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Total cost of ownership analysis for hydrogen and battery powertrains: A comparative study in Finnish heavy-duty transport

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ABSTRACT

The road transport sector is one of the major contributors to greenhouse gas emissions, as it still largely relies on traditional powertrain solutions. While some progress has been made in the passenger car sector with the diffusion of battery electric vehicles, heavy-duty transport remains predominantly dependent on diesel internal combustion engines.

This research aims to evaluate and compare three potential solutions for the decarbonisation of heavy-duty freight transport from an economic perspective: Battery Electric Trucks (BETs), Fuel Cell Electric Trucks (FCETs) and Hydrogen-fuelled Internal Combustion Engine Trucks (H2ICETs). The study focuses on the Finnish market and road network, where affordable and low-carbon electricity creates an ideal environment for the development of alternative powertrain vehicles. The analysis employs the Total Cost of Ownership (TCO) method, which allows for a comprehensive assessment of all cost components associated with the vehicles throughout their entire lifecycle, encompassing both initial expenses and operational costs. Among the several factors affecting the results, the impact of the three powertrain technologies on the admissible payloads has been taken into account. The study specifically focuses on the costs directly incurred by the truck owner. Additionally, to evaluate the cost effectiveness of the proposed powertrain technologies under different scenarios, a sensitivity analysis on electricity and hydrogen prices is conducted.

The outcomes of this study reveal that no single powertrain solution emerges as universally optimal, as the most cost-effective choice depends strongly on the truck type and its use (i.e., daily mileage). For relatively small trucks (18 t) covering short driving distances (approximately 100 to 200 km/day), BETs prove to be the best solution due to their higher efficiency and lower vehicle costs compared to FCETs. Conversely, for larger trucks (42 and 76 t) engaged in longer hauls (>300 km/day), H2ICETs exhibit larger cost benefits due to their lower vehicle costs among the three options under investigation. Finally, for small trucks (18 t) travelling long distances (200 km/day or more), FCETs represent a competitive choice due to their high efficiency and cost-effective energy storage system. Considering future advancements in FCETs and BETs in terms of improved performance and reduced investment cost, the fuel cell-based solution is expected to emerge as the best option across various combinations of truck sizes and daily mileages.

1. Introduction

The transport sector is one of the primary contributors to global CO_2 emissions. In 2018, it ranked as the second largest contributor (after energy production), responsible for >25% of global greenhouse gas (GHG) emissions [1,2]. Within the transport sector, road transport is by

Acronyms: BET, Battery Electric Truck; CNG, Compressed Natural Gas; DC, Direct Current; EU, Extra-Urban route; FC, Fuel Cell; FCET, Fuel Cell Electric Truck; GHG, GreenHouse Gas; GVW, Gross Vehicle Weight; H2ICE, Hydrogen-fuelled Internal Combustion Engine; H2ICET, Hydrogen-fuelled Internal Combustion Engine Truck; HCT, High-Capacity Transport; HDV, Heavy-Duty Vehicle; HVAC, Heating, Ventilation and Air Conditioning; ICE, Internal Combustion Engine; ICET, Internal Combustion Engine Truck; LCOT, Levelised Cost Of Transport; LH, Long-Haul route; RPE, Retail Price Equivalent; TCO, Total Cost of Ownership; TPC, Total Purchase Cost; U, Urban route.

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far the largest GHG source, accounting for 74% of the sector's emissions in 2022, well above the contributions of aviation and shipping [3].

In Finland, the transport sector emitted over 21% of the country's total equivalent emissions in 2021 [4]. The majority of domestic freight transport, both in terms of weight (tonnes) and weight-mileage (tonne-kilometres), occurs on roads. In 2020, road freight transport accounted for 90% (259 million tonnes) and 75% (27,861 million t·km) of domestic transport, with a trend that has remained almost constant in recent years [5].

To mitigate emissions and align with the European Union goals aimed at counteracting climate change [6,7], numerous initiatives have been launched (among others, RePowerEU [8] and Fitfor55 [9]). A key priority for the European Union in the coming years is to rapidly transition road fleets towards carbon-neutral vehicles [10]. At present, low- and zero-emission vehicles based on batteries and fuel cells are rapidly penetrating the passenger car market [11], while they are encountering difficulties in establishing themselves in the Heavy-Duty Vehicle (HDV) segment [12–14]. In this context, the most promising alternatives for HDVs appear to be Battery Electric Trucks (BETs), Fuel Cell Electric Trucks (FCETs) powered by hydrogen, and Hydrogen-fuelled Internal Combustion Engine Trucks (H2ICETs). These are today the best options among the carbon-free (based on a tank-to-wheel approach) alternatives for road transport [15].

The technical characteristics of batteries pose challenges, especially for long-haul applications demanding extensive driving ranges [16]. This is primarily due to the weight of the battery, which reduces the payload capacity of the truck [17], although there has been considerable progress in recent years in increasing the specific energy density of lithium-ion batteries (reaching 0.125–0.250 kWh/kg) [18,19].

Fuel cell electric vehicles still face limited adoption due to the high investment costs and uncertainties regarding their lifetime [13,15]. The hydrogen-fuelled Internal Combustion Engine (ICE) is the least widespread technology, although it has similarities with natural gas-based ICEs, which makes it possible to keep prices relatively low by exploiting already well-established knowledge [20,21]. In addition to the limitations described above (which are likely to be overcome by further technological advances), a major obstacle to the widespread adoption of hydrogen-powered technologies is the lack of hydrogen infrastructure [22,23].

Total Cost of Ownership (TCO) is the prevailing methodology to assess the economic benefits of different decarbonisation pathways of heady-duty vehicles. The TCO approach allows the assessment of all the costs associated with the vehicle throughout its entire lifetime, facilitating direct comparisons between different powertrain options. Hunter et al. [24] and Burnham et al. [25] compared diesel-fuelled ICETs, FCETs, BETs, Compressed Natural Gas (CNG)-fuelled trucks and hybrid diesel-battery trucks. According to Hunter et al. [24], FCETs and BETs exhibit similar TCOs, drastically higher than diesel (about 2.00 USD/mile for BET and FCET, while it is 1.30 USD/mile for the diesel case, referred to 2021), except in a long-term scenario where FCETs become convenient on long-haul applications thanks to a reduced price of fuel cells (60 USD/kW). In addition, Burnham et al. [25] stated that BETs could become cost-competitive with diesel in 2025 for day-cab trucks (1.20 USD/mile for BET and 1.10 USD/mile for diesel). The California Air Resources Board [26] performed a similar assessment on diesel ICETs, FCETs and BETs. According to their findings, BETs could emerge as viable competitors to diesel by 2025, with TCOs in the range of 400,000 USD, compared to 600,000 USD for diesel vehicles (corresponding to 0.83 USD/mile and 1.25 USD/mile, respectively). On the other hand, FCETs could potentially achieve TCO values comparable to diesel trucks by around 2030, with a TCO of about 650,000 USD, corresponding to 1.36 USD/mile. Noll et al. [27] conducted an analogous study across multiple European countries (not including Finland), focusing on legislation and incentives. Basma et al. [28] developed a comparison between BETs and diesel trucks across various European countries. Their findings suggest that BETs could achieve competitiveness with diesel trucks in the near future, particularly if the battery price falls to around 120 €/kWh and the electricity price is 0.16 €/kWh. The outlook for FCETs appears less favourable, as they would only attain cost parity with diesel if the price of fuel cells drops below 200 €/kW and the price of hydrogen remains around 3 €/kg [29]. Additionally, Rout et al. [30] pointed out that FCETs become economically viable compared to diesel when the hydrogen price is approximately 2.0–2.3 €/kg. Lastly, a comparison including H2ICETs is exclusively presented in the study by Munshi et al. [31]. They showed that although H2ICETs are more expensive than diesel-based vehicles, they prove to be more economical than FCETs.

Some of the aforementioned works also acknowledged that the payload might change depending on the powertrain solution, but none of them provided a quantitative assessment of the effect of the powertrain on payload capacity, presenting results solely in euros or euros per kilometre. In order to incorporate information about payload capacity, it is necessary to calculate the Levelised Cost Of Transport (LCOT). This indicator represents the total cost per unit of mass transported and distance travelled, expressed as c€/(km·t). Ruf et al. [15] included the LCOT in a comparative assessment between diesel trucks, FCETs and BETs. After analysing various case studies, they concluded that FCETs could become economically favourable compared to BETs and diesel in the near future. In particular, considering hydrogen priced at 7.30 €/kg and electricity at 0.30 €/kWh, the resulting LCOTs are respectively 9.9 and 11.7 c€/(km·t) for FCET and BET, assuming a rigid-type truck travelling 95,000 km/year.

The present study focuses on an economic evaluation of various decarbonisation pathways for HDVs using the TCO methodology, also employing the LCOT indicator to examine the impact of different powertrain technologies on the payload. Specifically, Finnish heavy-duty road transport is investigated considering FCETs, BETs and H2ICETs as powertrain options. To the best of our knowledge, this is the first study that includes FCETs, BETs and H2ICETs considering different payload capacities and encompassing various case studies.

