alternative fuels by academic institutions and automobile manufacturers.

In the same manner, the experts focused on the weaknesses by highlighting that Germany still needs to tackle several challenges regarding high GHG emissions and the failure to meet previous targets in reducing them. Moreover, subsidies for fossil fuels and strong lobbying by manufacturing companies, as well as fuel companies are further weaknesses of the transport sector. Finally, three technical weaknesses for the transition are a lack of infrastructures for alternative fuels, volatility of the availability of renewable energy, and a lack of expertise in fuels.

The defossilization of the current transport fleet and achieving emissions reduction targets, getting aligned with German and EU regulations on the use of alternative fuels, the long-term efficiency and viability of alternative fuels, and prompting manufacturing companies to adopt new fuels, are the most important opportunities in Germany for a sustainable transition in the transport sector.

Increased land use for fuel production (e.g., biofuels), resource competition between alternative fuel producers and other industries, structural changes to the related industry and high transition costs, possible disruptions in the alternative fuel supply chains due to volatility of resources, and high expectations regarding the implementation of alternative fuels, are major threats to the sustainable transition.

The identified SWOT factors from the experts highlight the need to increase support for the adoption of alternative fuels and reduce support for fossil fuels. The SWOT analysis generates four types of strategies, namely strength–opportunities (SO) strategies to properly exploit opportunities based on current strengths, strength–threats (ST) strategies for reducing threats using current strengths, weakness–opportunities (WO) strategies for obtaining the benefits of opportunities considering possible weaknesses, and weakness–threats (WT) strategies for decreasing threats considering existing or potential weaknesses (Fig. 5). On this basis, the following strategies can be defined:

SO 1: Reducing the competitiveness of fossil fuels through increased prices. This can be achieved by reducing subsidies for fossil fuels, increasing taxation, or increasing climate compensation payments for emissions.

SO 2: Increasing the competitiveness of alternative fuels through monetary incentives on purchases, tax exemptions, subsidies on companies, free parking, and refuelling.

ST 1: Starting a public campaign to highlight the necessity of alternative fuels for tackling climate change challenges in Germany.

ST 2: Enhancing the competitiveness of alternative fuels can be achieved through non-financial incentives such as dedicated lanes and parking spaces for vehicles and priority at ports and airports for ships and planes, respectively.

WO 1: Facilitating technological developments in the field of alternative fuels by improving fuel efficiency.

WO 2: Decreasing the competitiveness of fossil fuels by introducing inconveniences, such as decreasing

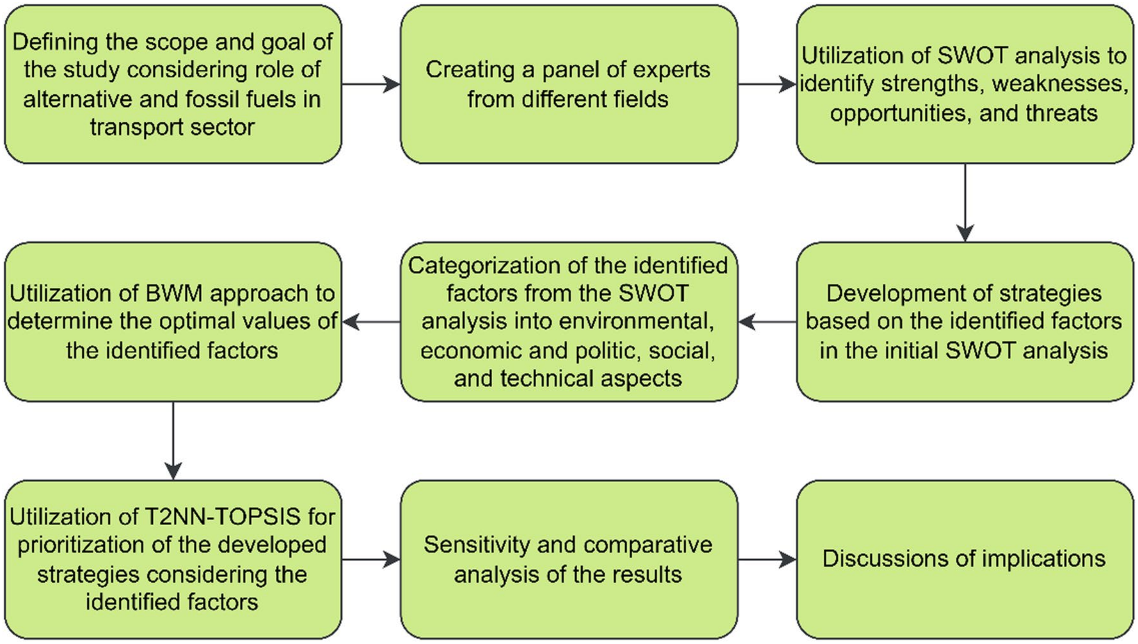

Fig. 3 Flowchart of the proposed approach

the number of refuelling stations and establishing prohibition zones for fossil fuel-based vehicles.

WT 1: Enhancing infrastructural capacities for using alternative fuels by upgrading refuelling stations.

WT 2: Improving the electricity network by enhancing the power grid for generating renewable electricity considering the crucial role of renewable electricity for the production of most of alternative fuels.

Weight coefficients of SWOT factors

Based on the collected SWOT factors (Fig. 4), a sustainability framework was developed to categorize the factors into different groups, each addressing a critical aspect. In this regard, factors were divided into environmental, economic and regulatory, social, and technical categories.

The *Environmental* (C1) category includes the potential for GHG emission reduction (C11), the potential for local emission reduction (smog, water, and soil pollution) (C12), the defossilization of the existing fleet by replacing traditional fuels with alternative ones (C13), land use for energy generation and fuel production (C14), resource competition (C15), and compatibility with environmental regulations (C16).

The *Economic and regulatory* (C2) category addresses the long-term economic viability of alternative fuels (C21), structural impacts on the fuel production and automotive industries (C22), disruption potential in the fuel supply chain (C23), the impacts of subsidies for fossil fuels (C24), the effects of laws and regulations for encouraging the automotive industry to transition (C25), and the impacts of the transport lobby on fuel alternatives (C26).

The *Social* (C3) category includes potential social acceptance of alternative fuels (C31), public expectations regarding the benefits of alternative fuels (C32), and potential job creation (C33).

The *Technical* (C4) category covers the impacts of the lack of infrastructure for alternative fuels (C41), the insufficiency of renewable energy sources for fuel production (C42), the effects of R&D on alternative fuels (C43), and the lack of knowledge and expertise regarding alternative fuels (C44).

Following the categorization of the factors, experts were invited again to determine the weight coefficients of the identified factors. To collect the input data for the BWM, the experts were asked to use a 1–9 scale for pairwise comparisons between the factors. For this purpose, experts first used the scale to determine the weight

