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A Multi-Criteria Decision-Making Framework for Zero Emission Vehicle Fleet Renewal Considering Lifecycle and Scenario Uncertainty

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Abstract: In the last decade, with the increased concerns about the global environment, attempts have been made to promote the replacement of fossil fuels with sustainable sources. For transport, which accounts for around a quarter of total greenhouse gas emissions, meeting climate neutrality goals will require replacing existing fleets with electric or hydrogen-propelled vehicles. However, the lack of adequate decision support approach makes the introduction of new propulsion technologies in the transportation sector a complex strategic decision problem where distorted non-optimal decisions may easily result in long-term negative effects on the performance of logistic operators. This research addresses the problem of transport fleet renewal by proposing a multi-criteria decision-making approach and takes into account the multiple propulsion technologies currently available and the objectives of the EU Green Deal, as well as the inherent scenario uncertainty. The proposed approach, based on the TOPSIS model, involves a novel decision framework referred to as a generalized life cycle evaluation of the environmental and cost objectives, which is necessary when comparing green and traditional propulsion systems in a long-term perspective to avoid distorted decisions. Since the objective of the study is to provide a practical methodology to support strategic decisions, the framework proposed has been validated against a practical case referred to the strategic fleet renewal decision process. The results obtained demonstrate how the decision maker's perception of the technological evolution of the propulsion technologies influences the decision process, thus leading to different optimal choices.

Keywords: logistics; hydrogen; total cost of ownership; well to wheel; Topsis; decarbonization; green mobility

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1. Introduction

In the last century, transportation activities have been major contributors to air pollution and greenhouse gas emissions caused by the combustion of fossil fuels. The unsustainability of such a situation is nowadays largely recognized, and substantial efforts are being made by governments and institutions to reduce the emissions of polluting substances and greenhouse gases through the establishment of suitable decarbonization strategies. The EU, in particular, issued a decarbonization plan in 2011, which was subsequently included in the generalized Green Deal strategy aimed at achieving full decarbonization by 2050. For transport, which currently depends largely on fossil fuels and accounts for a quarter of the EU's total greenhouse gas emissions, achieving climate neutrality is a very challenging objective that will require a 90% reduction of the sector's emissions by 2050, compared to 1990 levels. The adoption of EU Directive 2014/94 on alternative fuels marks the opening to the construction of infrastructures for the distribution of fuels to replace petrol and diesel, and recognizes compressed natural gas (CNG), liquefied petroleum gas (LPG), and liquefied natural gas (LNG) as alternative fuels.

While fossil fuels are seen as a short-term solution, electricity and hydrogen are generally considered the only valid solutions for complete decarbonization in the long run, as long as their production involves only renewable sources. However, such a condition is hardly viable due to several technical shortcomings related to the intermittency of renewable sources in relation to the variability of energy demand. The storage of electricity in electrochemical accumulators (i.e., batteries), which could be a valid solution to such a problem has indeed several disadvantages, related to the availability of rare and expensive metals used in their production, and to their questionable lifecycle environmental effectiveness considering the significant pollutions during the production and disposal phases. In addition, batteries can compensate for short-term (e.g., daily) fluctuations in supply and demand, but the self-discharge effect reduces their effectiveness on long (e.g., seasonal) cycles. A definitive solution to such problems might actually derive from the employment of hydrogen, which is the most abundant element in the universe and an excellent energy carrier. In addition, hydrogen can be produced from renewable sources by means of electrolyzers, transported along pipelines, and transformed back into electricity in a fuel cell. Among the advantages of hydrogen, there is also the conversion efficiency, in fact, a current fuel cell reaches an efficiency of 60% compared to 45% for a modern coal-fired thermoelectric plant. However, nowadays, green hydrogen is too expensive compared to more traditional production technologies, although the situation is evolving, and the International Energy Agency (IEA, 2019) predicts substantial price reductions by 2030.

In such context, transport companies are charged with the difficult task of complying with European directives by 2050, which will eventually require the replacement of traditional vehicles with new and more environmentally and socially sustainable solutions. This decision problem is affected by substantial uncertainty, considering the impact that the technological evolution of zero-emissions propulsion systems will have in determining the future scenario. In addition, the choice of the propulsion technology will eventually involve a substantial re-establishment of the organizational and managerial policies, as green vehicles will drastically impact some crucial cost drivers such as the maximum traveling distance, the refueling time, and the commercial speed, as well as the maintenance operations. Based on such considerations, logistics operators must find strategic solutions for replacing the traditional vehicles, choosing among different options of electric powered vehicles (BEVs) and hydrogen-propelled vehicles taking into account their merits and drawbacks in terms of cost and sustainability. While the literature increasingly confirms the technical possibility of introducing heavy-duty battery-electric trucks (BET) and several commercial solutions already exist, the real-world application of such technologies is currently being questioned by researchers and professionals, based on several technical and economic issues. In such an uncertain context, some fleet managers may adopt conservative decisions according to their perceived risks and individual beliefs, while others may delay their decisions until price parity for trucks with alternative powertrains is reached. However, this condition might still take some years, considering that the average price of a heavy-duty diesel truck is currently less than half the market price of an electric truck with similar features. However, according to many researchers [1,2], relying on the parity of the acquisition cost might lead to wrong and dangerous decisions, because when the cost over the lifetime is considered, electric trucks might achieve a substantial reduction due to the significantly lower cost of electricity compared to diesel fuel. Further considerations involve the inadequacy of the electric charging infrastructure and the technological turmoil that affects the market of electrochemical accumulators. The market of Lithium-ion batteries (LIBs) is in fact projected to reach a value of US $53.8 billion by 2024, with a compound annual growth rate (CAGR) of 11% during 2019–2024 [3], while the global electric truck market is projected to reach over 3.86 billion U.S. dollars in size by 2030, with a CAGR of 26.4% between 2021 and 2030. An additional source of market uncertainty is represented by the establishment of innovative solutions that might lead to new business opportunities.

In such complex scenery, decision-makers are charged with high responsibilities, since adopting a tardive or wrong decision may substantially affect the performance of logistic companies, while over-cautious approaches aiming at meeting the short-term decarbonization targets with a combination of evolutionary improvements to the Internal Combustion Engines (ICEs) and limited adoption of hybrid or full electric systems only where tight regulations hold (i.e., city delivery), might result in sub-optimal solutions.

This paper addresses the research gap related to the absence of appropriately structured approaches to the vehicle-renewal decision problem, taking into account the multiple objectives involved. The methodology proposed focuses on the tradeoff between costs and long-term environmental sustainability (and related regulatory compliance) considering also the main technical limitations of the different technologies and taking into account the substantial scenario uncertainty which affects the decision problem. From a methodological point of view, the novelty of the approach proposed lies in combining multi-criteria decision-making methods with lifecycle analysis by considering two fundamental parameters such as the Total Cost of Ownership (TCO) and the Well to Wheel (WTW) emissions. This approach also demonstrates how different fleet operating conditions (e.g., annual kilometers traveled by vehicles) may affect the optimum choice and highlights the importance of the attitude of the decision maker towards risk and his perception of future scenarios.