Moreover, none of the analysed literature works on this subject precisely address the Finnish context. Finland's potential for decarbonising the HDV market is significant, driven by factors like affordable grid electricity [32] and its low carbon intensity [33]. Consequently, with a well-established network of electrolysers, the produced hydrogen stands to become economically competitive while maintaining a low carbon footprint. Coupled with ongoing European initiatives aimed at enhancing hydrogen refuelling and recharging infrastructure [34], Finland emerges as one of the frontrunners poised to make hydrogen- and electric-powered trucks economically competitive against conventional vehicles in the foreseeable future. Moreover, Finland's distinctive context introduces unique challenges, including low environmental temperatures, which may potentially hinder the efficiency of electric powertrains. Additionally, truck size limitations are different from the rest of Europe: in Finland, the maximum weight of a truck is 76 t, while in most European countries it is limited to 40 or 44 t [35]. These distinctive characteristics necessitate a tailored investigation to comprehensively address their implications.

The paper is structured as follows: Section 2 shows the complete methodology employed for the analysis including all the analysed scenarios, while results are presented in Section 3. Finally, conclusions are drawn in Section 4.

2. Methodology

The aim of conducting a Total Cost of Ownership (TCO) analysis is to provide a comprehensive perspective on the costs associated with a particular vehicle throughout its lifespan. A notable advantage of TCO analysis is its ability to summarise in a unique indicator all costs, including not only the initial purchase cost but also the operational expenses, which enables meaningful comparisons between different equipment options and facilitates informed decision-making.

This section provides a complete overview of the methodology employed in the TCO analysis, from the general equations to the definition of all cost items included in the model. The different scenarios analysed (in terms of payload and mileage) are also presented and discussed.

2.1. TCO model description

In Fig. 1 the cost components considered for the TCO evaluation are reported. These include vehicle purchase costs, fuel costs, insurance costs, maintenance and repair costs, taxes and fees, road tolls and other costs specifically related to HDVs. Among these, purchase and fuel costs are generally the most impacting ones, as shown in the following sections.

The perspective of the first owner of the vehicle is assumed for this model. The TCO (in €) is calculated, as an aggregate term, according to the following expression:

$$TCO = \sum_{i=1}^{N} \frac{C_i}{(1+d)^i} \tag{1}$$

where C_i (in €) is the total cash flow of the i-th year, d (in %) the discount rate and N is the final year of the analysis.

The total yearly cash flow C_i can be determined by summing all the costs incurred in the year i-th, considering both fixed costs and variable costs (depending on the yearly mileage):

$$C_i = \sum_j C_{fixed,j,i} + D_i \cdot \sum_k C_{var,k,i} \tag{2}$$

where $C_{fixed,j,i}$ (in €) is a generic j-th fixed cost occurring in the i-th year (e.g. purchase cost, insurance cost, etc.), D_i (in km) are the kilometres travelled by the vehicle in the i-th year and $C_{var,k,i}$ (in €/km) is a generic k-th variable cost in the i-th year that is function of the travelled kilometres (e.g. fuel cost, maintenance costs, etc.).

Considering that this study refers to commercial vehicles, in particular trucks whose main use is freight transportation, particular focus should be given to freight transport capability. To properly describe the costs, final results are reported by means of the LCOT indicator, expressed in c€/(km·t). This unit allows to fast represent possible changes in the payload capacity, due to the different powertrain technologies. To express the results on a per-tonne-kilometre basis, it is sufficient to amortise the costs over the distance driven and the freight transported in each year [25,36]. The LCOT (in c€/(km·t)) can be evaluated as:

$$LCOT = \frac{TCO}{\sum_{i=1}^{N} \frac{D_i \cdot TF_i}{(1+d)^i}} \tag{3}$$

where TF_i (in t) is the transported freight in the i-th year.

2.2. Case studies description

Regarding truck weight segments, in particular those related to HDVs, it must be considered that Finland has its own legislation, different from the majority of European countries. In October 2013, there was a modification in the Finnish legislation regarding size limits, allowing full trailer combinations with a maximum length of 25.25 m and weight of 76 t [37], while most other European and North American countries typically employ vehicles with a maximum length of 18.75 m and weight of 44 t [35]. Then, starting in January 2019, the category of High-Capacity Transport (HCT) was introduced, with limit sizes of 34.50 m and maximum weight maintained at 76 t [38]. These new size limits from 2019 have led to the choice of reporting results discounted on a weight basis, ignoring the difference in volume between the trucks: in Finnish transports, the limit on the trucks is generally reached on total weight, while full volume is generally not exploited [35,39].

For a comprehensive analysis, different case studies are selected, combining truck weights and daily mileages, summarised in Table 1 and Fig. 2. They are defined as Urban route (U), Extra-Urban route (EU) and Long-Haul route (LH) and are characterised by different Gross Vehicle Weight (GVW) and related payload. For each route, two mileage values (expressed in km/day) are investigated. U and EU cases are relevant for most European countries, as they respectively involve 18 t and 42 t trucks, while the LH cases are tailored specifically to the Finnish context since they assume a 76 t truck.

In the U and EU cases, the energy storages are dimensioned in order to ensure fulfilment of the daily needs, and the required recharge or refuelling activity is performed only overnight. In the LH cases, an intraday recharge or refuelling is assumed, in order to limit the size of the battery to a reasonable dimension (an additional analysis of the same case studies operated without intraday recharging and refuelling is provided in the Supplementary Material). For the FCETs, the fuel cell is assumed to operate as a load-follower, coupled with a small-sized battery used to cover peaks of power demand [40]. Hydrogen is supposed to be stored in pressurised tanks at 700 bar.

The focus of this study is on the truck as the 'control volume' for the analysis, focusing on the costs directly incurred by the truck owner. Consequently, following the methodology of other studies [15,41], the electric and hydrogen infrastructures are assumed sufficiently developed to guarantee the required refuelling and recharging in all the described case studies. This assumption is justified by the European AFIR regulation [34], which mandates that by 2030 at the latest, public hydrogen refuelling stations will be installed in every urban node and at a maximum distance between them of 200 km on the main road network, while distance between recharging stations for HDVs is set at 60 km. These public stations will complement ongoing initiatives by truck fleet managers for installation of private refuelling stations [42]. Moreover, the cost of the infrastructure is intrinsically reflected in the prices of electricity and hydrogen. Since the analysis is not focused on infrastructure costs and this factor has a certain degree of uncertainty, a sensitivity analysis on hydrogen and electricity prices is provided in the Results section.

2.3. Cost components

This section provides all the major costs included in the TCO. This detailed description not only provides the readers with a justification for the assumptions made during the study but also allows this analysis to be easily adapted and modified in case it is applied to different case studies.

2.3.1. Vehicle purchase cost

In this study, a bottom-up approach, following the methodologies outlined by Kuhn et al. [43], Noll et al. [27] and Lane et al. [44], is adopted whenever possible. According to this method, the costs of the individual components are used to determine the final purchase cost of the vehicle. The advantage of this approach is that the results are easily verifiable and, in case of future changes in component costs, adjustments can be made without invalidating the entire calculation. In addition to the costs of the components (direct costs), the Total Purchase Cost (TPC) also includes indirect manufacturing costs and the manufacturer's net profit. Following a simplified approach, Kuhn et al. [43] used the Retail Price Equivalent (RPE) factor, which – based on the current truck market – links direct costs (C_{direct}) and TPC by taking into account both indirect costs and net profit. The Total Purchase Cost (TPC, in €) is defined as:

$$TPC = RPE \cdot C_{direct} \tag{4}$$

The RPE factor is assumed equal to 1.36, which was reported by Kuhn et al. [43] for diesel trucks. This assumption aligns with the findings of Rogozhin et al. [45], who identified the range 1.09–1.52 as reasonable for more advanced technologies, as the three powertrains considered in this study. The term C_{direct} is evaluated according to the

