International Journal of Hydrogen Energy 211 (2026) 153615

Contents lists available at ScienceDirect

International Journal of Hydrogen Energy

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

Cost efficiency in clean urban mobility: TCO breakdown of hydrogen and electric buses in the European Union with projections for 2030 and 2050

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ARTICLE INFO

Keywords:
Hybrid hydrogen internal combustion engine
Fuel cell vehicle
Battery electric vehicle
Total cost of ownership (TCO)
European Union

ABSTRACT

The decarbonization of urban public transport is a key objective of European climate and energy policies, driving the adoption of alternative propulsion technologies for city buses. Battery-electric and hydrogen-based powertrains are among the most promising solutions for greenhouse gases abatement, however, even economic competitiveness, which depends on technology evolution, energy costs, and vehicle design characteristics, must be evaluated. This paper presents a Total Cost of Ownership (TCO) analysis of urban buses equipped with four different propulsion systems: battery electric, and three hydrogen-based concepts. The analysis is performed for the whole European market under three temporal scenarios: 2024, 2030, and 2050. Key factors such as vehicle mass and the number of major component replacements over the vehicle lifetime are explicitly considered. The results indicate that the most cost-effective powertrain varies across scenarios, demonstrating that no single technology is universally optimal, emphasizing the importance of scenario-dependent evaluations for strategic planning.

SYMBOLS/ABBREVIATIONS

100 GH	100 % Green Hydrogen Scenario
BEV	Battery Electric Vehicle
capex	Capital Cost Expenditure
C_{En}	Average Energy Cost
C_{ES}	Cost of Energy Storage
C_G	Cost of Glider
C_{In}	Average Insurance Expenses
C_{PWT}	Cost of Powertrain
CtG	Cradle-to-Grave
C_{Tn}	Average Taxes Expenses
EGM	Electricity Generation Mix
EM	Electric Motor
EU	European Union
FC	Fuel Cell
FCV	Fuel Cell Vehicle
GM	Gross Margin
H_2ICE	Hydrogen Internal Combustion Engine
H_2ICEV	Hydrogen Internal Combustion Engine Vehicle
HFV	Hydrogen-Fuelled Vehicle
HH_2ICE	Hybrid Hydrogen Internal Combustion Engine
HH_2ICEV	Hybrid Hydrogen Internal Combustion Engine Vehicle
HM	Hydrogen Mix Scenario
km_{life}	Vehicle Kilometric Lifespan
LCA	Life Cycle Assessment
maintenance	Maintenance Cost
$M_{extra-ord}$	Extra-Ordinary Maintenance
M_{ord}	Ordinary Maintenance
NMC	Nichel-Manganese–Cobalt
opex	Operating Cost Expenditure
PEM-FC	Proton-Exchange Membrane Fuel Cell
SFC	Specific Fuel Consumption
TCO	Total Cost of Ownership
$year_{life}$	Vehicle Yearly Lifespan

1. Introduction

The European Green Deal, unveiled by the European Commission in 2019, represents a transformative policy with the goal of making the European Union the first climate-neutral region by 2050 [1]. A key component of this ambitious objective is the decarbonization of the

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https://doi.org/10.1016/j.ijhydene.2026.153615
Received 9 July 2025; Received in revised form 16 January 2026; Accepted 18 January 2026