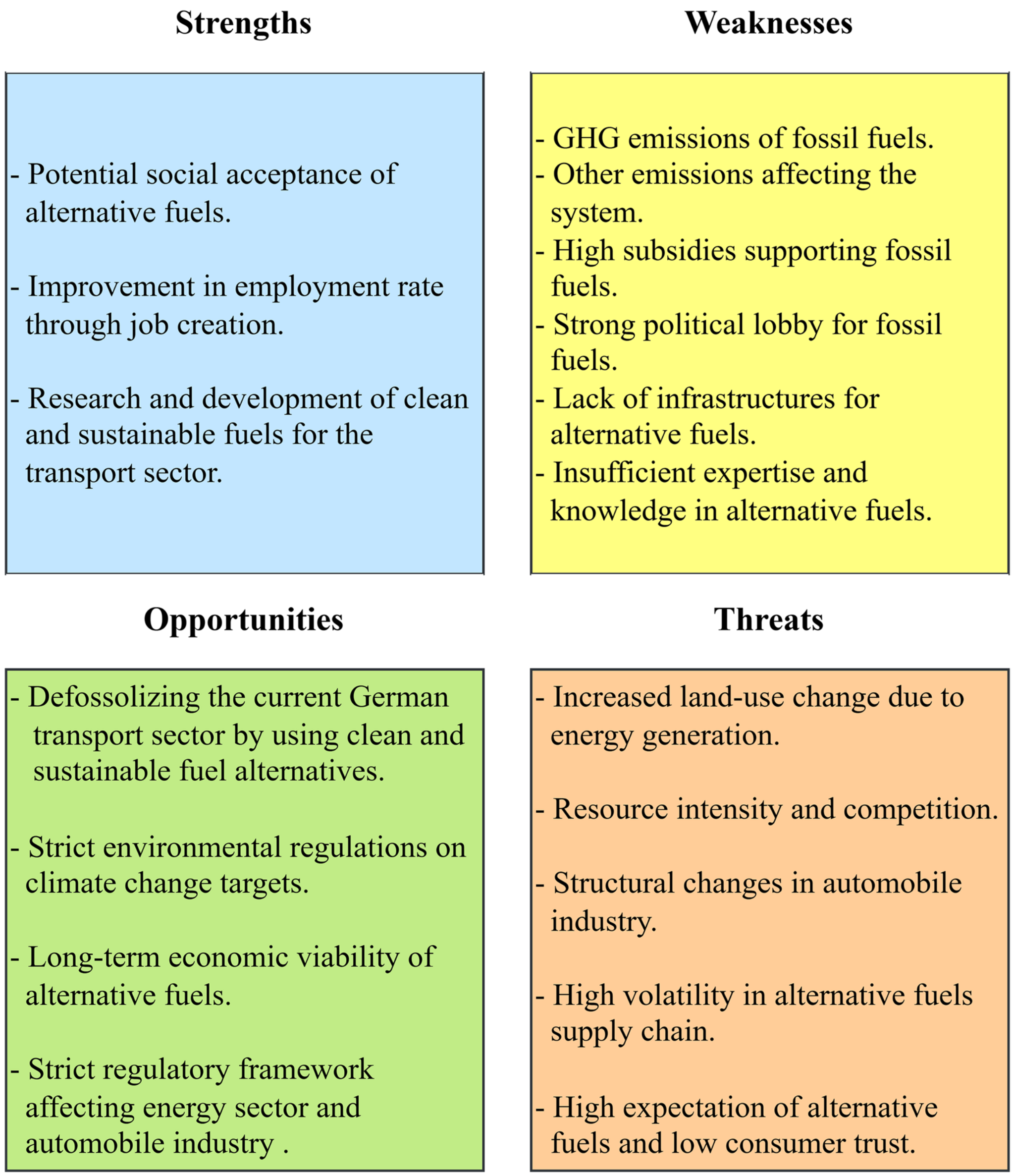

Fig. 4 SWOT matrix

coefficients of the categories. In this regard, the experts decided on the best and worst criteria; then, best-to-others and others-to-worst vectors were constructed. In our analysis, all experts were considered to have equal importance. Table 4 presents the experts' inputs and the calculated weight coefficients of the factors. The results indicate that the environmental category is the most important, with a value of 0.47, and the technical category the least important category, with a value of 0.12.

In the next stage, the experts were consulted to provide input for the BWM calculation for each category. Table 5 represents the experts' opinions on the best criterion, worst criterion, and input weight vectors. Finally, the average local weight coefficients of the environmental factors were determined. Using the weight coefficient of the environmental category and local coefficients, the global weight coefficients of environmental factors were determined. According to the results in Table 5, GHG emission reduction (C11) and resource competition (C15) are the most important factors in the environmental category.

Similarly, local and global weight coefficients of economic and regulatory factors were calculated. The results

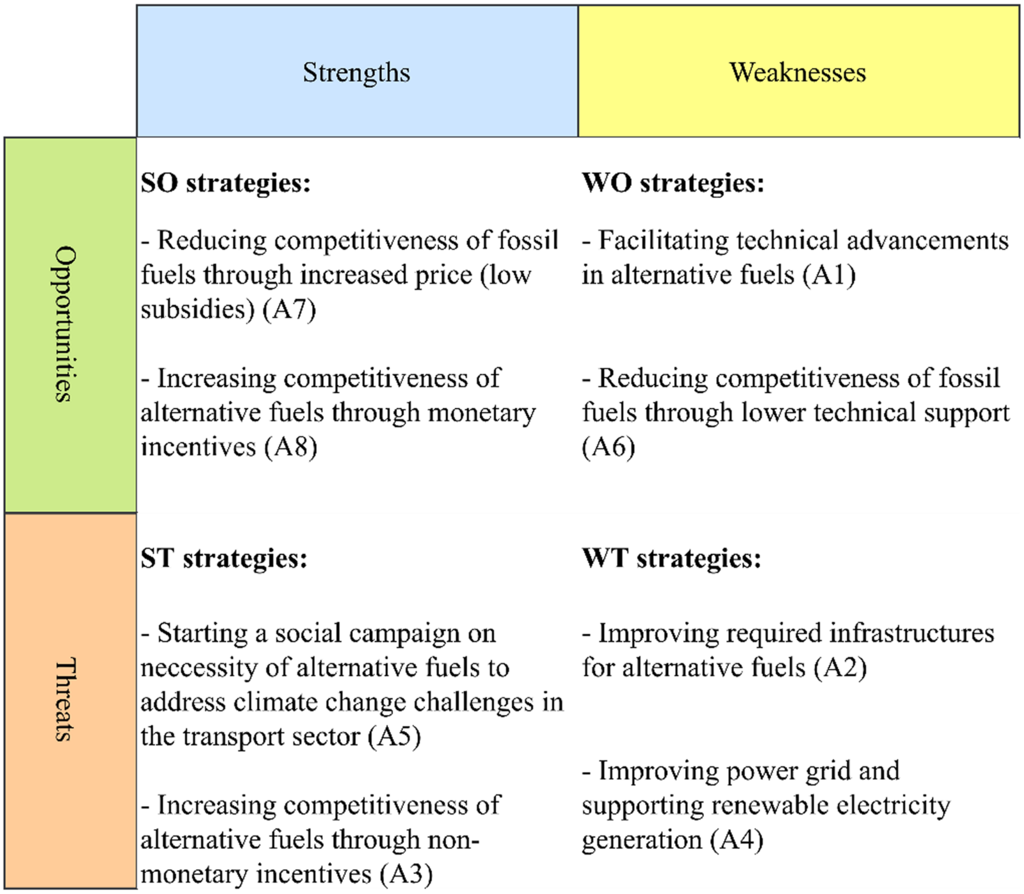

Fig. 5 Strategies for a sustainable transition in the transport sector

presented in Table 6 indicate that long-term economic viability for alternative fuels (C21) and high subsidies for fossil fuels are the most important factors, and disruption potential in the supply chain is the least important in the economic and regulatory category.

Table 7 shows the input data and final results for the social factors. According to the results, the social acceptance of alternative fuels is the most important factor in the social category, and potential job creation the least important.

Table 8 presents the input data and final results for the technical factors. According to the results, the impacts of the insufficiency of renewable energy sources for fuel production is the most important factor, whereas the lack of knowledge and expertise was determined to be the least important.

To provide a better visualization of each expert's weight coefficients, Fig. 6 depicts the weight coefficients by each, as well as global weight coefficients. The global weight coefficients indicate that the potential for GHG reduction (C11), resource competition (C15), compatibility with environmental regulations (C16), and the potential social acceptance of alternative fuels (C31) are the most important factors.

Prioritization of strategies

To prioritize the SWOT strategies against the factors, experts were invited to evaluate the performance of the developed strategies in addressing the factors using T2NN–TOPSIS. For this purpose, a questionnaire was used to collect the required input data using the T2NN scale in Table 3.

Table 9 presents the collected data from experts in a consolidated form with each cell representing the performance scores provided by all five experts. As all experts were considered to be of equal importance, an aggregated decision matrix was constructed (Table 10) using the T2NN score values. Later, an aggregated decision matrix was normalized (Table 11). Using the weight coefficients calculated by the BWM, a weighted decision matrix was constructed and is shown in Table 12. The final results of T2NN–TOPSIS are presented in Table 13.

According to the results, reducing the competitiveness of fossil fuels through increased prices, the introduction

Table 4 BWM results for the main categories

Experts	Criterion		C1	C2	C3	C4
E1	Best	C1	1	3	5	4
	Worst	C3	5	3	1	4
E2	Best	C1	1	7	5	9
	Worst	C4	9	5	7	1
E3	Best	C2	4	1	9	6
	Worst	C3	6	9	1	4
E4	Best	C1	1	3	4	3
	Worst	C3	4	2	1	2
E5	Best	C1	1	4	2	4
	Worst	C4	9	4	8	1
Weight			0.47	0.26	0.15	0.12

of inconveniences, and increasing the competitiveness of alternative fuels through monetary and non-monetary incentives, were determined to be the top four most effective strategies for the transition to a sustainable transport sector in Germany. On the other hand, initiating public campaigns for highlighting the necessity of alternative fuels for mitigating climate change challenges was determined to be the least preferred and most ineffective strategy in our case study.