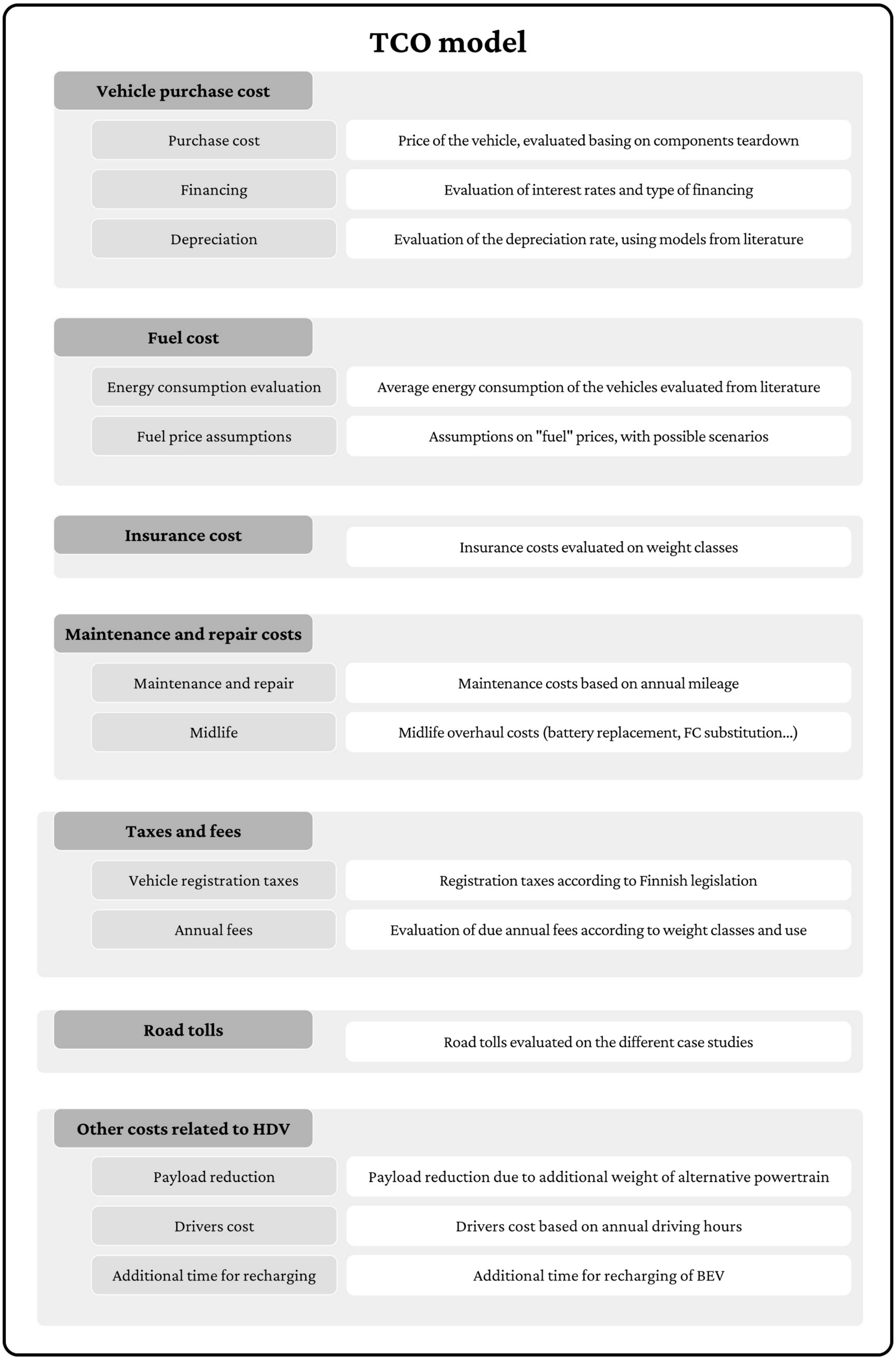

Fig. 1. TCO cost components.

Table 1
Main parameters of the six investigated case studies.

	U1	U2	EU1	EU2	LH1	LH2
Type	Rigid 4 × 2	Rigid 4 × 2	5-axle with semitr.	5-axle with semitr.	9-axle with trailer	9-axle with trailer
Cab	Day cab	Day cab	Day cab	Day cab	Sleeper cab	Sleeper cab
GVW	**18 t**	**18 t**	**42 t**	**42 t**	**76 t**	**76 t**
Max payload	12 t	12 t	25 t	25 t	50 t	50 t
Average payload	6 t	6 t	22 t	22 t	45 t	45 t
Powertrain	200 kW	200 kW	340 kW	340 kW	560 kW	560 kW
Daily mileage	**80 km**	**120 km**	**160 km**	**320 km**	**500 km**	**720 km**
Operating hours per day	5 h	6 h	5 h	6 h	8 h	9 h
Rate of decrease in yearly mileage	0%	0%	5%	5%	10%	10%
Useful period	15 years	15 years	15 years	15 years	12 years	8 years
Intraday H_2 refuelling	No	No	No	No	1	1
Intraday battery recharging	No	No	No	No	45 min	1 h 30 min

cost items shown in Table 2. The majority of cost terms depend on the power of the truck, except for those related to the type of truck (cabin, chassis, ventilation system, etc.) and the two types of storage systems, which are dependent on the energy capacity. The unit costs are assumed to be constant for all case studies, and no scale factor is included, as most of the components do not rely on a well-established manufacturing process. Total direct costs are calculated simply by summing up the cost of components of each truck. Regarding H2ICET components, the similarity between CNG truck and engine is exploited, considering identical costs [20].

The vehicles are all assumed to be bought with a 5-year financing. According to data provided by Suomen Pankki [52], the loan interest rate is set equal to 5%. After their use period at the first owner, the vehicles are supposed to be sold in the second-hand market. The Residual Value (RV, in €) of the vehicles is estimated according to Burnham et al. [25]:

$$RV(a,m) = TPC \cdot e^{(A \cdot a + M \cdot m)} \quad (5)$$

where a (in years) is the vehicle age at the end of the analysis, m (in thousands of miles) is the cumulative mileage at the end of the analysis, TPC (in €) is the total purchase cost estimated through Eq. (4), A is the percentage price retention from the previous year and M is the percentage price retention from the previous 1000 miles. Parameters A and M are evaluated based on the truck segment and their values are shown in Table 3 [25].

2.3.2. Fuel cost

The fuel cost is evaluated based on average energy consumption, a parameter strongly influenced by the powertrain type. Additionally,

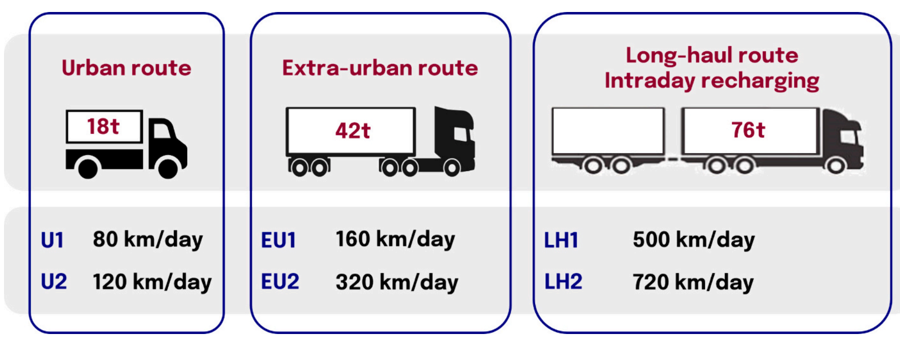

Fig. 2. Overview of the six selected case studies.

Table 2
Purchase cost breakdown. The "x" sign indicates that the component is not part of the analysed propulsion system.

Component	Cost			Unit	Reference
	BET	FCET	H2ICET		
Cab, cooling modules, chassis & driveline*	19,150–23,730	19,150–23,730	19,150–23,730	€	[28,43]
Electrical & wires, HVAC, air brakes*	6380–7910	6380–7910	6380–7910	€	[43]
Battery pack system	230	545	x	€/kWh	[15,43,46]
On board charger	65	60	x	€/kW	[28,43,47]
DC/DC converter	82	82	x	€/kW	[43,48]
HV distribution system	25	23	x	€/kW	[28,43]
Battery and electronics thermal management	19	8	x	€/kW	[28,43]
Electric HVAC system	132	132	x	€/kW	[28,43]
Electric drive unit	75	75	x	€/kW	[43]
Electric air brake compressor	1360	1360	x	€/kW	[28,43]
Electric steering pump system	273	273	x	€/kW	[28,43]
Fuel cell system	x	430	x	€/kW	[15,49]
Hydrogen storage system	x	1435	1435	€/kg	[43,50]
Internal combustion engine	x	x	55	€/kW	[27,51]
Aftertreatment unit	x	x	0.71	€/t	[27]
Transmission	x	x	5320	€	[27]

* These costs are dependent on the type of cabin: the lower value is referred to a day-cab truck, the higher value to a sleeper-cab truck.

Table 3
Values of the percentage price retention.

	Day-cab truck	Sleeper-cab truck
exp(A)	0.9113	0.9071
exp(M)	0.9991	0.9990

energy consumption depends on factors such as the size class of the vehicle, payload, type of travel and road, technical quality of the vehicle, driving mode, and more. Noll et al. [27] used data collected from the literature to define an exponential function of Energy Consumption (*EC*, in kWh/km) for FCETs, BETs and CNG trucks based on their powertrain and weight:

$$EC = a \cdot ln(w) + b \quad (6)$$

where w (in kg) is the weight, and a and b are parameters that depend on the considered powertrain technology (as shown in Table 4). In this study, the H2ICET solution is considered equal to CNG truck cases.

Unlike ICE-based vehicles, electric vehicles (both FCEVs and BEVs) suffer a sharp decrease in their efficiency at low ambient temperatures [53], mainly due to the energy demand for cabin heating. Despite an extensive literature review, no detailed analysis regarding the energy need for truck cabin heating has been found. Therefore, it is necessary to define an ad-hoc simplified model for this study. The heat transfer coefficients multiplied by the cabin areas (i.e. expressed in W/K) are found to range from 50 to 155 W/K for a day-cab truck and from 65 to 201 W/K for a sleeper cab truck, depending on the vehicle speed [54–56] (more information can be found in the Supplementary Material).