In the remainder of the paper, after reviewing the relevant literature in the following section, the methodology proposed is discussed in Section 3 while a validation based on a case study is given in Section 4. The results will finally be discussed, and conclusions drawn up in Section 5.

2. Literature Review

The recent establishment of the "Green Deal" by the European Community as an overall strategy for reaching climate neutrality within the year 2050 involves the spread of green propulsion systems and promotes the development of hydrogen as the definitive solution to achieve full decarbonization. In particular, the Green Deal foresees an increase in the production volume of green hydrogen to 10 million tonnes/year through the installation of an additional 40 GW electrolyzer capacity by 2030, while by 2050, the expected share of hydrogen in the European energy mix by 2050 should reach 14%. According to the Green Deal, the European program and investments are thus divided into three sequential phases:

- Phase 1 (from 2020 to 2024): birth of the hydrogen market and definition of an ad hoc legislative-regulatory framework.
- Phase 2 (from 2025 to 2030): development of the hydrogen market, creation of the first localized applications, and construction of the transport infrastructure.
- Phase 3 (from 2031 to 2050): large-scale diffusion of hydrogen with massive penetration of the vector into the energy mix of final consumption.

The roadmap of the Green Deal poses some fundamental challenges for the operators of transport and logistic services, considering the growing demand for transport and the strong dependence on traditional (fossil) fuels. In particular, as pointed out by many authors [4–7], compliance with the long-term objectives of the Green Deal requires the conversion of the fleet to electric-powered or hydrogen-propelled vehicles as the only viable possibility to achieve full decarbonization. Clearly, the Green Deal relies on some fundamental assumptions about the evolution of the propulsion technologies in the next 25 years; however, the technological landscape is currently evolving, therefore the reliability of the plan is questionable. Nevertheless, compliance with the Green Deal is currently a hot topic in the transportation sector, which involves strategic decisions related to the renewal of the fleets of vehicles. In order to clarify the different technological alternatives to consider in the decision problem, a detailed review of the technological landscape is provided in the next section, while the decision methodologies are discussed in Section 2.2.

2.1. Transportation Technologies

The category of electric vehicles can be broadly subdivided into All-Electric Vehicles (AEV), which run entirely on a battery and an electric drive, and Hybrid Electric Vehicles (HEV) equipped with both an electric and an Internal Combustion Engine (ICE). Hydrogen-based propulsion systems can be sub-classified into Hydrogen Internal Combustion Engine Vehicles (HICEVs), generating kinetic energy from the combustion of hydrogen and Fuel Cell Electric Vehicles (FCEVs) exploiting the reaction of hydrogen and oxygen in a fuel cell. As many authors [2,8] pointed out, green vehicles have some relevant advantages compared to traditional combustion engines powered by fossil fuels, related to their weight, space, and, above all, environmental sustainability. In particular, as long as the electric energy produced for powering the electric vehicles or for producing hydrogen derives from renewable sources, the absence of life cycle emissions [6,7] makes them a most promising possibility to achieve full decarbonization. Although the advantages of zero-emission vehicles (ZEVs) have been widely discussed in the literature [9,10], their performance in logistics operations is questionable, particularly in long-haul operations, which is currently a technically difficult penetrable market frontier. A critical issue in such regard is represented by the operational costs of such vehicles, which is a key driver of economic competitiveness in long-haul transportation [11,12], where very narrow management margins are left to service operators. In recent years, many researchers focused on this topic with the aim of formulating appropriate cost analyses to compare traditional and green vehicles. Al-Alawi and Bradley [1], compared green and traditional vehicles, and showed that a comprehensive ownership cost model may substantially reduce their net cost of ownership thus shortening the payback period. Offer et al. [2] showed that although electric and hydrogen vehicles have higher capital costs than traditional vehicles, considering all operating costs throughout their useful life, green vehicles are more economical. Another study conducted by Contestabile et al. [13] demonstrated that electric vehicles offer economic advantages compared to traditional vehicles. A similar result was obtained by Wu et al. [14] by formulating a probabilistic model to estimate the costs of small electric and combustion vehicles in an urban context. Contrarily, Davis [15] studied green and traditional vehicles coming to the conclusion that green vehicles are currently more expensive; however, the technological evolution will lead to a substantial inversion in the future. The above-reported scientific literature confirms that a reliable representation of the cost implications related to the substitution of a traditional transport vehicle with a ZEV should take into account the overall lifecycle, through a comprehensive indicator such as the Total Cost of Ownership (TCO). The TCO has been used since the late 1990s in relevant procurement procedures since it allows us to consider both the initial acquisition cost and the costs of operations (maintenance, consumables, etc.), which are categorized into different cost classes and itemized separately in traditional cost models. Clearly, the concept of aggregating the cost elements of different categories distributed over the entire asset lifecycle derives from the adoption of a value-chain [2,16] and lifecycle-oriented approach [6,11]; therefore, implying several assumptions related to the usage conditions of the vehicle. Different computational models have thus been employed by researchers and practitioners in different application scenarios; therefore, a standardized procedure does not actually exist. However, the notion of TCO is well-established in the scientific literature and widely employed in the acquisition process of transportation vehicles comparing different propulsion technologies [17,18]. Burke [19], for example, conducted a TCO analysis on diesel, electric, and fuel cell electric trucks and concluded that full electric trucks equipped with large batteries cannot be cost-competitive with diesel trucks until the battery pack price drops to $100/kWh for long haulers. Similarly, other researchers [20,21] report that, to outperform diesel trucks, the costs of BEV long haulers with a mileage exceeding 100,000 miles per year (about 170,000 km/year), should decrease by 12%, while, by the end of the decade, new technologies will allow green vehicles to equate the costs of traditional vehicles. Wolff et al. [22] attribute the superiority of traditional trucks to the reduced carrying capacity of green vehicles, which significantly affects their TCO. However, referring to the environmental aspect, and considering the relevance that it has gained in the last decade, the judgment on green propulsion technologies can be substantially different. In this regard, it is worth underlining that up to now the environmental impact of transport vehicles has been measured referring to their exhaust emissions in terms of CO_2 and air pollutants, but with the advent of electric and hydrogen propulsion, a new methodological approach must be adopted since such vehicles do not produce any emissions during their operations. It is thus necessary to refer to the entire life cycle of the energy source to make an appropriate assessment. A suitable approach, adopted since 2016 by the Europeans and widely diffused in the modern scientific literature is the WTW analysis, which can be used to determine the environmental impact generated by a propulsion system considering both the production and use phase. The WTW analysis can be divided into Well-to-Tank (WTT) and Tank-to-Wheel (TTW). The first indicator (WTT) allows calculation of the "upstream" pollutants emitted during the extraction and/or production of the fuel or energy carrier, while the second (TTW) refers to the "downstream" part involving the pollutants emitted during the combustion of fuel. Several researchers have applied this methodology to evaluate the greenhouse gas emissions of electric cars. Liu et al. [23] discussed the influence of regional power grids on WTW greenhouse gas emissions from battery-electric heavy-duty trucks in the United States. Li et al. [24] used WTW analysis for the evaluation of battery and fuel cell vehicles and suggested cleaner hydrogen production routes and cleaner electricity generation. Gupta et al. [25] established the WTW cycle for heavy-duty vehicles, evaluated a blend of 20% hydrogen and compressed natural gas for engines, and suggested that a cleaner hydrogen feedstock was essential.