Sensitivity analysis: managerial insights

An important contribution of this study was the development of a sustainability framework to evaluate and prioritize strategies for transitioning to sustainable transport and achieving GHG-neutrality. The categorization of the SWOT factors into economic and regulatory, environmental, social and technical groupings enabled experts to have a broad and improved understanding of the suitability of the developed strategies. In this context, the final prioritization order of transition strategies was also affected by the weight coefficients of the SWOT factors. For this purpose, a managerial sensitivity analysis was conducted to measure the effects of possible changes in the weight coefficient of the SWOT factors and the developed strategies in each category.

Figure 7 illustrates the different ranking orders of the strategies based on the initial results and individual criteria categories. According to the results, strategy A7 had the best performance in the economic and environmental category. However, A7 exhibited slightly lower performance in the technical and social categories, ranking second and third, respectively. In both categories, A8 was selected as the best-performing strategy. Unlike A8, A6 only performed well in the environmental category, as its ranking dropped to fourth place in the economic category, fifth in the social category, and sixth in the technical category. A7's best performance in the initial results could be attributed to the high weight coefficients of economic and environmental categories. On the other hand, although A2 was ranked as the fifth strategy in the initial results, it showed the best performance in the technical category by placing it in the second position. Ranked as the least effective strategy in the initial results, A5 performed better in the social category. This improvement was due to A5's focus on a social campaign around alternative fuels and climate change challenges. The remaining differences in the ranking orders of the strategies under various categories are represented in Fig. 7.

Comparative analysis: methodological insights

A comparative analysis was conducted to compare the results of the applied approach with T2NN–WASPAS [79], T2NN–CODAS [80], and T2NN–MARCOS [48] to measure the reliability of the generated results to find the most effective strategy for the sustainable transition in the transport sector. The ranking order of strategies in all the methods is illustrated in Fig. 8. According to the results, T2NN–TOPSIS has full consistency with the other methods in choosing A7 as the best strategy. In terms of the second and third strategies, all methods yield consistent results except for T2NN–WASPAS. The ranking order of A1, A2, and A3 remain the same for all methods. A slight difference can be observed in the ranking order of A4 and A5 for T2NN–MARCOS. Moreover, ranking the similarity of the proposed approach with other methods was investigated using Spearman's rank correlation coefficient. The findings indicate that T2NN–TOPSIS has a 97% correlation with T2NN–WASPAS and T2NN–MARCOS, and a 100% correlation with T2NN–CODAS.

Table 5 BWM input and results for the environmental category

DM	Criterion		C11	C12	C13	C14	C15	C16
E1	Best	C11	1	4	4	2	2	2
	Worst	C14	5	3	2	1	2	3
E2	Best	C11	1	2	3	5	3	3
	Worst	C14	9	9	3	1	5	7
E3	Best	C15	4	5	9	3	1	7
	Worst	C13	5	4	1	7	9	3
E4	Best	C11	1	9	4	3	3	4
	Worst	C12	9	1	6	7	7	6
E5	Best	C15	2	3	5	2	1	1
	Worst	C13	6	4	1	6	6	5
Local weight			0.26	0.12	0.09	0.13	0.25	0.16
Global weight			0.12	0.05	0.04	0.06	0.12	0.08

Table 6 BWM input and results for the economic category

DM	Criterion		C21	C22	C23	C24	C25	C26
E1	Best	C22	2	1	3	2	2	2
	Worst	C23	2	2	1	2	2	2
E2	Best	C21	1	9	7	7	7	5
	Worst	C22	9	1	5	5	5	5
E3	Best	C21	1	3	5	6	9	7
	Worst	C25	9	7	5	3	3	2
E4	Best	C22	2	1	5	2	3	4
	Worst	C23	6	7	1	6	5	4
E5	Best	C24	2	6	6	1	6	8
	Worst	C26	6	2	2	7	3	1
Local weight			0.30	0.19	0.09	0.20	0.11	0.11
Global weight			0.08	0.05	0.02	0.05	0.03	0.03

Table 7 BWM input and results for the social category

DM	Criterion		C31	C32	C33
E1	Best	C31	1	2	2
	Worst	C32	2	1	2
E2	Best	C31	1	9	5
	Worst	C32	9	1	5
E3	Best	C32	5	1	9
	Worst	C33	4	9	1
E4	Best	C31	1	5	2
	Worst	C32	5	1	3
E5	Best	C31	1	6	3
	Worst	C32	6	1	6
Local weight			0.54	0.24	0.21
Global weight			0.08	0.04	0.03

Discussion

Alternative fuels in transport

With global emissions rising and the effects of climate change becoming ever more apparent, governments are implementing serious plans for achieving GHG reduction targets. As discussed earlier, Germany has been following various plans for achieving sustainability and reducing GHG emissions. The transport sector is now being given higher priority considering the failure to meet previous targets. The new German government in 2021, in alignment with the goals of the Fit for 55 package, has reflected serious attention to improve policy support for defossilizing the transport sector.

In accordance with the need to move from fossil fuels to alternative ones, Germany has paved the way to defossilizing its transport sector. According to the European Alternative Fuels Observatory, by the end of 2023, Germany had registered 3,055,625 alternative fuel vehicles,

Table 8 BWM input and results for the technical category

DM	Criterion		C41	C42	C43	C44
E1	Best	C42	2	1	2	3
	Worst	C44	3	3	2	1
E2	Best	C42	5	1	5	9
	Worst	C44	9	5	5	1
E3	Best	C42	6	1	9	3
	Worst	C43	4	9	1	6
E4	Best	C41	1	3	7	8
	Worst	C44	9	8	2	1
E5	Best	C42	4	1	3	5
	Worst	C44	3	9	6	1
Local weight			0.26	0.47	0.16	0.10
Global weight			0.03	0.06	0.02	0.01

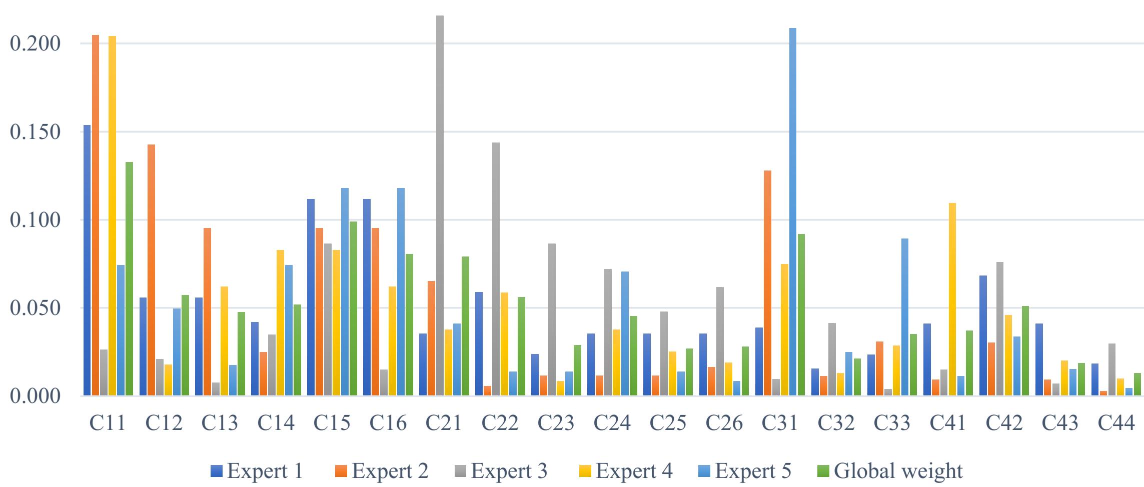

Fig. 6 Weight coefficients of the identified factors

accounting for 5.6% of the total vehicle fleet for the same year.