The final energy need for the cabin heating is then evaluated by approximating the average speed and the outside temperature along the considered routes on a monthly basis. Although this method may be rough on a single journey, it is acceptable for evaluating the average fuel economy on a yearly basis. The total average energy consumption $EC_{tot,avg}$ (in kWh/km) is calculated as:

$$EC_{tot,avg} = EC + \frac{\alpha_{avg}}{12 \cdot v_{avg}} \cdot \sum_{j=1}^{12} \left(T_{in,avg} - T_{out,avg,j}\right) \quad (7)$$

where EC (in kWh/km) is the energy consumption calculated according to Eq. (6), v_{avg} (in km/h) is the average speed of the case study under analysis, α_{avg} (in kW/K) is the average heat transfer coefficient multiplied by the cabin area, $T_{in,avg}$ (in °C) is the average temperature inside the cabin (assumed equal to 20 °C) and $T_{out,avg,j}$ (in °C) is the average outside temperature in the j-th month (average monthly temperatures in main cities of Finland are reported in the Supplementary Material).

The assumed average speeds for the three case studies are reported in Table 5.

The resulting energy consumptions ($EC_{tot,avg}$) for the analysed case studies are reported in Table 6.

Based on the fuel economy evaluation, the sizing of the battery storage and the hydrogen tank is performed. For the electric powertrains, as a worst-case scenario, it is assumed that the entire travel occurs at −30 °C. An extra consumption of 10% on the total average fuel economy is considered for the H2ICET cases. Furthermore, on the required driving range, a "safety" residual charge is added, equal to 100 km for the BETs and 200 km for the hydrogen-based powertrains: these different ranges are justified considering the lower diffusion of hydrogen refuelling stations compared to electric chargers, at least in the near future. The usable capacity of the battery is assumed to be 90% of the rated capacity [57], whereas hydrogen tank capacity is assumed to be 100%. The resulting energy storage sizes are shown in Table 7.

Table 4
Parameters for average energy consumption evaluation.

Vehicle type	a	b
BET	0.3814	−2.6735
FCET	0.6570	−4.1059
H2ICET (urban)*	1.1182	−6.0915
H2ICET (extra-urban)	0.9091	−6.0915

*The parameters for H2ICET in urban cases are derived by fitting the data reported by Söderena et al. [37].

Table 5
Average truck speeds for the analysed case studies.

Case	Average truck speeds (km/h)
U	30
EU	50
LH	75

Table 6
Energy consumptions for the analysed case studies.

Case	Energy consumption (kWh/km)		
	BET	FCET	H2ICET
U	1.10	2.37	4.51
EU	1.43	2.93	3.59
LH	1.65	3.32	4.13

In the reference scenario, grid electricity and hydrogen prices for overnight recharges are set at 0.10 €/kWh and 5 €/kg, respectively. For fast intraday recharge, the grid electricity price is assumed to be 0.35 €/kWh, while no difference is assumed for hydrogen price (which is kept constant at 5 €/kg). Given the high margin of error on forecasts in this field, a sensitivity analysis will be presented in the Results section for both grid electricity price and hydrogen price.

2.3.3. Insurance cost

The annual insurance cost is estimated at 5% of the residual value of the vehicle [58], computed according to Eq. (5).

2.3.4. Maintenance and repair cost

In addition to ordinary and extraordinary maintenance and repair costs, this section also includes regular inspections and major midlife costs.

Kleiner et al. [59] provided maintenance costs for different powertrain technologies (including BETs, FCETs, and CNG trucks) and two truck-segments: long-haul tractor-trailer with a gross weight of 40 t and rigid urban truck of 12 t. A linear interpolation of their results is used to evaluate the maintenance costs related to all the considered weight classes (H2ICETs are assumed to be equivalent to CNG trucks [31,59]). The resulting costs are shown in Table 8.

As far as inspections are concerned, the majority of tests on vehicles must be conducted annually, provided that no problems or malfunctions arise during the period between the scheduled checks. The estimated costs for a Finnish operator are 585 €/year for all the vehicles [60].

Midlife overhaul costs include the costs of partial or complete replacement of the major propulsion components of the vehicle due to deterioration. Regarding BETs, midlife costs entail the substitution of the battery pack, because of the decrease in its capacity caused by age

Table 7
Energy storage sizes for the analysed case studies.

Case	Energy storage		
	BET	FCET	H2ICET
U1	250 kWh	20 kg	40 kg
U2	300 kWh	25 kg	50 kg
EU1	450 kWh	35 kg	45 kg
EU2	700 kWh	45 kg	60 kg
LH1	900 kWh	45 kg	60 kg
LH2	1050 kWh	60 kg	75 kg

Table 8
Specific maintenance costs.

Vehicle	Maintenance unit cost (c€/km)		
	BET	FCET	H2ICET
18 t	6.5	7.7	11.8
42 t	10.1	10.5	15.8
76 t	15.2	14.5	21.4

and charge-discharge cycles. Usually, a battery is deemed suitable for vehicle use as long as its capacity remains above 80% of its initial value [61]. In this study, the battery lifetime is set at 500,000 km; in case this mileage threshold is not reached within 10 years, the replacement of the battery is assumed to occur in the 10th year [62,63]. The battery is then replaced with a new one and finds second-hand use in stationary applications. A residual value, equal to 15% of the original purchase price, is assigned to the replaced battery [28,64]. Concerning fuel cells, their lifetime is assumed to be 15,000 h of operation [40]: after this limit, the fuel cell efficiency is generally too low to be suitable for mobile applications. Similar to batteries, the fuel cell stack can be sold on the second-hand market and repurposed for stationary applications, with the residual value set at 25% of the original value [40]. The cost associated with the replacement of the stack amounts to 33% of the initial purchase cost of the fuel cell [43]. Considering H2ICETs, literature works reporting data about the durability of these engines are extremely limited. According to Cummins [65], hydrogen-powered ICEs are expected to have a comparable lifetime to that of traditional diesel engines in term of years and mileage, given proper maintenance. This means that powertrains of this kind could comfortably cover distances ranging from 1,300,000 to 1,600,000 km before requiring replacement [25,63]. Consequently, it is conceivable to simplify the model by supposing that no midlife costs arise throughout the lifespan of the H2ICET. Nevertheless, given the low cost of hydrogen ICEs, their duration has a relatively minor impact on the final TCO (a more in-depth analysis on this aspect is provided in the Supplementary material).

2.3.5. Taxes and fees

Many countries have introduced purchase and registration tax incentives for vehicles with new alternative powertrain, aiming to promote the diffusion of environmentally friendly cars and trucks. Unfortunately, in Finland incentives are only applicable to vehicles with a purchase price below 50,000 € [66]. This implies that mainly passenger cars or small vans are eligible for this form of support, while larger trucks are excluded from these incentives as their price is generally above this limit. No other incentives are available in Finland for alternative HDV powertrains [66].

Except for the Value-Added Tax (VAT), which amounts to 24% of the purchase cost of the vehicle [67], the other taxes incurred when purchasing the vehicle are relatively low, resulting in approximately 30 €.

In Finland, there are also currently no reductions or exemptions on annual fees for alternative powertrain vehicles, since these fees are determined solely on the basis of weight class and dimensions [68]. Annual fees corresponding to each vehicle class are reported in Table 9.

2.3.6. Road tolls

In Finland, there are no toll roads or bridges [69], making this cost term null in all the considered cases.

Table 9
Annual fees for each vehicle class.

Vehicle class	Daily fee	Annual fee
	c€/(day•100 kg)	€/year
18 t	1.3	547.50
42 t	1.0	1533.00
76 t	1.2	3328.80

2.3.7. Other costs related to HDVs

When dealing with trucks and freight transport vehicles, the main parameter for evaluating their operation is the payload: for this reason, it has been chosen to present results not only in terms of TCO, expressed in €, but also in terms of LCOT, expressed in c€/(km·t).

To accurately determine the payload capacity, weights of the energy storage devices are subtracted from the payload. The battery specific weight is assumed to be 7 kg/kWh [43], while the gravimetric density of a 700-bar hydrogen storage tank is assumed to be 4.2% [70]. The estimated weights of the energy storage units, and the resulting reduction in payload, are shown in Table 10.

Based on the data reported by Kuhn et al. [43], differences in weight due to the powertrain or other truck components, apart from the energy storage, have been considered negligible.

Considering the drivers' wage, the average gross hourly salary for a truck driver is about 22.50 €/h according to Finnish statistics [71]. In most cases, costs associated with drivers are neglected, as they are the same for the three powertrain options. According to EU legislation, a 45 min break is mandatory during the daily driving activity [72]: this break is sufficient for a complete hydrogen refuelling in LH cases, where an intraday refuelling is assumed, so no additional time is necessary. On the other hand, the intraday recharging of the battery in LH cases requires a longer time to be fulfilled, as reported in Table 1: this extra time, compared to the hydrogen-based powertrains, has been evaluated in terms of an additional driver cost.

2.4. Discount rate

The discount rate for this analysis is assumed to be 7%. This choice is made taking into account the study by Burnham et al. [25], which highlighted the need for a premium above the bond interest rate. Furthermore, the value of 5% proposed by that report is increased here, as the present analysis deals with alternative powertrain technologies, which entail a higher degree of uncertainty about future cash flows.

While the TCO is strongly influenced by the discount rate, the LCOT is not heavily affected by variations in the discount rate (a sensitivity analysis is provided in the Supplementary Material). This is because, in the definition of LCOT, the discount rate appears in both the numerator and denominator, as shown in Eq. (3).