2.2. Strategic Decision-Making Approaches

The problem of choosing the right type of vehicle for the needs of a logistic operator is a complex decision problem involving several objectives and requiring an appropriate decision-making approach. Multi-criteria decision-making (MCDM) methods are methodologies developed in the general context of decision science to structure and formalize complex decision-making processes. The context of decision-making methods can be broadly subdivided into two categories, the Multi-Attribute Utility Theory (MAUT) methods [26,27], and the methods based on the outranking concept [28]. The application of either multi-criteria decision approaches in ranking or selecting the most suitable vehicle among a set of different technological alternatives is a topic frequently discussed in the literature [29–33]. Recently MCDM has been successfully employed in conjunction with Life Cycle Analysis (LCA) [34–37], in the transportation sector where MCDA methods have been employed to rank the alternatives, by means of weighted sums and additive value functions [38–40], the Analytic Hierarchy Process [41], PROMETHEE and SMAA-LCA [42–44], compromise programming [45]. Such methodologies have been extensively used in the context of sustainability decisions related to transport. Kolak et al. [46] applied the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method to assess the sustainability of the transport networks in 15 European countries. Awasthi and Chauhan [47] presented a composite indicator of transport sustainability using the Analytic Hierarchy Process (AHP) method and Dempster–Shafer theory to assess the impact of sustainable transport solutions, Haghshenas and Vaziri [48] compared the transport sustainability of 100 cities around the world considering nine transport indicators.

In this research, the TOPSIS method has been employed in the decision problem related to the renewal of a fleet of vehicles. The TOPSIS method is based on the concept that the ranking of alternatives results from their distances from the (positive) ideal solution (PIS) and from the negative ideal solution (NIS) or nadir. With such features, the TOPSIS method has the merits of providing a robust result with a simple decision-making approach that limits the occurrence of rank reversals. Finally, the complexity of the decision-making problem considered is linked to the substantial uncertainty that characterizes the decision-making context. In general, uncertainty can be classified into three categories [49]: scenario uncertainty, parameter uncertainty, and model uncertainty. While model and parameter uncertainty typically refer to performance measurement errors and a misinterpretation of correlations and uncertainty, respectively, scenario uncertainties include descriptive errors and incomplete information about the decision context that are typically present in problems of long-term decision-making [50,51]. In this context, scenario analysis is often used to analyze and demonstrate the implications of alternative policy options or to explore the impacts of uncertainties on strategic policies. Based on the above literature, this research proposes an original integrated decision-making framework in which the TOPSIS method is used to classify different vehicle propulsion technologies taking into account the inherent life cycle environmental and economic implications as well as the uncertainty of the long-term scenario. The employment of the TOPSIS methodology in decision-making problems involving the choice of vehicles with different propulsion alternatives is well established in the literature [52,53] since the simplicity of this method makes it preferable in the application in practical contexts. However, this research proposed an original implementation of such methodology in a generalized lifecycle approach, involving economic and environmental objectives and considering the inherent scenario uncertainty. With such features, this research constitutes a novel contribution to the scientific literature related to strategic decision problems in the context of transportation.

3. Methodology

This section discusses the decision framework proposed for addressing decision problems related to vehicle selections in logistics involving multiple criteria and lifecycle considerations. As discussed before, due to the long-term implications, the relevant financial investment involved, and the substantial uncertainties involved, such decision problems belong to the strategic management level; therefore, having a substantial impact on the business performance and on compliance with future environmental regulations. In addition, the inherent uncertainty related to the dynamic nature of the technological and regulatory context further complicates the decision problem; therefore, an appropriate and well-structured decision framework can be a valuable support for the decision-makers. According to the above considerations, the decision problem is preliminary structured by identifying the set of technological alternatives and the set of criteria (and related indicators) considered. Such elements are discussed in detail below.

3.1. Technology Alternatives

The current technological scenario of ground transportation involves three main alternatives, namely fossil fuels, electric, and hydrogen-propelled vehicles. Currently, propulsion systems based on fossil fuels are the most consolidated and spread technology, benefitting from the lowest acquisition cost and highest reliability while raising some fundamental concerns in terms of environmental sustainability due to their emissions of polluting and greenhouse gases. The exhaust gas treatment systems, indeed, ensure compliance with current environmental regulations, but they are not able to meet the objectives of the EU Green Deal and related forthcoming regulations. Compared to traditional fossil fuels, electric vehicles do not produce any polluting and greenhouse gases; therefore, they are fully ecological, as long as the electric energy is generated from renewable sources. However, besides such environmental benefits, when the whole lifecycle of the vehicle and its components are considered, some environmental concerns still arise e.g., the disposal of the Li-PO batteries, which up to today do not have a reliable end-of-life treatment. In addition, the novelty of electric propulsion technology does not allow us to make reliable estimations of the maintenance and operation costs. The third available technology is hydrogen propulsion, employed in HICEVs and FCEVs, with the latter being more competitive from a commercial point of view due to the lower complexity and operating cost. Such technology however has a substantially higher acquisition cost, since the Proton-exchange membranes (PEM) employed in such systems are very expensive, with metal catalysts, gas diffusion layers, and bipolar plates accounting for up to 70% of their overall cost. Additional problems of FCEVs are related to the limited operating temperature range of

PEMs (typically between 20 and 80 °C) [54] and to their degradation at high temperatures. Despite their several drawbacks and technological limits, FCEVs are superior to all other mobility technologies from an environmental point of view since they ensure the complete decarbonization of the chain when operated with green hydrogen.

3.2. Decision Criteria

The decision framework proposed relies on the establishment of three decision criteria, namely long-term sustainability (i.e., environmental performance), cost-effectiveness (i.e., economic performance), and technical complexity as given in Figure 1. The first two criteria are measured by referring to the entire lifecycle of the vehicle and of the energy source, by means of two referenced numerical indicators such as the WTW and the TCO, discussed in detail in the sections below.