Figure 9a displays the trends in alternative fuels-based passenger vehicles in Germany. The number of battery–electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) in use by passenger vehicle owners has risen significantly since 2019. By 2024, there were over 1.5 million BEVs and more than 1 million PHEVs on the road. This surge is a clear indication of a significant and rapid shift towards electric transport, driven by government incentives, improved charging infrastructure, and growing consumer awareness about environmental sustainability. Conversely, other alternative fuels such as hydrogen, liquefied petroleum gas (LPG), and compressed natural gas (CNG), showed modest growth or decline. LPG maintains a steady presence but has not expanded significantly, mainly due to infrastructure challenges, higher costs, and lower consumer acceptance.

For heavy-duty trucks, the trend is almost similar but on a smaller scale (Fig. 9b). The number of BEVs for trucks increased significantly in 2024, followed by a gradual growth in PHEVs and CNG vehicles. The adoption of hydrogen and liquefied natural gas (LNG) trucks is still in its infancy, with minimal uptake to date. The slower rate of adoption in the trucking sector can be attributed to the higher initial costs, limited range, and the necessity for more extensive refuelling infrastructure.

Germany is encouraging the use of alternative fuel vehicles through incentives and laws. Amongst these, a prominent initiative is the 10-year tax exemption for BEVs, and fuel cell–electric vehicles (FCEVs) registered until December 31, 2025, which was later extended until the end of 2030. This long-term tax relief benefits consumers

Table 9 Initial expert decision matrix

	C11	C12	C13	C14	C15	C16	C21	C22	C23	C24
A1	L,M,VL,AL,L	ML,M,ML,AL,L	M,M,M,AL,ML	VL,M,AH,AL,ML	VL,L,H,AL,L	VL,M,MH,H,M	M,L,ML,AL,L	M,M,ML,M,M	VL,M,H,AL,ML	VL,M,H,MH,M
A2	L,H,H,M,M	L,M,M,M,ML	L,M,ML,M,ML	L,L,H,M,ML	L,L,L,M,L	VL,ML,ML,AL,L	M,M,ML,M,M	L,M,L,M,ML	L,M,ML,VL,L	L,L,M,AL,L
A3	VL,H,H,H,MH	VL,H,M,H,M	L,H,ML,H,M	AL,M,ML,VL,L	AL,M,MH,VL,ML	AL,M,AH,AL,ML	AL,M,L,VL,L	AL,M,VL,H,ML	AL,H,M,VL,ML	AL,M,L,VL,L
A4	MH,M,VL,VH,MH	MH,L,ML,L,ML	AL,M,L,L,L	VL,M,M,H,M	VL,M,AH,H,MH	AL,M,L,AL,VL	AL,M,M,H,M	ML,M,MH,H,M	VL,L,ML,AL,L	VL,L,VH,VL,ML
A5	VL,M,MH,AL,L	VL,M,L,AL,L	ML,M,M,AL,ML	AL,M,VH,AL,ML	AL,M,H,AL,L	VL,M,H,AL,ML	VL,M,ML,AL,L	L,M,H,MH,M	VL,L,M,AL,L	AL,M,ML,AL,L
A6	ML,M,ML,H,M	ML,M,M,H,M	ML,M,MH,H,M	AL,M,M,H,ML	AL,M,ML,H,ML	AL,L,VH,VL,L	VL,M,L,MH,ML	AL,M,VL,H,ML	AL,M,VL,H,ML	AL,M,M,H,ML
A7	L,H,H,H,MH	VL,H,M,H,M	ML,H,ML,H,M	AL,L,M,H,ML	AL,L,ML,H,ML	AL,L,H,H,M	L,M,ML,H,M	L,M,MH,H,M	AL,L,H,H,ML	AL,M,L,H,ML
A8	ML,H,ML,H,M	VL,H,L,ML,ML	ML,H,M,H,MH	AL,M,AH,M,M	AL,M,VH,M,M	AL,M,L,AL,VL	AL,H,MH,H,M	VL,L,MH,H,ML	AL,L,ML,MH,L	AL,M,M,H,M

	C25	C26	C31	C32	C33	C41	C42	C43	C44
A1	VL,M,MH,MH,M	VL,M,VH,L,ML	M,M,H,H,MH	M,M,MH,M,M	ML,L,MH,H,M	ML,M,AH,AL,M	L,M,M,AL,L	MH,H,M,H,MH	MH,M,M,H,MH
A2	L,ML,MH,AL,L	VL,ML,AH,AL,ML	MH,H,MH,AH,H	ML,L,H,VH,M	L,M,L,M,ML	MH,ML,H,AH,H	ML,ML,VH,H,MH	VL,ML,M,AL,L	VL,L,M,AL,L
A3	AL,M,AL,H,ML	AL,M,H,VL,ML	L,H,MH,H,MH	AL,H,AL,H,ML	AL,H,ML,VL,ML	AL,M,H,H,M	AL,M,MH,VL,L	AL,M,L,AL,L	AL,M,VH,AL,ML
A4	VL,L,MH,VL,L	VL,L,M,VL,L	AL,M,M,H,ML	AL,M,MH,H,M	ML,M,MH,H,MH	L,L,AL,VL,VL	ML,L,VL,H,ML	AL,M,ML,AL,L	AL,L,H,AL,L
A5	AL,L,M,AL,VL	AL,M,MH,MH,ML	ML,M,H,H,MH	VL,L,MH,H,ML	VL,M,MH,AL,ML	L,M,M,AL,L	AL,M,L,AL,VL	L,M,L,AL,L	L,L,AH,AL,ML
A6	AL,M,L,H,ML	AL,M,H,L,ML	VL,M,MH,H,M	AL,L,L,H,L	VL,M,H,H,M	AL,M,M,VL,L	AL,M,MH,VL,L	AL,M,AH,VL,ML	AL,M,ML,VL,L
A7	L,M,MH,H,M	AL,M,M,VL,L	ML,L,L,H,ML	L,L,MH,H,M	VL,M,L,H,ML	L,M,MH,VL,ML	VL,M,AH,VL,ML	L,M,VH,VL,ML	AL,L,VH,AL,L
A8	AL,M,H,H,M	AL,M,ML,VL,L	ML,L,AL,MH,L	AL,M,VH,MH,M	VL,H,H,VL,ML	AL,L,ML,AL,VL	AL,M,MH,AL,L	VL,M,M,AL,L	AL,M,M,AL,L

Table 10 Aggregated decision matrix

	C11	C12	C13	C14	C15	C16	C21	C22	C23	C24	C25	C26	C31	C32	C33	C41	C42	C43	C44
A1	0.734	0.769	0.786	0.802	0.765	0.820	0.758	0.810	0.788	0.820	0.803	0.810	0.856	0.817	0.824	0.821	0.760	0.859	0.841
A2	0.843	0.798	0.795	0.808	0.757	0.747	0.810	0.786	0.763	0.743	0.766	0.799	0.886	0.848	0.786	0.881	0.858	0.750	0.734
A3	0.859	0.836	0.840	0.750	0.771	0.797	0.734	0.788	0.788	0.734	0.783	0.788	0.850	0.805	0.785	0.832	0.761	0.728	0.792
A4	0.832	0.788	0.743	0.816	0.851	0.719	0.811	0.834	0.732	0.790	0.752	0.739	0.808	0.815	0.837	0.700	0.798	0.744	0.759
A5	0.761	0.734	0.782	0.792	0.773	0.788	0.750	0.827	0.734	0.744	0.719	0.795	0.853	0.806	0.771	0.760	0.719	0.743	0.798
A6	0.827	0.830	0.834	0.808	0.804	0.775	0.784	0.788	0.788	0.808	0.796	0.796	0.820	0.773	0.836	0.752	0.761	0.802	0.750
A7	0.865	0.836	0.847	0.796	0.793	0.821	0.820	0.827	0.817	0.796	0.827	0.752	0.805	0.816	0.801	0.784	0.807	0.810	0.770
A8	0.847	0.798	0.853	0.824	0.820	0.719	0.835	0.806	0.766	0.811	0.832	0.750	0.766	0.824	0.815	0.717	0.756	0.752	0.746