2.5. Future scenarios

In order to investigate the role of technology learning (and related cost reductions) in the competitiveness of the selected powertrain technologies in the Finnish HDV market, an additional analysis explores potential improvements in the battery and fuel cell solutions. This assessment outlines a future scenario focusing on the costs and performance of these technologies. In this scenario, predicted for 2030, battery and fuel cell vehicles are expected to transition from a niche market to a more mass-market presence [15], leading to a decrease in their prices and an improvement in their performance. Concerning the battery technology, the foreseen improvements include a reduction in the purchase cost from 230 to 200 €/kWh [15] and a 30% increase in its specific energy [46]. For fuel cells, the cost drop will be even stronger, given that

Table 10
Weight of energy storages.

Case	Energy storage weight (in t)		
	BET	FCET	H2ICET
U1	1.75	0.48	0.95
U2	2.10	0.60	1.19
EU1	3.15	0.83	1.07
EU2	4.90	1.07	1.43
LH1	6.30	1.07	1.43
LH2	7.35	1.43	1.79

Table 11
Changed parameters from current scenario to future scenario [15,25,46].

Component	Specific	Current scenario	Future scenario	Improvement
Battery	Unit cost	230 €/kWh	200 €/kWh	−13%
	Specific energy	0.143 kWh/kg	0.186 kWh/kg	+30%
Fuel cell	Unit cost	430 €/kW	150 €/kW	−65%
	Energy consumption	2.37 kWh/km (U)	2.13 kWh/km (U)	−10%
		2.93 kWh/km (EU)	2.64 kWh/km (EU)	−10%
		3.32 kWh/km (LH)	2.99 kWh/km (LH)	−10%

H2-fuelled ICE is assumed to have no remarkable improvements in the near future.

today their market is still very narrow (not only for transport applications): the future costs scenario envisions a reduction in the purchase cost of the fuel cell stack from 430 to 150 €/kW [15] and a 10% reduction in energy consumption [25]. Considering current and foreseen markets, the price trends for FCs and batteries are not likely to proceed at equal pace. However, the investigation of a future scenario set in a specific year (2030) allows making comparisons between these two technologies, taking into account the different projected technological learning rates. The current and future indicators for batteries and fuel cells are summarised in Table 11. Hydrogen-fuelled ICEs, built upon the established technology of conventional ICEs, are not expected to undergo remarkable improvements in the coming years.

3. Results

The results section comprises three sub-sections: in the first (3.1), results related to the purchase costs of the vehicles are described to underscore the key components impacting the vehicle purchase cost. Secondly, in sub-section 3.2, TCOs and LCOTs for each case study are discussed. Finally, sensitivity analysis and future projections are addressed in sub-section 3.3.

3.1. Purchase cost

As a representative case, cost components of the purchase cost for the case LH1 are illustrated in Fig. 3. The purchase cost of the H2ICET is the lowest (159 k€), while the FCET is the most expensive (418 k€). This trend is consistent across all the analysed case studies: Basma et al. [28] reported 300 k€ as retail price for BET in 2023, Noll et al. [27] found 325 k€ for a 343 kW FCET and Munshi et al. [31] assumed about 150 k€ for the H2ICET. For the BET and the H2ICET, the major cost components are respectively the battery (dark blue bar) [61] and the hydrogen storage system (pink bar), while for the FCET the fuel cell (green bar) represents the most impacting component. It can be concluded that for BETs and H2ICETs, the purchase cost is primarily influenced by the storage capacity (i.e. which is related to the driving range), while the cost of FCETs is more connected to the rated power of the vehicle (i.e. the size of the truck). For a more detailed overview on the components of the purchase cost, including the minor ones, a table is provided in the Supplementary Material.

3.2. Case studies

In this section, the results obtained from all the case studies are presented, both in terms of TCO, in €, and LCOT, in c€/(km·t).

The TCO for the six analysed case studies is shown in Fig. 4. It is evident that, regardless of the powertrain technology, the TCO increases with the distance to be travelled (i.e. moving from the first to the second row in Fig. 4) and the size of the vehicles (i.e. from U to EU to LH cases). H2ICETs emerge as the most cost-effective solution across all analysed scenarios, except for the two urban cases (U1 and U2). In these specific case studies, despite the lower purchase cost of the ICE-based vehicle, the TCO is higher due to increased fuel costs (yellow bars), resulting from a higher energy consumption. Regarding operating costs during the vehicle lifetime, maintenance costs (orange bars) of H2ICETs are higher with respect to the electric powertrains (powered by batteries or fuel cells). Anyway, the H2ICETs entail no midlife costs (dark blue bars). The midlife costs are relatively low for fuel cells, whereas they have a significant impact on BETs, especially in the LH cases, due to the large size of the battery.

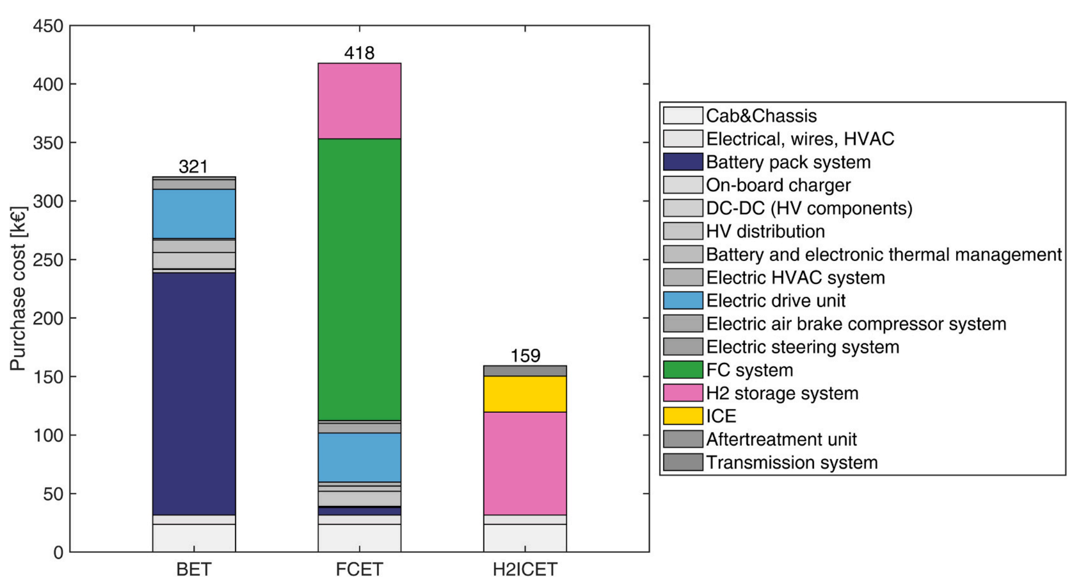

Fig. 3. Purchase cost for the three selected powertrain technologies in the LH1 case study. The figure highlights the key contributions in the purchase cost composition. A table summarising the detailed cost composition is available in the Supplementary material.

In the U1 and U2 case studies, BETs prove to be much cheaper than the alternatives, mainly because of the lower fuel costs (yellow bars): on urban routes, the battery-based powertrain is largely more efficient than the hydrogen-based options (in particular, fuel economy of the H2ICET is very low on urban routes), keeping fuel costs low. In the U1, EU1 and LH1 case studies (shorter mileage cases), FCETs stand out as the most expensive solution, primarily due to the high purchase cost (green bars) and, compared to BETs, the lower efficiency.

The case studies with higher mileage (U2, EU2 and LH2) are slightly more favourable for FCETs. Indeed, the storage sizes need to be increased to cope with the greater distance. This leads to higher purchase and midlife costs for BETs while the hydrogen tanks, which must be increased as well, do not impact so much on the TCO. Furthermore, the higher efficiency of FCETs compared to H2ICETs is better exploited on long routes.

As previously mentioned, the TCO analysis does not account for the effect of the different payload. To incorporate this aspect, the LCOT is calculated and presented in Fig. 5 for the six case studies. Since the battery system is generally heavier than the hydrogen tank, for the same TCO, the LCOT tends to favour the two hydrogen-based powertrains (FCET and H2ICET) over BET. As an example, in the EU2 case study, BETs and H2ICETs have very similar TCO values (773 and 772 k€ respectively, as shown in Fig. 4). However, when considering the LCOT, H2ICETs become the cheapest solution (6.2 and 5.1 c€/(km•t) for BETs and H2ICETs, respectively).

Except some specific cases, LCOT results generally align with the those observed in the TCO analysis. BETs represent the best solution for the urban cases (U1 and U2), as the weight and costs of the battery can be kept relatively low. In the remaining case studies, H2ICETs emerge as the most cost-effective choice, due to the lowest purchase cost (green bars) of the vehicle. The FCET is the worst solution in the cases with low mileage (U1, EU1 and LH1) since the high fuel cell cost is not compensated by the higher efficiency and the lower maintenance costs compared to H2ICETs. In the high mileage cases (U2, EU2 and H2), the FCET becomes more competitive with the alternatives but is never cheap enough to be the most economical option.