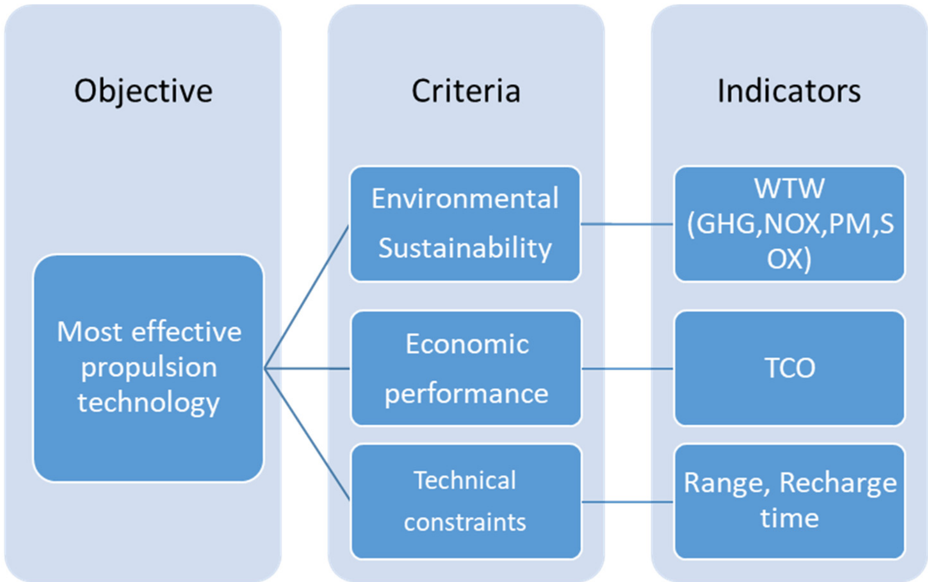

Figure 1. Decision-making criteria for the application of the Topsis.

3.2.1. Economic Performance

The evaluation of the economic performance of a vehicle has been referred to as its total cost of ownership (*TCO*), calculated considering the vehicle capital cost (*VCC*) and the actualized value of the annual operating costs (*AOC*) referred to its useful life and average annual vehicle kilometers traveled (*VKT*).

$$TCO = VCC + AOC \quad (1)$$

The annual operating cost of fossil fuel-powered vehicles has been calculated considering the annual fuel consumption cost (*FC*), the annual fixed costs related to the insurance (*IC*), and the maintenance and repair cost (*MC*), including ordinary and extraordinary maintenance interventions as well as the cost of consumables (e.g., tires).

$$OC_F = FC_F + IC_F + MC_F \quad (2)$$

The annual fuel consumption cost can thus be evaluated as:

$$FC_F = VKT \, * \, f_C * \, f_p. \quad (3)$$

where f_c is the average fuel consumption and f_p is the fuel price. For electric vehicles, the total annual cost can be calculated as:

$$OC_E = EC_E + IC_E + MC_E \quad (4)$$

where ECE represents the energy cost of the electric vehicle, calculated as:

$$EC = VKT \, * \, E_{km} * \, p_{kWh} \tag{5}$$

where E_{Km} is the energy requirement per km and p_{kWh} is the energy retail price per kWh. The fixed cost is related to the annual battery leasing fee, average annual insurance cost, and annual maintenance and repair cost. The total annual cost of hydrogen vehicles is calculated as:

$$OC_H = FC_H + IC_H + MC_H \tag{6}$$

where FC_H represents the fuel consumption as a function of the average annual kilometers calculated as:

$$FC = VKT \, * \, H_{km} * \, p_H \tag{7}$$

where H_{km} is the Hydrogen consumption per km and p_H is the Hydrogen retail price.

3.2.2. Environmental Performance

The sustainability of different propulsion technologies has been evaluated taking into account the lifecycle of the fuel/energy production and utilization according to the WTW index and the related sub-indices: WTT and the TTW. In particular, the WTT emission index takes into account the pollutant mass emitted in the extraction, chemical processing, and transport, while the TTW index takes into account the pollutant mass emitted referred to a reference distance. Finally, the WTW emission index gives the total pollutant emitted from a fuel production pathway and powertrain combination:

$$WTW_p \left[\frac{g}{km} \right] = WTT_p \left[\frac{g}{km} \right] + TTW_p \left[\frac{g}{km} \right] \tag{8}$$

Such parameters have been evaluated for both greenhouse gases (CO_2, NO_2, CH_4) and local air pollutants (NOx, SOx, PM). For electric vehicles, the electric energy produced is the combination of different pathways that reflect a European mix of sources (named "EU-mix") considering a forecasted 2030 value where renewables will be almost a quarter of the EU-mix of 2010 [19]. For hydrogen-powered vehicles, only "green" hydrogen has been considered which is the total decarbonization option.

3.2.3. Technical Implications: Range Charging Time

This criterion takes into account the impact of the vehicle technology on fleet management operations. Vehicles based on different propulsion technologies typically achieve a different combination of payload and range and may substantially differ in terms of refueling/recharging time. Such elements must be taken into account during the fleet scheduling and routing process; therefore, impacting the overall performance of the fleet. However, evaluating this impact at a strategic level is complicated since it depends on the typology of service performed by the vehicle and on the specific operational context; however, such technical limitations can be taken into consideration by the decision maker in the approach proposed, by attributing a specific weight to the criteria. The specific indicators introduced to take into account the technical limitations of vehicles with different propulsion technologies are the range and the recharging/refueling time. The range is the distance that can be covered between two subsequent refueling/recharging operations, and the replenishment/recharge time is the time required for the energy storage system to reach its full capacity.

3.3. Multi-Criteria Decision-Making Approach

The decision-making approach adopted in this paper is the well-known TOPSIS method, which involves the initial establishment of the alternatives, the decision criteria, and the weights assigned to each criterion reflecting the decision maker's preferences. Each alternative is scored according to each criterion, thus obtaining the evaluation matrix which is then normalized according to Equation (9). The normalization formula employed is the referenced Vector Normalization norm, which is commonly employed in distance-based MADM methods (see e.g., [55]). Finally, the normalized scores are multiplied by the weights according to Equation (10) to obtain for each criterion the related normalized and weighted matrix.

$$z_{ij} = \frac{g_{ij}}{\sqrt{\sum_i g_{ij}^2}} \tag{9}$$

$$u_{ij} = w_j \, * \, z_{ij} \tag{10}$$

where: g_{ij} is the score of the ith-alternative with respect to criterion j, z_{ij} is the normalized score, w_j is the weight attributed to criterion j, and u_{ij} is the weighted normalized score.