Table 11 Normalized decision matrix

	C11	C12	C13	C14	C15	C16	C21	C22	C23	C24	C25	C26	C31	C32	C33	C41	C42	C43	C44
A1	0.316	0.340	0.343	0.355	0.341	0.375	0.340	0.354	0.361	0.371	0.362	0.368	0.364	0.355	0.361	0.371	0.345	0.392	0.384
A2	0.363	0.353	0.347	0.357	0.338	0.341	0.363	0.344	0.349	0.336	0.345	0.363	0.377	0.369	0.344	0.398	0.390	0.342	0.335
A3	0.369	0.370	0.366	0.331	0.344	0.364	0.329	0.345	0.361	0.332	0.353	0.358	0.361	0.350	0.344	0.376	0.346	0.332	0.362
A4	0.358	0.349	0.324	0.361	0.380	0.328	0.364	0.365	0.335	0.358	0.338	0.335	0.344	0.354	0.367	0.316	0.362	0.340	0.347
A5	0.327	0.325	0.341	0.350	0.345	0.360	0.336	0.362	0.336	0.337	0.323	0.361	0.363	0.350	0.338	0.343	0.326	0.339	0.364
A6	0.356	0.367	0.364	0.357	0.359	0.354	0.352	0.345	0.361	0.366	0.358	0.361	0.349	0.336	0.366	0.340	0.346	0.366	0.342
A7	0.372	0.370	0.369	0.352	0.354	0.375	0.368	0.362	0.374	0.360	0.372	0.341	0.343	0.355	0.351	0.354	0.367	0.370	0.352
A8	0.364	0.353	0.372	0.364	0.366	0.328	0.375	0.352	0.351	0.367	0.374	0.340	0.326	0.358	0.357	0.324	0.343	0.343	0.341

Table 12 Weighted decision matrix

	C11	C12	C13	C14	C15	C16	C21	C22	C23	C24	C25	C26	C31	C32	C33	C41	C42	C43	C44
A1	0.042	0.020	0.016	0.028	0.012	0.021	0.010	0.033	0.008	0.019	0.036	0.017	0.010	0.010	0.013	0.019	0.006	0.032	0.005
A2	0.048	0.020	0.017	0.028	0.012	0.019	0.010	0.032	0.007	0.017	0.034	0.017	0.010	0.010	0.013	0.020	0.007	0.028	0.004
A3	0.049	0.021	0.017	0.026	0.012	0.020	0.009	0.032	0.008	0.017	0.035	0.016	0.010	0.010	0.013	0.019	0.006	0.027	0.005
A4	0.047	0.020	0.015	0.029	0.013	0.018	0.010	0.034	0.007	0.019	0.033	0.015	0.009	0.010	0.014	0.016	0.007	0.027	0.005
A5	0.043	0.019	0.016	0.028	0.012	0.020	0.010	0.033	0.007	0.017	0.032	0.016	0.010	0.010	0.013	0.018	0.006	0.027	0.005
A6	0.047	0.021	0.017	0.028	0.013	0.020	0.010	0.032	0.008	0.019	0.035	0.016	0.009	0.009	0.014	0.017	0.006	0.029	0.004
A7	0.049	0.021	0.018	0.028	0.012	0.021	0.011	0.033	0.008	0.019	0.037	0.016	0.009	0.010	0.013	0.018	0.007	0.030	0.005
A8	0.048	0.020	0.018	0.029	0.013	0.018	0.011	0.032	0.007	0.019	0.037	0.015	0.009	0.010	0.013	0.017	0.006	0.028	0.004

Table 13 Prioritization of the proposed strategies

Strategies	S_i^*	S_i'	CC_i	Rank
A1	0.008	0.009	0.488	6
A2	0.009	0.006	0.611	5
A3	0.009	0.006	0.609	4
A4	0.007	0.008	0.487	7
A5	0.004	0.010	0.292	8
A6	0.009	0.005	0.630	2
A7	0.011	0.003	0.780	1
A8	0.010	0.006	0.621	3

who choose alternative fuel vehicles. Additionally, there was a significant reduction in company car tax for BEVs and PHEVs, making them more attractive for corporate fleets. The purchase subsidies for EVs ended on January 1st, 2024. Nonetheless, the government upholds its interest in further developing the required infrastructure for alternative fuel vehicles. Substantial investments are directed towards the expansion of charging stations and other essential facilities to ensure that the transition to electric transport is as seamless as possible. Germany invests €130 billion in alternative fuels infrastructure. Local incentives are also part of the plan, focusing on

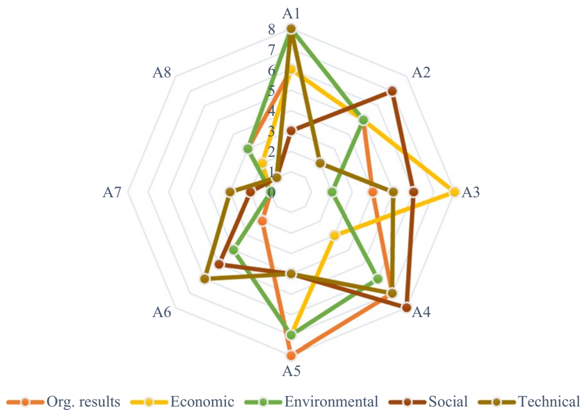

Fig. 7 Sensitivity analysis of the strategies' performance in each category

companies and municipalities. These incentives take forms such as grants and rebates, and encourage the adoption of alternative fuels and related technologies. The objective is to create a comprehensive network that supports the widespread use of environmentally friendly vehicles.

In aviation and maritime contexts, legislation for regulating incentives is currently quite vague, as the existing policies for these sectors (FuelEU Maritime, ReFuelEU Aviation, EU Hydrogen Strategy, National Hydrogen Strategy, and PtL Roadmap) mainly focus on defining the quota for different alternative fuels. The primary incentive programs within these policies focus on promoting R&D projects affecting the production of alternative fuels, with a particular emphasis on PtX technologies and advanced biofuels.

Managerial implications

The results showed that reducing the competitiveness of fossil fuels through increased prices (A7) was assessed by experts to be the most important and effective strategy for moving towards GHG-neutrality in the transport sector. The Federal Environmental Agency concluded that an increase in CO_2 prices would not lead to significant reductions for the 2030 target. Prices over 200€/ton were recommended for aiming toward the 2030 and further targets [82]. Conversely, reducing subsidies for fossil fuels and their derivatives can facilitate the transition to alternative fuels by increasing the prices of fossil fuels. In the same context, increasing the competitiveness of alternative fuels through monetary incentives (A8) was ranked as the second-best strategy. Currently, strong attention is given to EVs by the government, as well as by large automotive manufacturing companies.

Reducing the competitiveness of fossil fuels through increased inconveniences (A6) has received comparatively little consideration by the federal government of Germany. Although some cities have implemented specific driving restrictions for vehicles with very high emissions, these measures are fairly rare and typically do not focus exclusively on CO_2 emissions and rather concern older vehicles.

The development of better infrastructure for the use of alternative fuels (A2) is another important strategy for