In order to assess the economic viability of the carbon-neutral solutions investigated in this work with the state-of-the-art powertrains, a comparison with literature data regarding diesel trucks is presented. In its comparative analysis, Ruf et al. [15] presented LCOTs referred also to the diesel trucks. In a use case with similar characteristics of U2, diesel truck LCOT is about 14 c€/(km·t), whereas in a case study aligning with EU2, diesel LCOT is evaluated 4.4 c€/(km·t). Notably, due to the limitations on truck sizes diffused in most of Europe, to the best of our knowledge, 76 t trucks are not included in existing literature except the present study. It is clear that, due to its technical maturity, diesel currently emerges as the most effective solution based on purely economic evaluations. This is largely attributable to the lower purchase costs of the vehicles and the cheap cost of diesel compared to hydrogen (in terms of €/kWh). However, it must be acknowledged the dynamic nature of fossil fuel costs, with diesel prices susceptible to escalation due to potential tax increments and penalties on carbon-based transport. On the other hand, it is highly likely that alternative powertrains will observe a decrease in their LCOTs, due to the anticipated declines in powertrain costs and the evolving prices of electricity and hydrogen.

3.3. Global overview

In this section, some additional analyses are presented to uncover the conditions that make each powertrain technology the most cost-effective solution.

3.3.1. Impact of daily mileage

Various combinations of truck weights and daily mileage have been investigated. Specifically, Fig. 6 extends the analysis presented in the previous sections to encompass a broader range of case studies. The three powertrain options (BET, FCET and H2ICET) are analysed for three truck gross weights (18, 42 and 76 t), considering a variable daily mileage ranging from 100 to 700 km/day. The results are displayed as a heatmap, where each cell shows the LCOT value associated with the selected combination. The colour of the cells represents the level of cost-competitiveness of the selected combination according to the LCOT

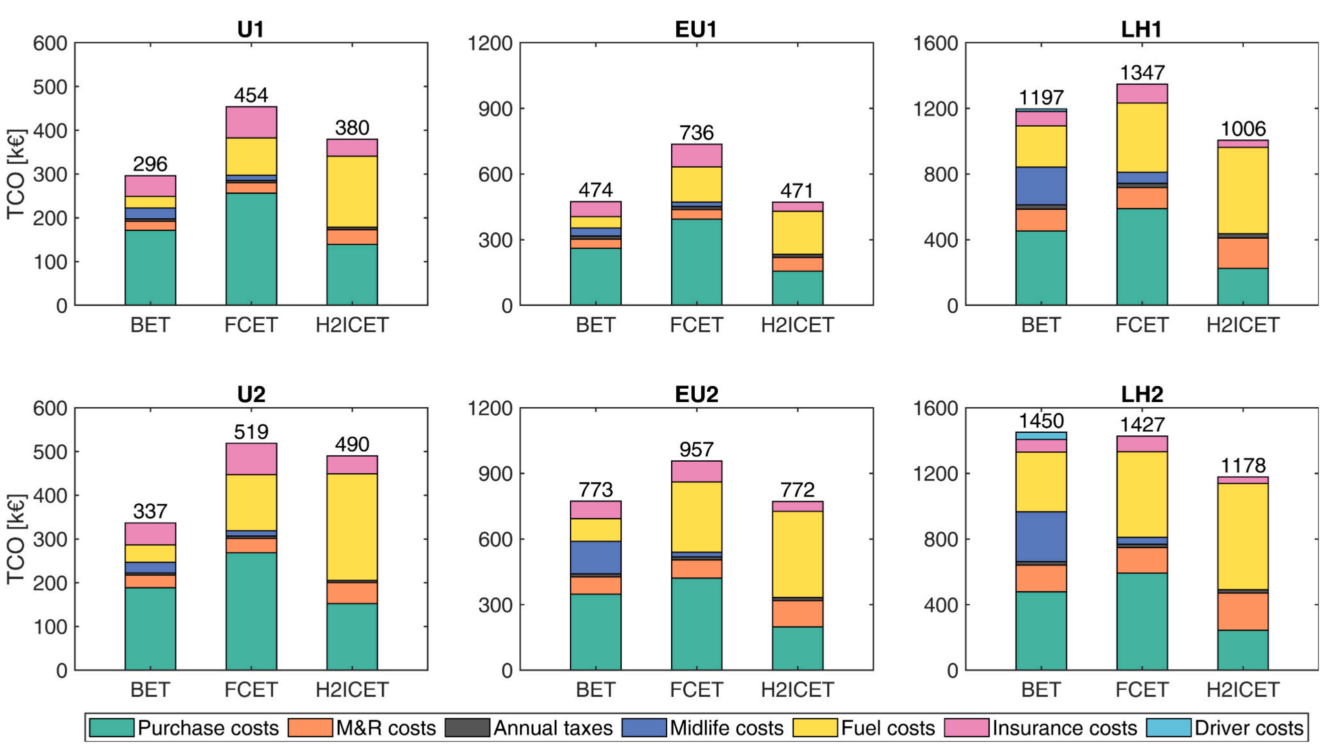

Fig. 4. Total cost of ownership (TCO) for the six investigated case studies. M&R refers to "Maintenance and repair" costs. Grid electricity price is assumed equal to 0.10 €/kWh (0.35 €/kWh in fast recharging spots) and hydrogen price equal to 5 €/kg.

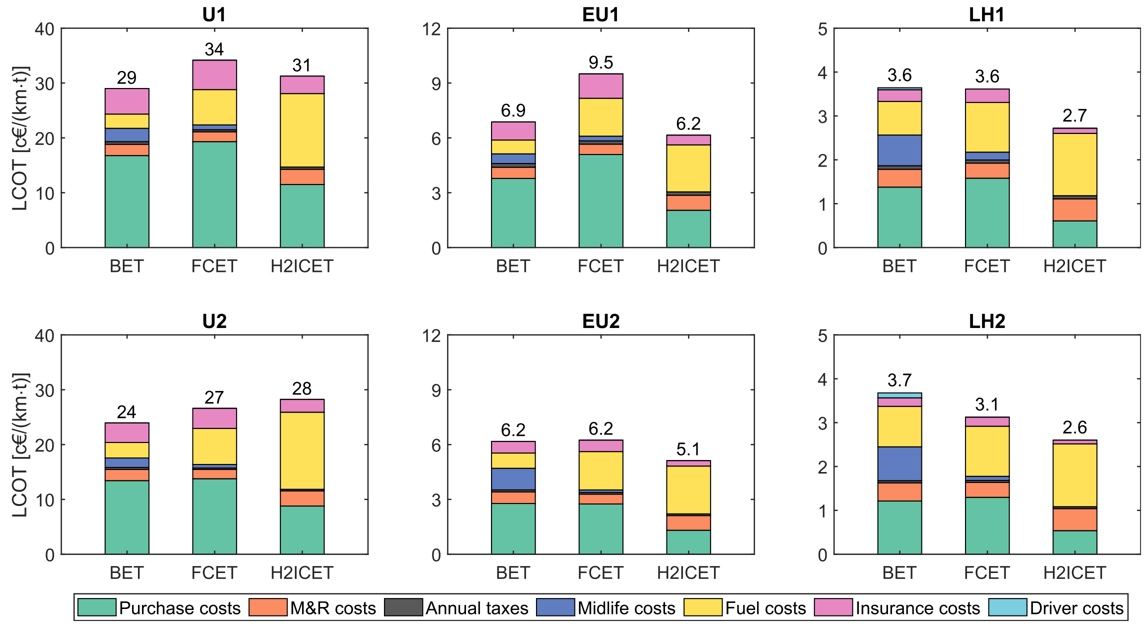

Fig. 5. Levelised cost of transport (LCOT) for the six investigated case studies. M&R refers to "Maintenance and repair" costs. Grid electricity price is assumed equal to 0.10 €/kWh (0.35 €/kWh in fast recharging spots) and hydrogen price equal to 5 €/kg.