For each alternative the Euclidean distances from the positive and negative ideal points A^* and A^- (obtained as the max and min score of all the alternatives in each criterion, depending upon the related maximization or minimization objective) are then calculated according to the Equations (11) and (12).

$$S_i^* = \left(\sum_{j=1}^{n} \left(z_{ij} - A_j^*\right)^2\right)^{\frac{1}{2}} \tag{11}$$

$$S_i^- = \left(\sum_{j=1}^{n} \left(z_{ij} - A_j^-\right)^2\right)^{\frac{1}{2}} \tag{12}$$

The final ranking is then obtained by calculating the $C_i{}^*$ parameter according to Equation (13).

$$C_i^* = \frac{S_i-}{S_i^* + S_i^-} \tag{13}$$

Finally, the alternatives are classified according to C_i^*: the solutions characterized by the highest C_i^* value are preferred.

4. Case Study

The proposed methodology has been applied to the practical problem of replacing traditional diesel tractor-trailers with electric or hydrogen propulsion alternatives for a long-haul logistic operator, considering the economic issues as well as long-term sustainability implications and regulatory compliance. The case considered has a significant industrial relevance, since lightweight electric vehicles for urban distribution are nowadays a consolidated reality, while long-haul transport represents the biggest challenge for zero-emission vehicles, because of the big loads and high daily distance covered (Wentzel., 2020). The target vehicle considered is a tractor with 40 ton capacity, 350 kW power, and a maximum range of approx. 500 km. Such features are quite common in traditional long-haul diesel trucks such as the Iveco Stralis truck 500 equipped with a 332 kW Diesel engine, and a gross weight rating (GWR) of 44 tons. Based on publicly available market data, the price of a diesel tractor-trailer is estimated at €135 K. An electric truck with similar features is the MAN TGX 4 × 2 LLS model with a 350 kW electric engine supported by a 270 kWh battery pack. However, this vehicle has some substantial technical limitations consisting of only a 200 km range and a 5–6 h recharge time with an industrial socket (45 min. with DC fast charging). The overall cost of the semi-truck considering inverter, chassis, drivetrain, transmission, electric HVAC, and support systems, can be estimated at 330 k€. Recent market evidence, for example, is the Port of Oakland purchase of 10 Peterbilt 579EVs (36 tons GWR, 400 kW Continuous power, 240 km range) at a cost of approximately $500,000 per semi-truck [56]. A substantial market change could be the semi-truck recently announced by Tesla with a price of $180,000 and a 500-mile range. Finally, hydrogen-propelled trucks with the requested target features have been recently proposed by some manufacturers, although the market is just in an early stage. One of the most advanced products currently available is, for example, the Hyundai XCIENT a 36 tons GWR vehicle equipped with 2 × 95 kWw fuel cells and 73 kWh energy storage systems coupled with an electric motor that develops 350 kW power and hydrogen tanks that can store up to 35 kg of H^2 at 350 bars. With such features, the truck has a range of 500 km and an esteemed cost of 385 k€, although it is commercialized exclusively through the Pay-Per-Use model, with an individually calculated flat rate per km. Further assumptions are the FCHV consumes hydrogen fuel in the range of 8.3 kg/100 km at combined load. Finally, it is assumed that the trucks will be purchased new and kept in service for 10 years, and the difference in resale value between a five-year-old zero-emission truck and a diesel truck is ignored. The undiscounted (i.e., with null interest rate) TCO for the three alternatives, calculated according to Equation (1) on the basis of the commercial data reported above is reported in the following Tables 1 and 2.

Table 1. Costs for the different alternatives assuming 350,000 kilometres/year.

	Diesel	HFC	BEV
Truck purchase Cost (€)	135,000	330,000	385,000
Energy cons. (kwh/km)			1.25
Fuel cons. (lt/100 km)	33	8	
Diesel fuel cost (€/liter)	1.5		
Energy fuel cost (€/kwh)			4.65
H2 fuel cost (€/kg)		4.65	
Distance traveled (Km)	350,000	350,000	350,000
Driver cost (€/Year)	60,000	60,000	60,000
Adblue (€/100 km)	0.5		
Tires (€)	2784	2784	2784

Table 2. TCO for the different alternatives considering 10 years useful life.

	Diesel	HFC	BEV
Turck Cost	150,000.00	330,000.00	385,000.00
fuel cost (€/year)	1,865,500.00	1,260,000.00	1,452,500.00
driver cost (€/Year)	600,000.00	600,000.00	600,000.00
tires	27,840.00	27,840.00	27,840.00
service	120,000.00	165,000.00	50,000.00
Total Cost	2,763,340.00	2,382,840.00	2,515,340.00

Referring to the sustainability criterion, the WTW data adopted for the energy and environmental analysis are based on the elaboration of recently referenced data [57] and shown in Figure 2 below.

After calculating the TCO and having extrapolated the data relating to the WTW analysis from the literature, Table 3 is obtained, which contains all the data relating to the criteria that will allow us to apply the Topsis method.

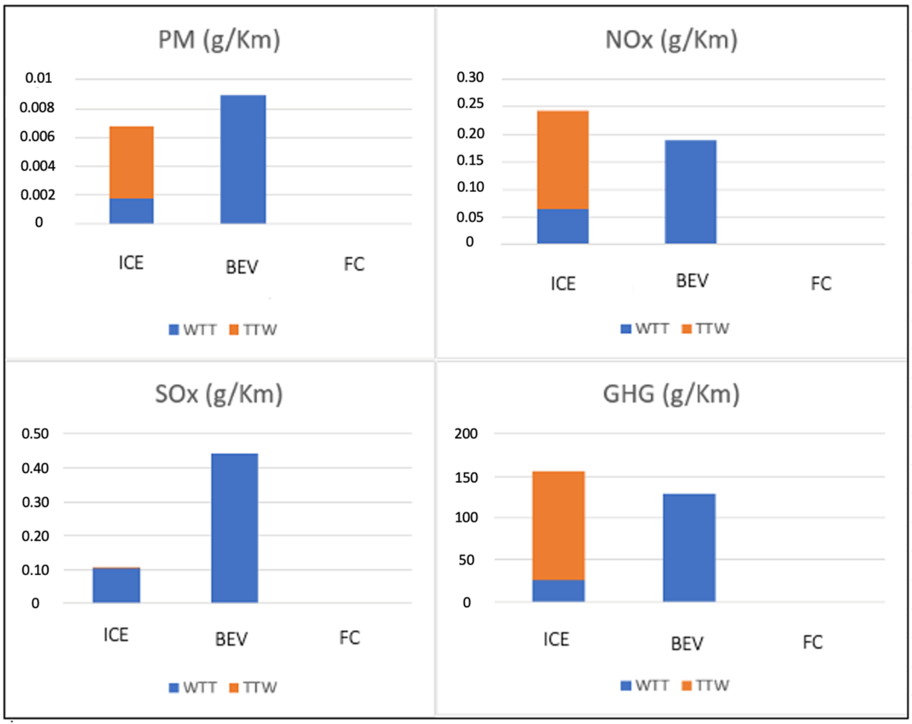

Figure 2. Comparison index WTW for vehicle electric, traditional, and hydrogen.