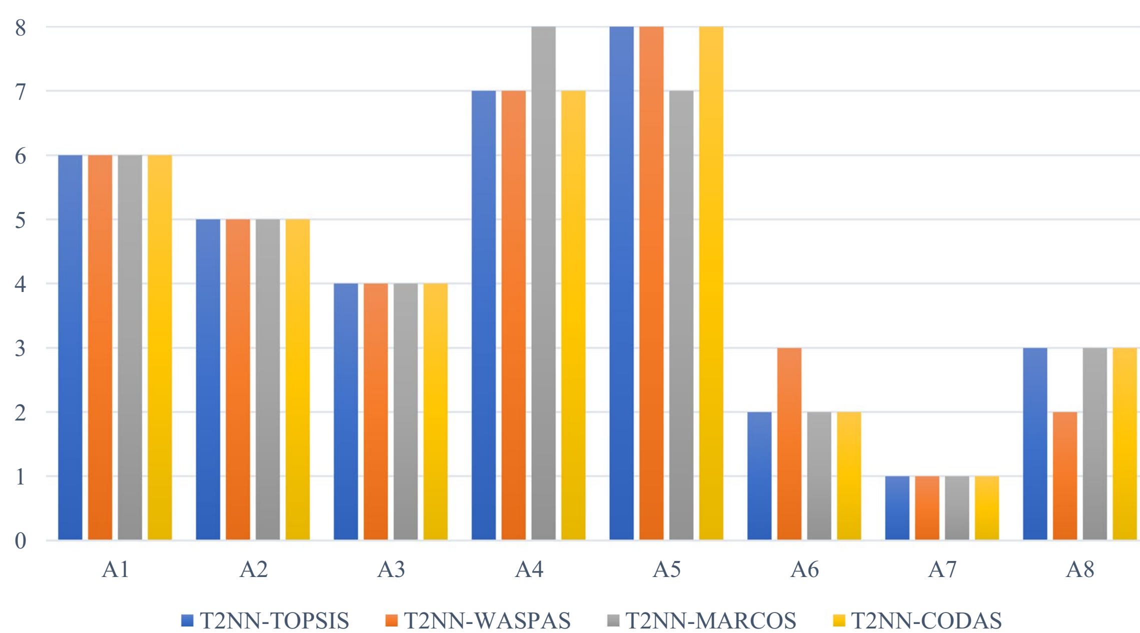

Fig. 8 Sensitivity analysis of T2NN-based methods

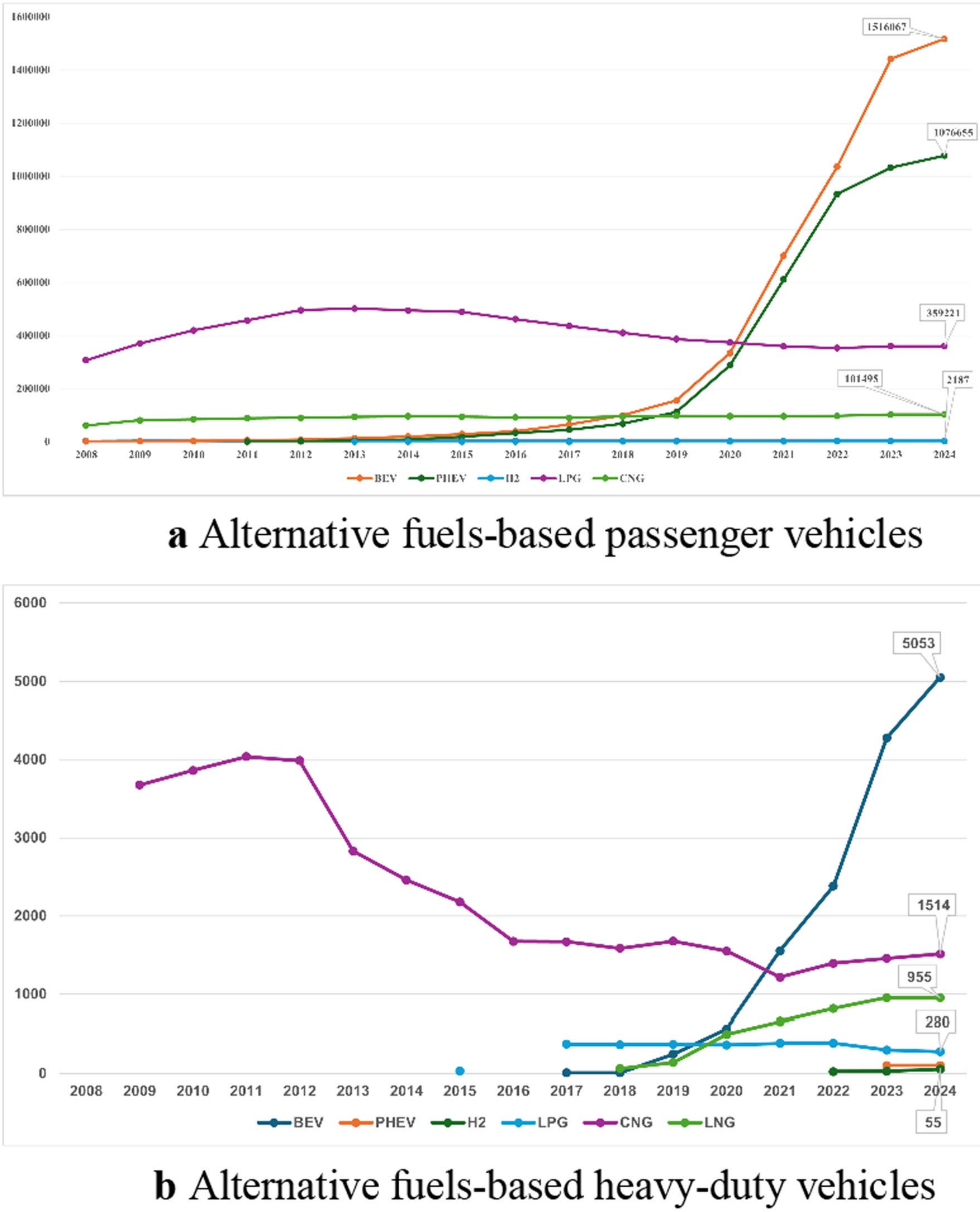

Fig. 9 Alternative fuels-based vehicles in Germany [81]

improving Germany's performance in mitigating GHG emissions in the transport sector. The Federal Transport Infrastructure Plan (FTIP) 2030 allocates €269.6 billion for transport infrastructure in Germany. Of this, €226.7 billion is designated for the maintenance of existing infrastructure, whereas only €42.8 billion will be used for developing new infrastructures. Another important aspect is the allocation of financial resources within different transport modes, where road infrastructures are obtaining the largest share with 49.3%. The new government stated that there will be updates on FTIP budget allocation with more investments into the rail infrastructure. Another illustration of the slow transition is that of train companies in the rail transport sector. In 2021, 61% of all power used by Deutsche Bahn (the state-owned train company) was renewably generated [83]. However, the current government is aiming for a target of 75% electrification in the rail industry by 2030 [16], whereas Deutsche Bahn aims to reach 100% electrification of all its fleets by 2038 [83]. According to the European Alternative Fuels Observatory, a total of 120,612 EV charging points (AC and DC) were available in Germany by 2023. The new government aims to increase this number to one million by 2030. Moreover, the refuelling stations for LPG, CNG, LNG, and hydrogen-fuelled vehicles were 5,888, 710, 172, and 106, respectively, by the end of 2030. There will likely be an increase in hydrogen refuelling stations due to a regulatory focus by Germany and the EU in the coming years. However, this change will primarily impact the maritime and aviation sectors.

Conclusions

This study conducted a multi-criteria approach to developing and evaluating strategies for addressing GHG emission and climate change challenges within the German transport sector. As fossil fuels are the main source of GHG emissions, a sustainable transition in the sector requires very accurate and careful strategies for replacing them with sustainable and clean fuels such as alternative fuels. In this regard, the current study followed important objectives to investigate and understand the current status of the transport sector using a SWOT analysis. The SWOT analysis was used for defining key factors under the SWOT themes to develop proper strategies for defossilization. For this purpose, eight strategies were developed considering the role of fossil and alternative fuels. The final goal was to prioritize the developed strategies for implementation in the German transport sector based on stakeholders' preferences.

A multi-criteria approach using SWOT, BWM, and TOPSIS was developed to address the problem. In the first stage, SWOT was used to identify relevant factors and accordingly develop strategies for the sustainable transition considering fossil and alternative fuels. Through the consultation of a panel of experts, the BWM was used to determine the weight coefficients of the identified factors via the SWOT analysis. In the second stage, TOPSIS was applied to prioritize the developed strategies. A sensitivity analysis was then conducted to measure the effects of various modifications to the result and ranking orders of strategies under different categories of factors.

The results indicate that reducing the competitiveness of fossil fuels through increased prices, increasing the competitiveness of alternative fuels through monetary incentives, decreasing the competitiveness from fossil fuels through increased inconveniences by the reduction of refuelling stations, establishing prohibited zones for fossil fuel-based vehicles, and developing better infrastructure for the use of alternative fuels, are the four top strategies for the sustainable transition in Germany's transport sector for achieving GHG-neutrality by 2045.

There are also limitations to the current study. As climate change challenges are interconnected with many aspects of our collective future, proposing strategies regarding transport and other connected sectors is of high importance for policymakers. Moreover, the dynamics of policies, regulations and targets show how important it is to update strategies to become aligned with national and EU targets. Therefore, a scenario-based approach that considers different future scenarios or different years can provide more insightful results. Another limitation of this study is its expert panel, which includes five experts; thus, a future approach could be to conduct the multi-expert study with a higher number of experts from different stakeholder groups including, politics, the automotive industry, environmental organizations, fuel producers, and the public. Another potentially fruitful avenue would be to apply the SWOT analysis with a focus on different renewable fuels in Germany or the EU.

Acknowledgements

The authors would like to thank Katharina Böhm and Jakob Rohner for their valuable support throughout the publication process.