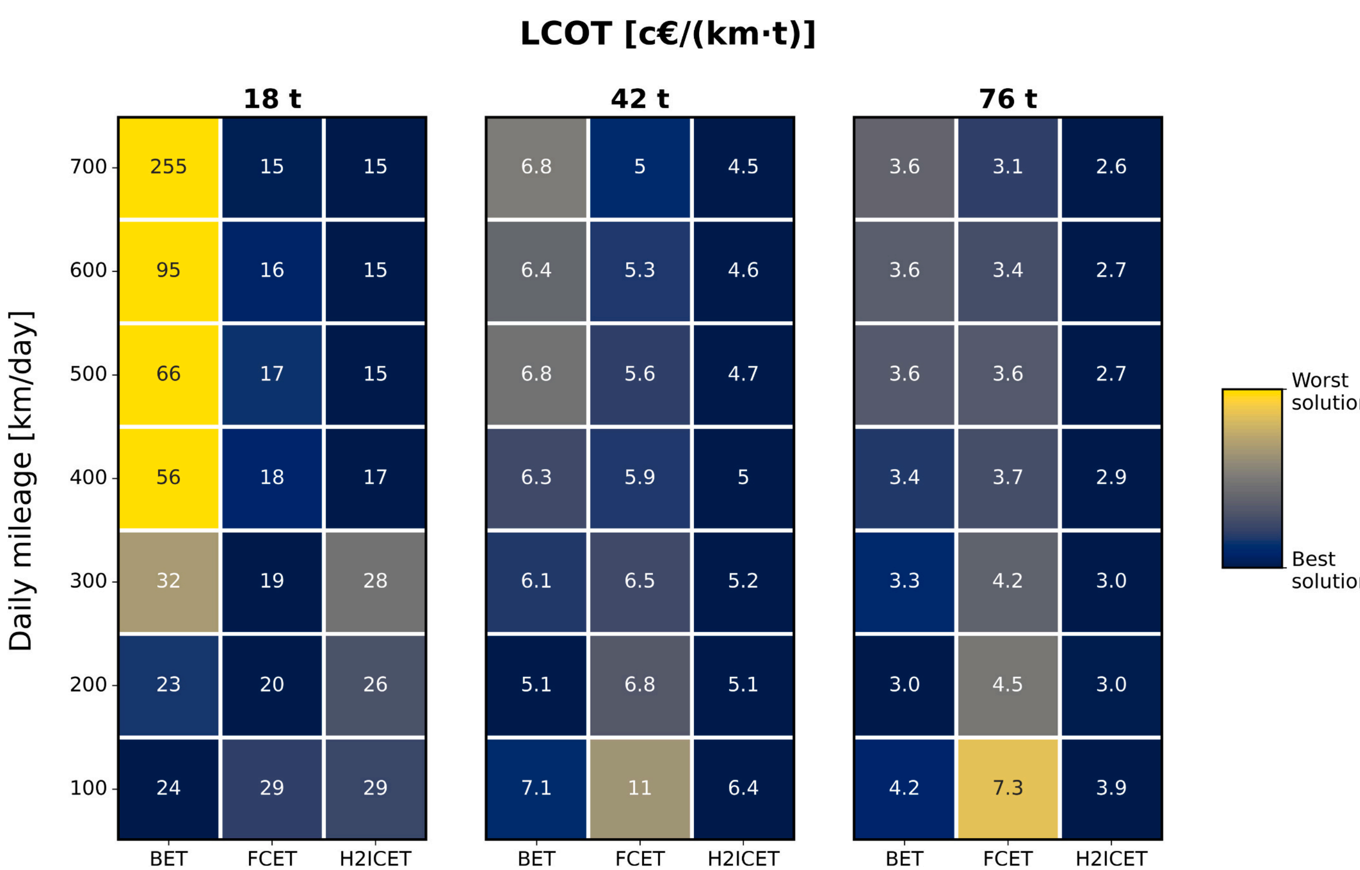

Fig. 6. LCOT (in c€/(km•t)) for the three powertrain technologies (BET, FCET and H2ICET), for three truck gross weights (18, 42 and 76 t) and variable daily mileages (100 to 700 km/day). The colour of the cells represents the level of cost-competitiveness of the selected combination of weight and daily mileage according to the LCOT indicator, from cost-optimal solutions, in dark blue colour, to the worst cases, in yellow colour. Grid electricity price is assumed equal to 0.10 €/kWh (0.35 €/kWh in fast recharging spots) and hydrogen price equal to 5 €/kg. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

indicator: from cost-optimal solutions, in dark blue colour, to the worst cases, in yellow colour.

By analysing Fig. 6, it becomes clear that BETs are the cost-optimal choice as long as the daily mileage is kept very low (about 100–200 km/day). However, as daily mileage (more specifically, the driving range) increases, the battery becomes too expensive and heavy, making the LCOT less competitive compared to the other types of powertrains. The FCET proves to be the best solution for cases involving a "small" truck (18 t) and high daily mileages (200 km/day or above). This is because the fuel cell stack is relatively small (with low weight) and cost-effective and the hydrogen storage is cheaper than the battery storage. For larger trucks (42 and 76 t), the H2ICET emerges as the most favourable solution in terms of LCOT in the current HDV market, primarily attributed to its low engine costs compared to fuel cell and battery powertrains.

When examining Fig. 6, it is noteworthy that, across various scenarios of daily mileage, a distinct superiority is not always evident, as the LCOT from the BET, FCET and H2ICET cases appear to be quite comparable.

3.3.2. Impact of electricity and hydrogen prices (current scenario)

Given the significant influence of both electricity and hydrogen prices in the definition of the cost-competitiveness of the analysed solutions, the LCOT indicator is analysed under variable electricity (0.04–0.24 €/kWh) and hydrogen (2–12 €/kg) prices. The findings are shown in Fig. 7, where the colour of the cell represents the cost-optimal powertrain among the three analysed, and the number within the cell indicates the corresponding LCOT.

In the cases of 18-t trucks (U1 and U2), when the hydrogen price exceeds 4 €/kg, the most convenient solution is the BET (light blue cells), due to the high efficiency and the low cost of batteries. As the truck size increases, H2ICETs (orange cells) become increasingly predominant, especially for the 76-t truck cases (LH1 and LH2), where H2ICETs are generally the best choice when the hydrogen price remains below 10 €/kg. Finally, it is noteworthy that in the current scenario (in terms of cost of technologies), FCETs are almost absent as a cost-optimal option.

3.3.3. Impact of electricity and hydrogen prices (future scenario)

A sensitivity analysis on electricity and hydrogen prices is conducted, using the predicted future costs and performances of the powertrain technologies outlined in Table 11. The results are shown in Fig. 8.

In this future scenario, FCETs (green cells) emerge as the best choice in various combinations of electricity and hydrogen prices, as their purchase cost becomes nearly competitive with that of H2ICETs. Furthermore, the lower efficiency of fuel cells compared to batteries is, in most of the cases, compensated by the lower cost and weight, leading to a convenience of the FCET option, except at high hydrogen prices (above approximately 6 €/kg and 10 €/kg for the U and LH cases, respectively).

The only exception is observed in the EU1 case study, where the combination of a short daily mileage (160 km/day) and a large truck (42 t) makes FCETs less convenient than the other two solutions. This is because the FCET purchase cost is higher than that of the H2ICET, and the higher efficiency of fuel cells compared to ICEs cannot be appreciated on such a short driving range.

On the other hand, in the urban case studies (U1 and U2), FCETs and BETs compete to be the most cost-effective solution in the ranges representing the most likely future electricity and hydrogen prices (about

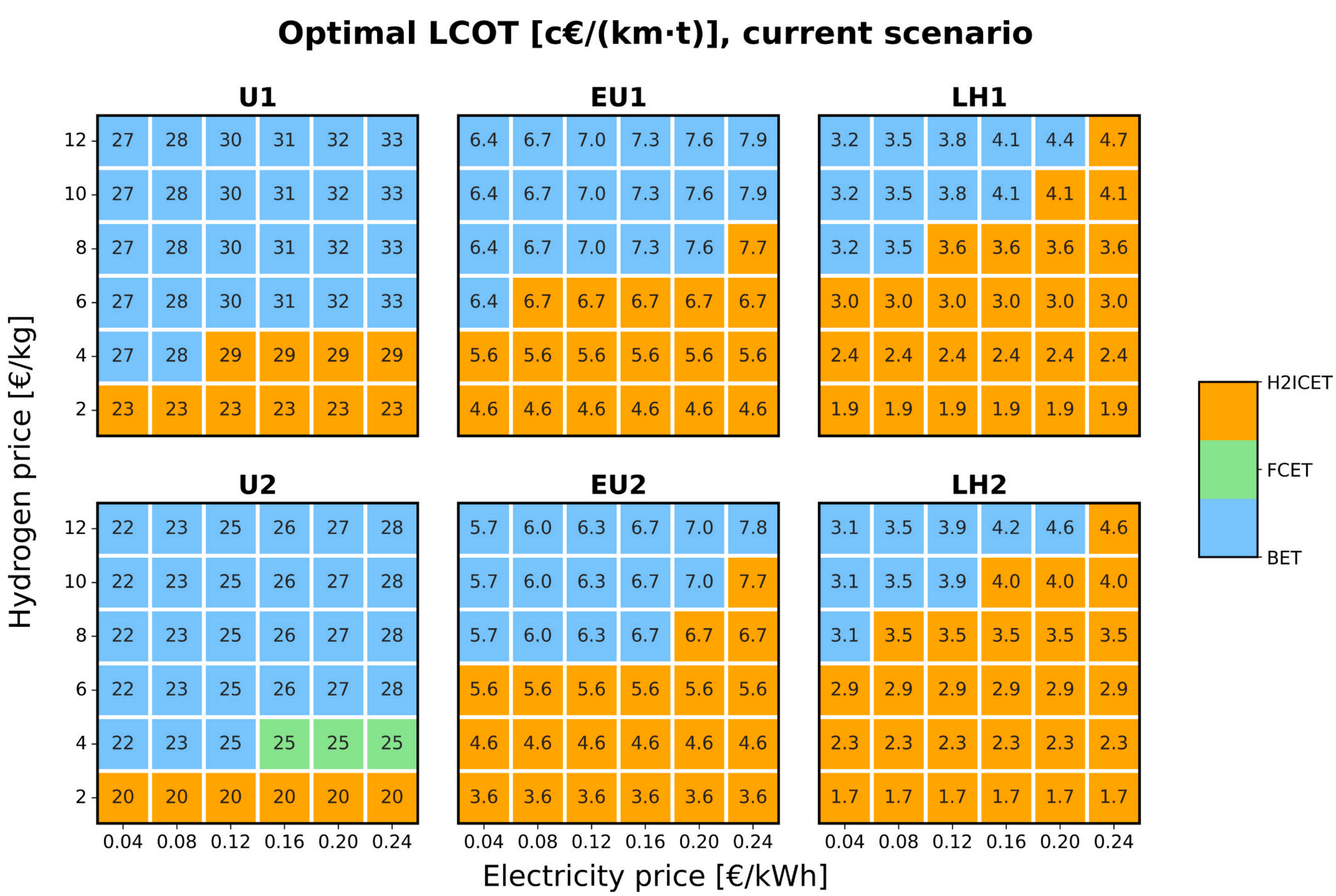

Fig. 7. Map of the cost-optimal solutions, in the current cost scenario, for the six investigated case studies under variable electricity (0.04–0.24 €/kWh) and hydrogen (2–12 €/kg) prices. The colour of the cell represents the cost-optimal powertrain among the three analysed.