Table 3. Score of the alternatives considered for multicriteria analysis.

Alternatives	Scores						
	Sustainability					Technical	
	NOx (g/kg)	PM (g/kg)	Sox (g/kg)	CO_2 (g/kg)	TCO (€)	Range (km)	Refueling Time (min)
Diesel	0.244	0.005	0.105	156.234	2,763,340.00	1250	15
Electric	0.190	0.009	0.445	128.871	2,515,340.00	200	45
Hydrogen	0.000	0.000	0.000	0.000	2,382,840.00	500	15

Once the alternatives have been scored according to the criteria considered and corresponding indicators, the decision maker's preference scheme is introduced by assigning the weights to the criteria. In this step, the scenario uncertainty substantially complicates the weight assignment process, since the outcomes of a long-term strategic decision-making process are significantly influenced by external factors, while the decision maker's preference scheme is affected by the related uncertainty. In the case study, three different scenarios are considered related to technological evolution and corresponding environmental regulations. All the scenarios start from the current situation of ZEV penetration in heavy-duty transport activities, which is in a very early stage considering that global sales of zero-carbon medium and heavy-duty vehicles reached roughly 0.2% of total sales in 2021 [58], with China being the largest market. In Europe, ZEV truck sales witnessed a significant increase over the past years, representing more than 40% of new zero emission-heavy duty vehicle registrations in 2020. However, more than 90% of such sales between 2010 and 2015 were represented by buses while more than 97% of registrations in 2020 were battery-electric vehicles, with a very limited presence of fuel-cell electric technologies [59]. Although several electric heavy-duty truck models are currently available on the market, hence, their actual employment in long-haul transportation is still minimal, while hydrogen fuel cell trucks are just appearing on the market although green hydrogen is still considered prohibitively expensive. As a matter of fact, the decarbonization process of long-haul transport activities is still in the preliminary stage, while the share of ZEV in the fleet of long-haul transporters is still negligible. Despite such a situation, the targets set by countries in Europe for the phase-out of conventional fueled trucks across the EU-27 appear very ambitious and to some extent unrealistic. Six Member States (Portugal, Luxembourg, Finland, Denmark, Netherlands, and Austria) have signed a Global Memorandum of Understanding, pledging for 30% of sales of trucks and buses to be zero-emission by 2030 and 100% by 2040. Based on such premises, three scenarios have been formulated concerning different evolutions of the propulsion technologies the first scenario ("Slow Technological Development") refers to a situation, where the technological developments on hydrogen and electric vehicles/infrastructures, will take longer than expected, and traditional combustion engines will thus maintain their leadership improving their environmental efficiency, while electric and hydrogen vehicles will not enter the market until 2040. The sale of diesel vehicles will not be suspended, and the current scenario will basically persist with minor variations until 2040, while zero-emissions, vehicles will finally replace ICE after 2040. The second scenario ("Moderate technological development") implies a faster transition to battery-powered vehicles until 2030 with a moderate development FCEV propulsion system. The objectives of 30% sales of trucks in 2030 and 100% by 2040 are thus respected, and BEVs will be the most spread solution for long-haul transport. The last scenario ("Fast technological development") concerns a rapid transition to a vehicle fleet dominated by BEV and FCEV by 2030, while subsequently, the development of hydrogen will be predominant and by 2040 the market will be dominated by FCEVs with a significant share of BEVs, while ICEs will be totally phased out. In this scenario, technological evolution is faster and the decarbonization of freight transport is almost completed in 2040. The three scenarios considered are depicted in Figure 3.

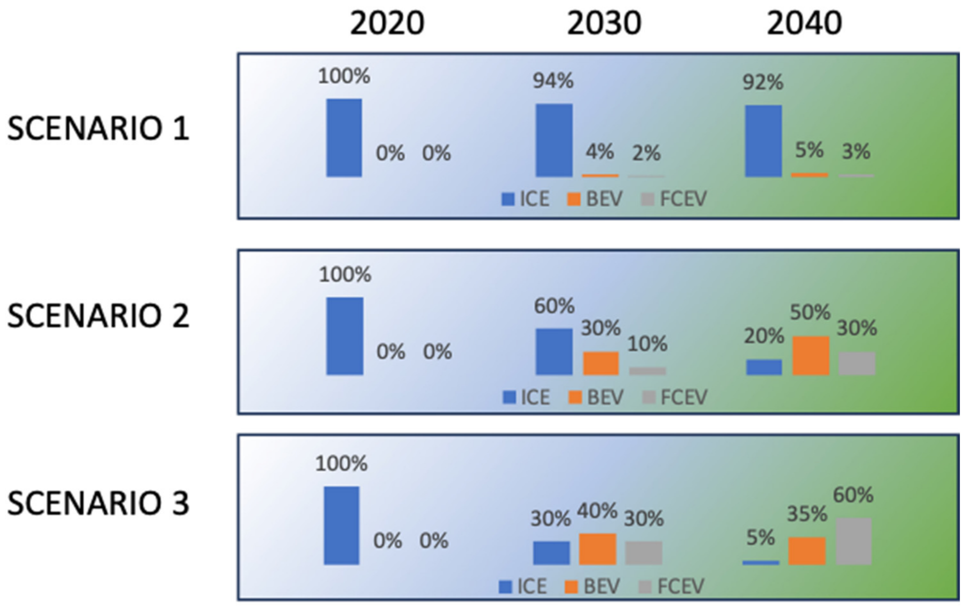

Figure 3. The scenarios considered.

To represent the preference pattern of the decision maker in the scenarios considered, Table 4 reports the weights assigned to the different criteria, while Table 5 shows the weights attributed to each sub-indicator. Referring to the assignment of the weights, in the first scenario, the slow technological evolution substantially leads the decision maker to focus on cost as the main decision criterion, while the preference of a zero-emission vehicle is penalized by the related technical limitations (which is the second most important criterion) rather than its attractiveness in terms of sustainability. In this case, hence, the assumption is that the limited technological developments in green mobility do not lead to tight environmental regulations; therefore, long-haul distribution does not develop as an environmentally friendly business and the managers do not acquire a sustainability-oriented business strategy. In the second scenario, technological evolution leads to electric mobility becoming predominant in 2040 and the regulatory framework is expected to tighten in terms of environmental impact. The sustainability objective thus gains importance, and the decision maker bases its choice on a compromise between costs and sustainability (which have the same weight) while the technical limitations become less relevant. Finally, in the third scenario, green mobility is assumed to become predominant in 2040 while fossil fuels will progressively fade out; therefore, sustainability becomes the most important decision criterion to ensure long-term compliance with the environmental regulations. The decisions about the fleet renewal are thus based on environmental compliance mainly, and cost becomes a secondary criterion. Technical limitations, finally remain in the background of the decision process.