Author contributions

Conceptualization, FCV and AET; methodology, FCV; Calculations, FCV; Figure, FCV; writing—original draft and writing—review, FCV, AET, SV. All authors read and approved the final manuscript.

Funding

Open Access funding enabled and organized by Projekt DEAL. Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany´s Excellence Strategy—Cluster of Excellence 2186 "The Fuel Science Center"—ID: 390919832.

Availability of data and materials

All data generated or analysed during this study are included in this published article.

Declarations

Ethics approval and consent to participate

The authors declare that they have adhered to the ethical standards of research.

Consent for publication

The authors declare their consent for publication.

Competing interests

The authors declare no competing interests.

Received: 17 January 2024 Accepted: 26 November 2024
Published online: 20 January 2025

References

1. Shao S et al (2022) Balancing the GHG emissions and operational costs for a mixed fleet of electric buses and diesel buses. Appl Energy 328:120188
2. Chen H et al (2022) Towards renewable public transport: Mining the performance of electric buses using solar-radiation as an auxiliary power source. Appl Energy 325:119863
3. Tan Z et al (2023) Sustainable urban mobility: Flexible bus service network design in the post-pandemic era. Sustain Cities Soc 97:104702
4. Eurostat (2022) Number of enterprises in the transportation and storage industry in the European Union (EU-28) from 2011 to 2019 (in millions). https://www.statista.com/statistics/1175515/enterprises-transportation-storage-industry-european-union/
5. Bundesamt K (2021) Pressemitteilung Nr. 08/2021: Der Fahrzeugbestand am 1. Januar 2021. https://www.kba.de/DE/Presse/Pressemitteilungen/Fahrzeugbestand/2021/pm08_fz_bestand_pm_komplett.html
6. Prussi M et al (2021) Potential and limiting factors in the use of alternative fuels in the European maritime sector. J Clean Prod 291:125849
7. Koalitionsvereinbarung (1998) Koalitionsvereinbarung zwischen der Sozialdemokratischen Partei Deutschlands und Bündnis 90/Die GRÜNEN - Aufbruch und Erneuerung- Deutschlands Weg ins 21. Jahrhundert. https://www.spd.de/fileadmin/Dokumente/Beschluesse/Bundesparteitag/koalitionsvertrag_bundesparteitag_bonn_1998.pdf
8. Koalitionsvertrag (2005) Koalitionsvertrag von CDU, CSU und SPD: Gemeinsam für Deutschland. Mit Mut und Menschlichkeit. https://archiv.cdu.de/artikel/gemeinsam-fuer-deutschland-mit-mut-und-menschlichkeit-koalitionsvertrag-2005
9. Koalitionsvertrag (2009) Koalitionsvertrag zwischen CDU, CSU und FDP: WACHSTUM. BILDUNG. ZUSAMMENHALT. https://www.kas.de/c/document_library/get_file?uuid=83dbb842-b2f7-bf99-6180-e65b2de7b4d4&groupId=252038
10. Koalitionsvertrag (2013) Koalitionsvertrag von CDU, CSU und SPD: Deutschlands Zukunft gestalten. https://www.cdu.de/sites/default/files/media/dokumente/koalitionsvertrag.pdf
11. Koalitionsvertrag (2018) Koalitionsvertrag von CDU, CSU und SPD: Ein neuer Aufbruch für Europa-Eine neue Dynamik für Deutschland-Ein neuer Zusammenhalt für unser Land. https://www.bundesregierung.de/resource/blob/974430/847984/5b8bc23590d4cb2892b31c987ad672b7/2018-03-14-koalitionsvertrag-data.pdf?download=1
12. Bundes-Klimaschutzgesetz (2019) https://www.gesetze-im-internet.de/ksg/BJNR251310019.html
13. Bundesverfassungsgericht (2021) Verfassungsbeschwerden gegen das Klimaschutzgesetz teilweise erfolgreich. https://www.bundesverfassungsgericht.de/SharedDocs/Pressemitteilungen/DE/2021/bvg21-031.html
14. Bundes-Klimaschutzgesetz (2021) Lesefassung des Bundes-Klimaschutzgesetzes 2021 mit markierten Änderungen zur Fassung von 2019. https://www.bmu.de/fileadmin/Daten_BMU/Download_PDF/Klimaschutz/ksg_aendg_2021_bf.pdf
15. Bundesministerium für Umwelt, Naturschutz, Nukleare Sicherheit und Verbraucherschutz (2021) https://www.bmu.de/fileadmin/Daten_BMU/Download_PDF/Klimaschutz/projektionsbericht_2021_bf.pdf
16. Koalitionsvertrag (2021) KOALITIONSVERTRAG ZWISCHEN SPD, BÜNDNIS 90/DIE GRÜNEN UND FDP: MEHR FORTSCHRITT WAGEN. https://www.bundesregierung.de/resource/blob/974430/1990812/04221173eef9a6720059cc353d759a2b/2021-12-10-koav2021-data.pdf?download=1
17. Reichenbach M, Fleischer T (2023) From ambition to implementation: institutionalisation as a key challenge for a sustainable mobility transition in Germany. Energy Sustain Soc 13(1):14
18. European Commission (2020) Sustainable and Smart Mobility Strategy – putting European transport on track for the future. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0789&from=EN
19. Council of the European Union. Fit for 55. https://www.consilium.europa.eu/policies/fit-for-55/
20. Torkayesh AE et al (2024) Fueling the future: Overcoming the barriers to market development of renewable fuels in Germany using a novel analytical approach. Eur J Oper Res 78:8
21. Gündoğdu HG et al (2023) Environmental, social, and governance risks and environmentally sensitive competitive strategies: A case study of a multinational logistics company. Bus Strateg Environ 89:7
22. Hendiani S, Walther G (2023) Sustainability performance evaluation of renewable energy systems using a new multi-expert multi-criteria interval type-2 fuzzy distance to ideal solution approach. Appl Energy 347:121436
23. Zarbakhshnia N et al (2023) Outsourcing logistics operations in circular economy towards sustainable development goals. Bus Strateg Environ 32(1):134–162
24. Saaty TL (1988) What is the analytic hierarchy process? In: Mathematical models for decision support. Springer, p. 109–121.
25. Saaty TL (2004) Decision making—the analytic hierarchy and network processes (AHP/ANP). J Syst Sci Syst Eng 13(1):1–35
26. Zavadskas EK et al (2007) Multi-attribute assessment of road design solutions by using the COPRAS method. Balt J Road Bridge Eng 2(4):195–203
27. Hwang CL, et al (1981) Methods for multiple attribute decision making. In: Multiple attribute decision making: methods and applications a state-of-the-art survey, p. 58–191
28. Brauers WK, Zavadskas EK (2006) The MOORA method and its application to privatization in a transition economy. Control Cybern 35(2):445–469
29. Nassereddine M, Eskandari H (2017) An integrated MCDM approach to evaluate public transportation systems in Tehran. Transp Res Part A: Policy Pract 106:427–439
30. Erdogan S, Sayin C (2018) Selection of the most suitable alternative fuel depending on the fuel characteristics and price by the hybrid MCDM method. Sustainability 10(5):1583
31. Trinh TA, Le TPL (2018) Biofuels potential for transportation fuels in Vietnam: A status Quo and SWOT analysis. In: IOP Conf. Ser.: Earth Environ. Sci. IOP Publishing
32. de Aquino JT et al (2019) Evaluation of quality in public transport services: the use of quality dimensions as an input for fuzzy TOPSIS. Int J Fuzzy Syst 21(1):176–193
33. Kheybari S, Rezaie FM, Rezaei J (2019) Measuring the importance of decision-making criteria in biofuel production technology selection. IEEE Trans Eng Manag 68(2):483–497
34. D'Adamo I et al (2020) RES-T trajectories and an integrated SWOT-AHP analysis for biomethane, Policy implications to support a green revolution in European transport. Energy Policy 138:111220
35. Kowalska-Pyzalska A, Kott J, Kott M (2020) Why Polish market of alternative fuel vehicles (AFVs) is the smallest in Europe? SWOT analysis of opportunities and threats. Renew Sustain Energy Rev 133:110076
36. Bouraima MB et al (2020) A study on the development strategy of the railway transportation system in the West African Economic and Monetary Union (WAEMU) based on the SWOT/AHP technique. Sci Afr. 8:12
37. Elavarasan RM et al (2020) SWOT analysis: A framework for comprehensive evaluation of drivers and barriers for renewable energy development in significant countries. Energy Rep 6:1838–1864
38. Ul-Haq A et al (2020) Electric transportation in Pakistan under CPEC project: Technical framework and policy implications. IEEE Access 8:162394–162420
39. Uhunamure SE, Shale K (2021) A SWOT Analysis approach for a sustainable transition to renewable energy in South Africa. Sustainability 13(7):3933
40. Mostafaeipour A et al (2021) A thorough analysis of renewable hydrogen projects development in Uzbekistan using MCDM methods. Int J Hydrog Energy 46(61):31174–31190
41. Almutairi K et al (2021) Technical, economic, carbon footprint assessment, and prioritizing stations for hydrogen production using wind energy: A case study. Energy Strateg Rev 36:100684
42. Al-Haidous S et al (2021) Evaluating LNG Supply Chain Resilience Using SWOT Analysis: The Case of Qatar. Energies 15(1):79
43. Ecer F (2021) A consolidated MCDM framework for performance assessment of battery electric vehicles based on ranking strategies. Renew Sustain Energy Rev 143:110916
44. Narwane VS et al (2021) Sustainable development challenges of the biofuel industry in India based on integrated MCDM approach. Renew Energy 164:298–309
45. Abdel-Basset M et al (2021) Evaluation of sustainable hydrogen production options using an advanced hybrid MCDM approach: A case study. Int J Hydrog Energy 46(5):4567–4591
46. Chai N, Zhou W (2022) A novel hybrid MCDM approach for selecting sustainable alternative aviation fuels in supply chain management. Fuel 327:125180