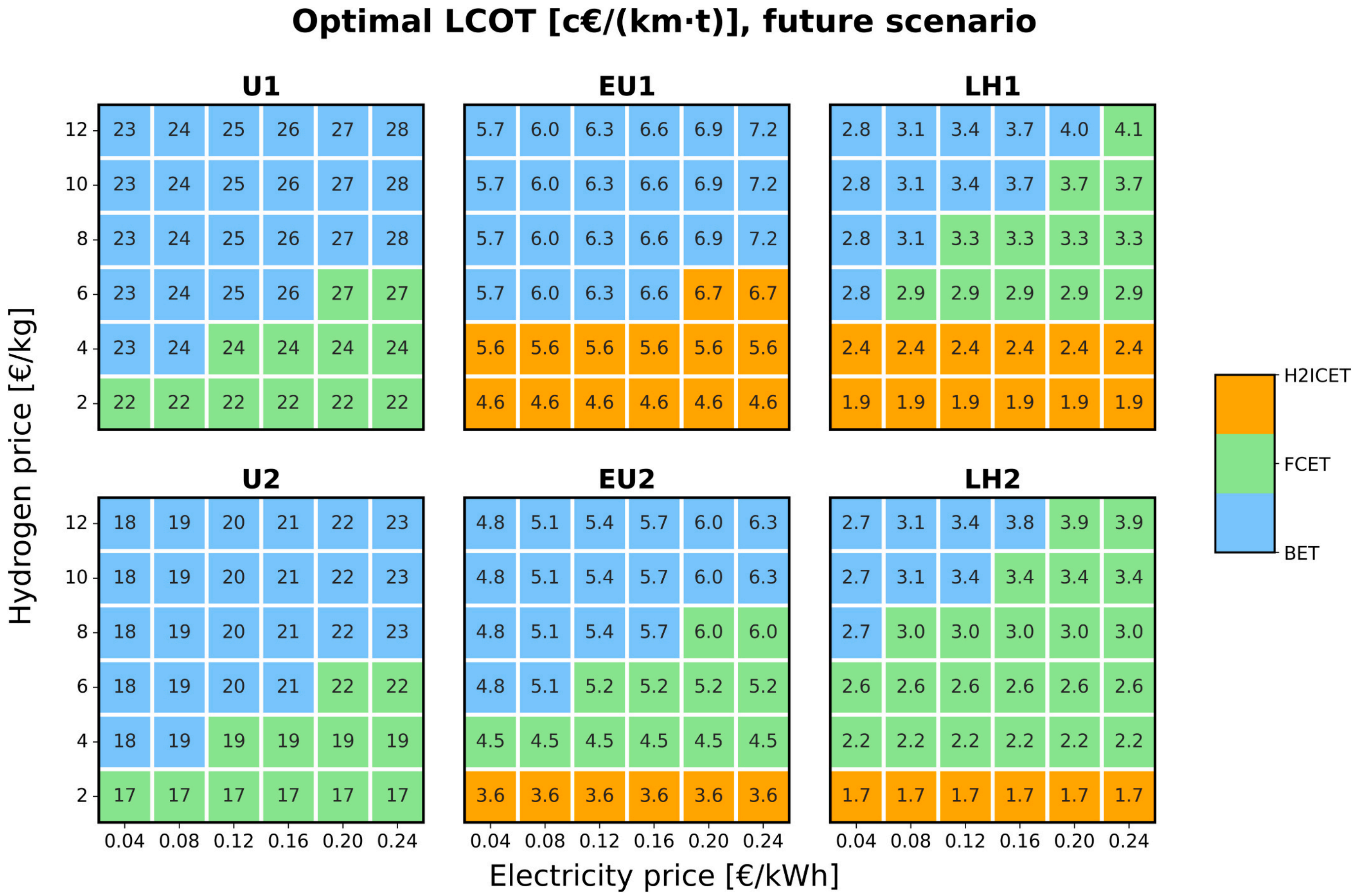

Fig. 8. Map of the cost-optimal solutions, in the future cost scenario, for the six investigated case studies under variable electricity (0.04–0.24 €/kWh) and hydrogen (2–12 €/kg) prices. The colour of the cell represents the cost-optimal powertrain among the three analysed.

0.10 €/kWh and 4–6 €/kg, respectively), with subtle differences in the LCOT values. When both electricity and hydrogen prices are high, the higher efficiency of the BET makes it advantageous, even if the payload reduction due to the battery weight is higher than that caused by the hydrogen storage.

It should be noted that in some reports, more optimistic values can be found regarding the future development of technologies and their associated costs, especially for fuel cells [28,29]. More optimistic scenarios would obviously enhance the competitiveness of FCETs across various combinations of electricity and hydrogen prices.

4. Conclusions

In this study, an economic comparison of alternative powertrain solutions for heavy-duty transport is presented using the Total Cost of Ownership (TCO) methodology. The assessment involves battery trucks (BETs) and hydrogen-powered trucks (H2ICETs and FCETs), and is specifically applied to the context of Finland. The work thoroughly investigates several case studies in terms of daily mileage and payload. Additionally, sensitivity analyses are included to attain a comprehensive overview of the key parameters affecting the cost-optimal solution, providing a general understanding of the strengths of each powertrain technology. The boundaries of this study are limited to the costs directly incurred by the truck owner, excluding the infrastructure costs for recharging and refuelling.

Overall, the study highlights that the most cost-effective powertrain option varies across different case studies due to diverse operating conditions and background parameters influencing the results. The main outcomes of this work can be summarised as follows:

- In the current cost scenario, BETs prove to be the most cost-effective option when operating with small trucks (18 t) on short mileages (below 200 km/day). This is attributed to the high efficiency and the low purchase cost of the vehicle, given that the battery size is relatively small due to the limited driving range. As the duration of the trips increases (above 200 km/day), and particularly with extended driving ranges, FCETs also become competitive, because of the lower cost of hydrogen storage compared to batteries and the reduced midlife costs. For larger trucks (42 or 76 t), the hydrogen-powered ICE, despite its lower efficiency, emerges as the best powertrain choice due to its lower purchase costs.
- Variations in the prices of electricity and hydrogen could yield different results, as indicated by the sensitivity analyses presented in previous sections. Generally, BETs demonstrate a more favourable response to high electricity and hydrogen prices, due to the high efficiency of the battery. Conversely, for low prices, the two hydrogen-based powertrains can become more cost-effective options. On urban cases, H2ICET would only be economically viable when the hydrogen price falls below 4 €/kg. This threshold increases to 8 and 10 €/kg for extra-urban and long-haul cases, respectively.
- Fuel cell powertrains are expected to become a promising technology in the future cost scenario. FCETs will indeed be effective in urban cases when the hydrogen price is about 2–6 €/kg and in long-haul applications unless the electricity price is particularly low (0.08 €/kWh or below).

The methodology developed in this work is versatile and can be adapted to different case studies. With minor adjustments to the input parameters, this model could effectively analyse diverse needs and situations, covering a wide range of potential applications for road heavy-duty vehicles. Moreover, the entire study, and in particular the sensitivity analyses on electricity and hydrogen prices, enlightens the need for data specifically tailored to each case study, in order to achieve accurate and precise results. To identify the best powertrain option, a complete knowledge of prices of electricity and hydrogen, driving range, payload and daily mileage of the specific case study is necessary.

In future studies, attention will be directed towards assessing the technical and economic feasibility of the required recharging and refuelling infrastructure networks, including considerations of both present scenarios and future projections. The fast development of the infrastructure is essential to maximise the widespread adoption of sustainable alternative technologies, such as battery and fuel cells electric vehicles.

CRediT authorship contribution statement

Alessandro Magnino: Writing – original draft, Visualization, Software, Methodology, Investigation, Data curation, Conceptualization. **Paolo Marocco:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Data curation, Conceptualization. **Aleksandra Saarikoski:** Writing – review & editing, Validation, Resources, Methodology, Investigation. **Jari Ihonen:** Validation, Supervision, Resources, Methodology, Investigation, Data curation, Conceptualization. **Markus Rautanen:** Validation, Supervision, Resources, Methodology, Investigation, Data curation, Conceptualization. **Marta Gandiglio:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Data curation, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.est.2024.113215.

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