Table 4. Weights attributed to the macro criteria.

	Cost	Sustainability	Technical
Scenario 1	0.50	0.20	0.30
Scenario 2	0.40	0.40	0.20
Scenario 3	0.40	0.50	0.10

Table 5. Weights of sub-indicators.

	Sustainability				Cost	Technical	
	Nox	**PM**	**SOx**	**CO_2**	**TCO**	**Range**	**Refueling Time**
Scenario 1	0.050	0.050	0.050	0.050	0.500	0.150	0.150
Scenario 2	0.100	0.100	0.100	0.100	0.400	0.100	0.100
Scenario 3	0.125	0.125	0.125	0.125	0.400	0.050	0.050

Based on the scores of the alternatives (Table 3), the normalized weighted matrix is created in each scenario and the ideal solutions S* and non-ideal S^- solutions are determined according to Equations (11) and (12). The alternatives are finally classified based on their distance from the extreme solutions. The solutions characterized by the highest C_i^* value (Equation (13)) are preferred, and the final rank obtained is shown in Table 6.

Table 6. Relative proximity to the ideal point.

	Scenario 1		Scenario 2		Scenario 3	
Alternative	**C***	**Ranking**	**C***	**Ranking**	**C***	**Ranking**
Diesel	0.511	1	0.446	2	0.410	2
Battery	0.404	3	0.279	3	0.188	3
Hydrogen Fuel Cell	0.452	2	0.683	1	0.841	1

The obtained results show that if the European “Green Deal” strategy maintains its objective to phase out fossil-fueled vehicles by 2040 (scenario 2), the best choice will be the switch towards hydrogen vehicles since this is the only technology allowing for complete decarbonization. BEVs are less efficient from an environmental point of view and have a worse operational performance (recharge time and range); therefore, they can hardly represent an optimum choice in long-haul transportation. In the slow technological evolution scenario (scenario 1), where the objectives of the Green Deal are postponed, the decision makers will substantially rely on cost-effectiveness; therefore, modern ICEs are still the most efficient choice, while the full decarbonization is postponed. The results obtained clearly show how the different sets of weights employed in the scenarios considered influence the ranking of the alternatives. In the slow technological development scenario, the decision maker’s choice will be mainly influenced by the cost criterion; therefore, the diesel truck will be on top of the rank, while the choice of hydrogen technology will be preferred in the other scenarios where sustainability criterion assumes a higher weight. Furthermore, with the aim of evaluating the reliability and accuracy of the model, the solutions corresponding to a variation of the weights have been calculated. In particular, the analysis involved the following four cases per scenario:

- Case 1: an increment of 10% has been considered for the weights related to the environmental sustainability criterion, the cost criterion has been maintained constant, while a suitable reduction has been considered for the weights related to the technical features ensuring the overall sum is equal to 1.
- Case 2: an increment of 10% has been considered for the weights related to the environmental sustainability criterion, the technical criterion has been maintained constant, while a corresponding reduction has been considered for the weights related to the cost features to ensure the overall sum is equal to 1.
- Case 3: a decrease of 10% has been considered for the weights related to the environmental sustainability criterion, the cost criterion has been maintained constant, while a suitable increment has been considered for the weights related to the technical features ensuring the overall sum is equal to 1.
- Case 4: a decrease of 10% has been considered for the weights related to the environmental sustainability criterion, the technical criterion has been maintained constant, while a corresponding increment has been considered for the weights related to the cost features to ensure the overall sum is equal to 1.

The results obtained demonstrate the robustness of the model (see Table 7).

Table 7. Results of the sensitivity analysis (bold shaded cells refer to the baseline scenario).

Sustainability				Cost	Technical		Best Alterantive	
W_{Nox}	W_{PM}	W_{SOx}	W_{CO2}	W_{TCO}	W_{Range}	$W_{RefuelingTime}$	**1**	
0.050	**0.050**	**0.050**	**0.050**	**0.500**	**0.150**	**0.150**	**1**	**Scenario 1**
0.055	0.055	0.055	0.055	0.500	0.140	0.140	1	
0.055	0.055	0.055	0.055	0.480	0.150	0.150	1	
0.045	0.045	0.045	0.045	0.500	0.160	0.160	1	
0.045	0.045	0.045	0.045	0.520	0.150	0.150	1	
0.100	**0.100**	**0.100**	**0.100**	**0.400**	**0.100**	**0.100**	**3**	**Scenario 2**
0.110	0.110	0.110	0.110	0.400	0.080	0.080	3	
0.110	0.110	0.110	0.110	0.360	0.100	0.100	3	
0.090	0.090	0.090	0.090	0.400	0.120	0.120	3	
0.090	0.090	0.090	0.090	0.440	0.100	0.100	3	
0.125	**0.125**	**0.125**	**0.125**	**0.400**	**0.050**	**0.050**	**3**	**Scenario 3**
0.138	0.138	0.138	0.138	0.400	0.012	0.012	3	
0.138	0.138	0.138	0.138	0.348	0.050	0.050	3	
0.113	0.113	0.113	0.113	0.400	0.074	0.074	3	
0.113	0.113	0.113	0.113	0.448	0.050	0.050	3	

It must be considered that the results obtained refer to specific service-related assumptions, and significant variations in the related parameters may substantially affect the solutions obtained. In particular, the annual truck operational costs depend significantly on the distance covered by the trucks each year; therefore, the TCO calculations are highly sensitive to the choice of the annual VKT and interest rate. This is shown in Figures 4–6, where the TCO has been evaluated as a function of the VKT and of the interest rate.

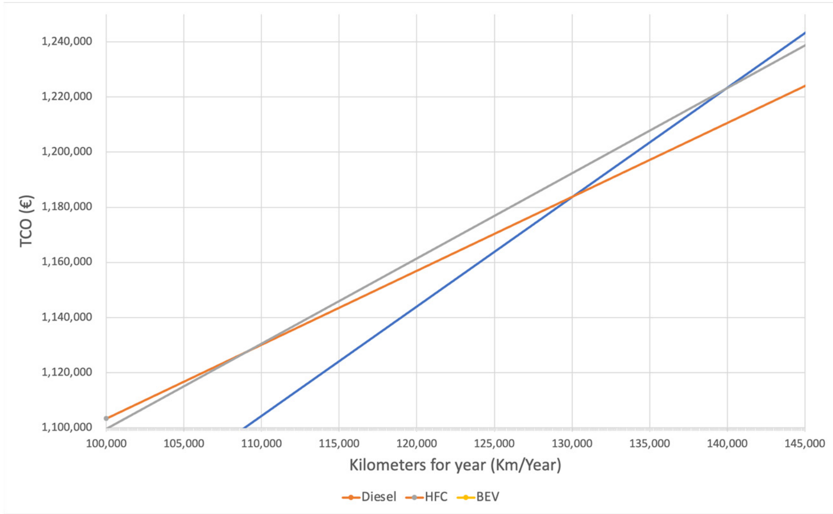

Figure 4. Break-even points of the TCO as a function of annual km traveled (interest rate = 3%).