47. Mehta AV, Mehta NS (2022) Extraction of algae biodiesel for power generation and comparison of sustainable fuels using MCDM. Int J Ambient Energy 43(1):3106–3116
48. Simic V, Gokasar I, Deveci M, Švadlenka L (2022) Mitigating Climate Change Effects of Urban Transportation Using a Type-2 Neutrosophic MEREC-MARCOS Model. IEEE Trans Eng Manag 67:7
49. Jusakulvijit P, Bezama A, Thrän D (2021) Criteria prioritization for the sustainable development of second-generation bioethanol in Thailand using the Delphi-AHP technique. Energy Sustain Soc 11:1–25
50. Wang M et al (2024) Regional bioethanol supply chain optimization with the integration of GIS-MCDM method and quantile-based scenario analysis. J Environ Manag 351:119883
51. Rahimirad Z, Sadabadi AA (2023) Green hydrogen technology development and usage policymaking in Iran using SWOT analysis and MCDM methods. Int J Hydrog Energy 48(40):15179–15194
52. Sun D, Guo D, Xie D (2023) Using multicriteria decision making to evaluate the risk of hydrogen energy storage and transportation in cities. Sustainability 15(2):1088
53. Olabi A et al (2024) Multiple-criteria decision-making for hydrogen production approaches based on economic, social, and environmental impacts. Int J Hydrog Energy 52:854–868
54. Lee J et al (2021) SWOT-AHP analysis of the Korean satellite and space industry: Strategy recommendations for development. Technol Forecast Soc Chang 164:120515
55. Büyüközkan G, Mukul E, Kongar E (2021) Health tourism strategy selection via SWOT analysis and integrated hesitant fuzzy linguistic AHP-MABAC approach. Socio-Econ Plan Sci 74:100929
56. Lin R et al (2019) Towards a sustainable distributed energy system in China: decision-making for strategies and policy implications. Energy Sustain Soc 9:1–25
57. Zincir BA, Zincir B, Arslanoglu Y (2023) SWOT Analysis of Carbon Capture, Storage, and Transportation for Maritime Industry. In: Decarbonization of Maritime Transport, p. 117–140.
58. Longhurst GJ et al (2020) Strength, weakness, opportunity, threat (SWOT) analysis of the adaptations to anatomical education in the United Kingdom and Republic of Ireland in response to the Covid-19 pandemic. Anat Sci Educ 13(3):301–311
59. Rezaei J (2015) Best-worst multi-criteria decision-making method. Omega 53:49–57
60. Salimi N, Rezaei J (2018) Evaluating firms' R&D performance using best worst method. Eval Program Plan 66:147–155
61. Meidute-Kavaliauskiene I et al (2021) An Integrated Approach for Evaluating Lean Innovation Practices in the Pharmaceutical Supply Chain. Logistics 5(4):74
62. Kayikci Y et al (2022) Critical success factors for implementing blockchain-based circular supply chain. Bus Strateg Environ 31(7):3595–3615
63. Gupta H et al (2023) Evaluation of strategies to manage risks in smart, sustainable agri-logistics sector: A Bayesian-based group decision-making approach. Bus Strateg Environ 67:89
64. Kumar P et al (2021) Analyzing challenges for sustainable supply chain of electric vehicle batteries using a hybrid approach of Delphi and Best-Worst Method. Resour Conserv Recycl 175:105879
65. Alsalem M et al (2019) Multiclass benchmarking framework for automated acute leukemia detection and classification based on BWM and group-VIKOR. J Med Syst 43(7):1–32
66. Balezentis T, Siksnelyte-Butkiene I, Streimikiene D (2021) Stakeholder Involvement for sustainable energy development based on uncertain group decision making: Prioritizing the renewable energy heating technologies and the BWM-WASPAS-IN approach. Sustain Cities Soc 73:103114
67. Zarrinpoor N, Khani A (2021) Designing a sustainable biofuel supply chain by considering carbon policies: A case study in Iran. Energy Sustain Soc 11:1–22
68. Torkayesh AE, Malmir B, Asadabadi MR (2021) Sustainable waste disposal technology selection: The stratified best-worst multi-criteria decision-making method. Waste Manag 122:100–112
69. Abdel-Basset M et al (2019) An approach of TOPSIS technique for developing supplier selection with group decision making under type-2 neutrosophic number. Appl Soft Comput 77:438–452
70. Smarandache F (2002) Neutrosophic set–a generalization of the intuitionistic fuzzy set. In: University of New Mexico. Citeseer.
71. Araujo CAS, Wanke P, Siqueira MM (2018) A performance analysis of Brazilian public health: TOPSIS and neural networks application. Int J Product Perform Manag 67:09
72. Norouzi A, Namin HG (2019) A hybrid fuzzy TOPSIS–best worst method for risk prioritization in megaprojects. Civ Eng J 5(6):1257–1272
73. Reshad AI et al (2023) Evaluating barriers and strategies to sustainable supply chain risk management in the context of an emerging economy. Bus Strateg Environ 6:45
74. Nilashi M et al (2019) Factors influencing medical tourism adoption in Malaysia: A DEMATEL-Fuzzy TOPSIS approach. Comput Ind Eng 137:106005
75. Zhang X et al (2018) Evaluation of urban public transport priority performance based on the improved TOPSIS method: A case study of Wuhan. Sustain Cities Soc 43:357–365
76. Hoseinpour M et al (2018) Evaluation of the effect of gasoline fumigation on performance and emission characteristics of a diesel engine fueled with B20 using an experimental investigation and TOPSIS method. Fuel 223:277–285
77. Diemuodeke E, Hamilton S, Addo A (2016) Multi-criteria assessment of hybrid renewable energy systems for Nigeria's coastline communities. Energy Sustain Soc 6:1–12
78. European Environment Agency (2024) EEA greenhouse gases — data viewer. https://www.eea.europa.eu/en/analysis/maps-and-charts/greenhouse-gases-viewer-data-viewers
79. Gokasar I, Deveci M, Kalan O (2022) CO2 Emission based prioritization of bridge maintenance projects using neutrosophic fuzzy sets based decision making approach. Res Transp Econ 91:101029
80. Deveci M, Simic V, Torkayesh AE (2021) Remanufacturing facility location for automotive Lithium-ion batteries: An integrated neutrosophic decision-making model. J Clean Prod 317:128438
81. European Alternative Fuels Observatory (2024) https://alternative-fuels-observatory.ec.europa.eu/transport-mode/road/germany
82. Umweltbundesamt (2021) CO2-Preis im Verkehrssektor. https://www.umweltbundesamt.de/sites/default/files/medien/366/dokumente/uba-kurzpapier_co2-preis_kliv.pdf
83. Bahn D (2022) Get to your destination with renewable power. https://gruen.deutschebahn.com/en/measures/ice

Publisher's Note