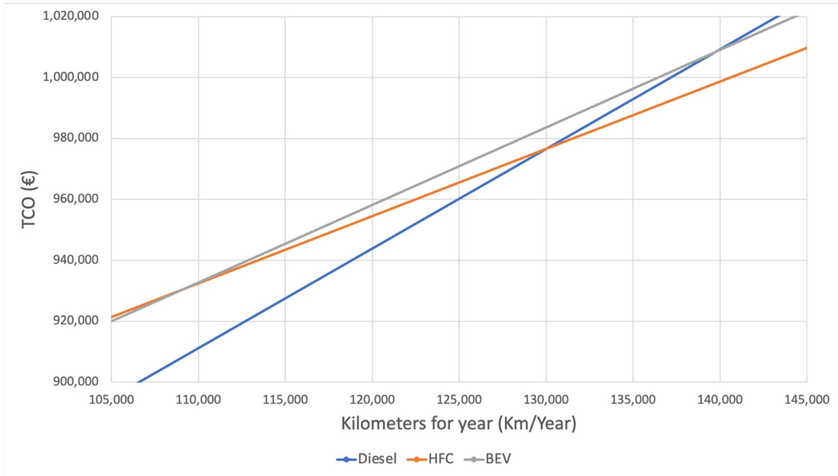

Figure 5. Break-even points of the TCO as a function of annual km traveled (interest rate = 5%).

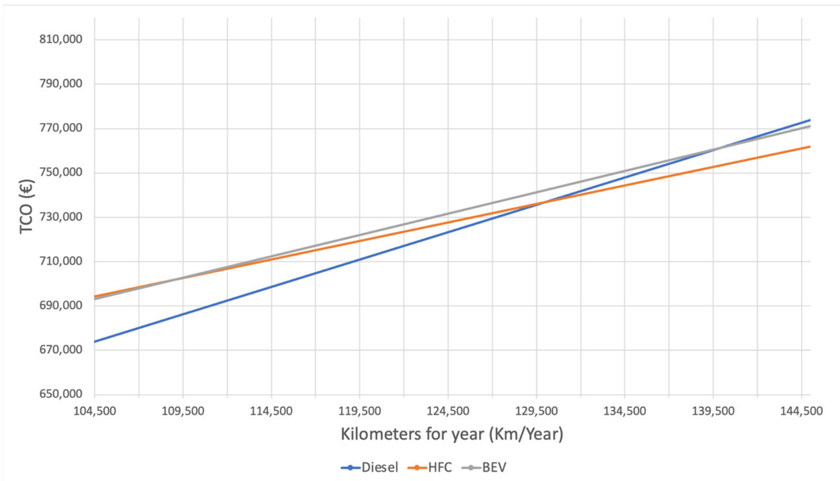

Figure 6. Break-even points of the TCO as a function of annual km traveled (interest rate = 8%).

Figures 4–6 represent the plots of the TCO of different propulsion systems as a function of the annual kilometers traveled, ultimately showing that the TCO is strictly linked to the features of the service operated, while the interest rate does not play a substantial role in the decision problem. In particular, as the annual distance traveled reduces, the ICE vehicles become more convenient, while as the distance increases, first BEVs and subsequently, FCEVs become the best solutions. In addition, such figures show that variations in the annual kilometers, significantly influence the TCO, thus resulting in raking inversions according to such criterion. Such an effect becomes more significant as the interest rate increases.

The above-reported results demonstrate how the methodology proposed can be employed in order to support logistic operators in strategic fleet renewal decisions. Clearly, the substantial scenario uncertainty affects the decision process, and the methodology presented is based on the assumption that the subjective decision maker's preference scheme changes in the different scenarios considered. In such context, the proposed methodology allows us to determine the most appropriate choice in each scenario. However, the decision framework does not lead to a final unique decision, which is a substantial limitation of the approach proposed. A further development would thus be to extend the approach to include the probability of occurrence of each scenario; therefore, allowing the decision maker to determine a single optimum choice based on the scenario expectations.

5. Conclusions

The increased attention towards the environmental situation and the consequent decarbonization strategies undertaken by governments and institutions on a global scale are pushing towards a substantial rethinking of the logistic systems. A fundamental step in such a sense will be the transition towards the new mobility technologies based on electricity and hydrogen, and the consequent renewal of the fleet of vehicles currently operated, mostly based on fossil fuels. Considering the dynamical technological landscape and the inherent uncertainty about future scenarios, the choice of the most effective technology is a complex strategic decision problem for logistic operators with significant industrial relevance in the medium/long term. In such context, this paper proposes an original multicriteria decision approach based on the TOPSIS method with the merit of integrating economic, environmental, and technical aspects into a comprehensive decision framework. The long-term implication of the economic performance is considered by taking into account the TCO of the vehicles, while the criterion related to the sustainability of the system takes into account the complete lifecycle of the fuel. This is necessary when comparing ZEVs with traditional diesel powertrains. In addition, the decision framework takes into consideration the context uncertainty by involving an integrated scenario analysis. In particular, the decision-maker's perception about the future scenarios is modelized through a specific preference scheme which substantially influences the optimal choice. The methodology proposed has been validated against a case study referring to the choice of different propulsion technologies for long-haul logistic operations, based on realistic data from commercial vehicles currently available on the market. The results obtained show that the choice of electric propulsion in long-haul transport is not convenient in any scenario, thus suggesting that investments from companies in such sector might be at high risk in the long run. Clearly, the final rank of the vehicle technology essentially depends upon the technological expected developments by the decision maker; therefore, different perceptions of the future scenarios might lead decision-makers to formulate different preference schemes by attributing different weights. Consequently, the decision framework proposed can be extended to more complex cases involving additional scenarios and technology alternatives as well as additional criteria. In such applications the methodology proposed explicitly aims at considering the subjective judgment of different decision makers, the results obtained still highlight that the domain of economic profitability for electric vehicles in long-haul transport is actually narrow, which is surely a significant managerial insight. The case study also highlights how robust the solution obtained is against the specific features of the operating scenario considered, and the economic parameters assumed. Finally, the proposed methodology can be helpful for policymakers as a tool for assessing the possible implications of new regulations, thus improving their effectiveness in orienting the decision processes of commercial entities.

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