transport sector, which contributes to more than a quarter of Europe's greenhouse gas emissions [2]. For sure, the best way to decarbonize the transport sector is to reduce the number of circulating vehicles, promoting collective transport solutions. Hydrogen-Fuelled Vehicles (HFVs) as well as Battery Electric Vehicles (BEVs) have been proven as viable alternatives for reducing the carbon footprint of the transport sector (the best solution depends on the considered scenario [3]). While BEV buses are already widely deployed, HFV buses are gradually gaining traction and public acceptance [4–11]. Despite the infrastructure-related challenges (especially for hydrogen) [12], the introduction of hydrogen in the collective transport sector is facilitated by the fact that operational routes are predetermined, allowing for refueling to be consistently carried out at the same locations (i.e., the depots). Hydrogen can be adopted in both Fuel Cells (FCs) and Hydrogen Internal Combustion Engines (H_2ICEs) without producing any CO_2 tailpipe emissions [13,14]. For automotive applications, Proton-Exchange Membrane Fuel Cells (PEM-FCs) are typically used due to their fast startup time and low operating temperature [13]. PEM-FCs convert the chemical energy of hydrogen directly into electrical energy through an electrochemical reaction, bypassing the thermodynamic losses associated with combustion, resulting in high conversion efficiency [13,15,16]. The efficiency of H_2ICEs differs significantly because of the nature of their energy conversion processes. H_2ICEs typically achieve peak efficiency at high loads (when the engine is near its maximum torque output). Conversely, FCs efficiency is generally higher than that of H_2ICEs, but it drops under fast transient conditions [17–19]. As noted by Muthukumar et al. [20], PEM-FC vehicles (FCVs) are always equipped with batteries to support dynamic power demands. Generally, for H_2ICEs, conventional powertrain have been considered (i.e., engine coupled with gearbox) [21] and only recently hybrid layouts have been proposed [3,22,23] to enhance overall efficiency by decoupling the engine from the wheels in a series hybrid configuration (HH_2ICEs). However, economic feasibility must be considered alongside environmental impact and efficiency to ensure that the chosen powertrain solutions are not only cost-effective but also sustainable and capable of reducing carbon emissions while maximizing energy use. To accurately assess the financial viability of different powertrain configurations, it is essential to employ a Total Cost of Ownership (TCO) framework [24]. This framework helps estimating the costs associated with capital expenses (*capexes*), with operating expenses (*opexes*), and with the maintenance of the vehicles. By factoring in not only initial acquisition costs but also fuel, maintenance (ordinary and extraordinary), infrastructure, and potential government incentives, the TCO model provides a comprehensive picture of the true cost over the lifespan of the vehicle. This is particularly important when comparing emerging technologies, as their economic feasibility can vary significantly depending on factors such as energy/hydrogen prices, technological advancements (i.e., breakthrough technologic development), and regulatory changes. In fact, as reported by Wang et al. [25] newly developed technologies as BEVs and FCVs present almost double the capexes of conventional vehicles, mainly owing to powertrain and energy storage components. Conversely, the situation changes when the focus is shifted to opexes. Energy costs show primary impact on opexes (BEVs present lower energy cost), even if for BEVs the main contribution in the total opexes is represented by insurance expenses [25]. Finally, the potential need for components replacement (e.g., battery, FC) could affect the overall TCO, therefore extraordinary maintenance potential must be carefully kept into account [26]. Ultimately, a TCO analysis enables informed decision-making for fleet operators, policymakers, and manufacturers, ensuring that sustainable transportation solutions are both environmentally and financially competitive. In this context, Ally and Prior [27] evaluated the lifecycle cost of diesel, natural gas, hybrid and fuel cell urban solutions in the energetic panorama of Australia. They discovered that the capex of innovative solutions is higher with respect to conventional ones (being less consolidated), and the only possible way to make such powertrains more competitive is to abate opexes (i.e., incentives). Rout et al. [26] came to the same conclusion, suggesting that FCVs could become more competitive than BEVs only under particular reduction of the hydrogen prices. According to them, conventional bus vehicles are still the least expensive solution with respect to FCVs, while BEVs might reach the same range depending on the Electricity Generation Mix (EGM). The effect of the ownership time has been assessed as well: if 6 years are considered, conventional vehicles remain the least expensive, while under the hypothesis of 16 years, BEVs reach the same values. HFVs always present higher costs, especially when carbon capture technologies are considered. The results change if carbon tax is considered on diesel leading to a scenario where BEVs become the optimal solution. However, the year of purchase influences TCO, owing to technologic advancements and prices reduction [28]. Even other aspects have to be considered: according to Muñoz et al. [28] the breakeven point between conventional and electric powertrains is a function of kilometric autonomy. BEVs TCO is almost 0.6 $/km higher than conventional powertrains (considering an autonomy of 200 km), while FCVs are extremely penalized by hydrogen cost (which accounts up to 0.8 $/km). Furthermore, as demonstrated by Chen and Wang [29] hydrogen cost is affected by the production method (for instance, green hydrogen could end up doubling the fuel cost with respect to grey hydrogen). In this context, Peiretti Paradisi et al. [30] suggested that hydrogen buses might be optimal if hydrogen price drops below 4 €/kg. These results are in agreement with the ones of Wang et al. [25] where a TCO model has been developed reporting up to 80 % higher costs for BEVs and FCVs, with respect to conventional vehicles. However, future batteries and FCs prices drop might lead to more competitive BEVs and FCVs capexes. Even Di Vece et al. [31] studied this aspect, expecting conventional vehicles to present a time-increasing TCO (owing to fuel cost), while FCVs' and BEVs' are expected to decrease. While BEVs start with lower TCO, the forecasted reduction over the years is more limited with respect to that of FCVs, and a breakeven with FCVs is expected in 2030 [31]. On the other hand, according to Kim et al. [11], the impact of batteries on BEV buses' TCO today is 33 %, reaching 7 % in 2030, while for FCV buses, the fraction would remain unaltered.

As emerged, TCO allows for an analysis of vehicle costs, but as highlighted in the literature, it is influenced by technological advancements (that make the cost of components evolve), as well as the cost of energy which can significantly change with the considered EGM (changing from country to country). Therefore, evaluating TCO for HFVs and BEVs is not enough. A detailed investigation, considering each European country with its associated energy mix costs (both present and future) provides a more accurate assessment of the economic impact of each configuration across the entire European Union (EU). Despite in the literature the TCO of BEVs/FCVs is usually compared with conventional vehicles, limited space has been given to H_2ICEs (while no TCO analyses on HH_2ICEVs have been found). For this reason, in the present work an analysis of the TCO for HFVs (including H_2ICE-powered vehicles) is provided, as these solutions could offer greater economic viability due to potential retrofit from existing conventional solutions. Furthermore, as these vehicles are relatively new with respect to conventional ones, the analysis of future scenarios (i.e., 2030 and 2050) is necessary to evaluate the technology improvements impact, which could change the TCO in a relatively short/medium period.

2. Materials and Methods

The development of the TCO model for urban vehicles involves a comprehensive analysis of all costs associated with acquiring (capital costs, including purchase price, financing and possible detaxation as for the first 5 years for the BEV), operating (such as energy cost and insurance), and maintaining buses over their entire lifecycle (i.e., service, battery replacement, etc.). In the present work, four different powertrain configurations have been considered: BEV, FCV and two types of H_2ICEV: pure H_2ICEV and HH_2ICEV [3].

2.1. Capex

For the calculation of the capex the model proposed by Wang et al. [25] has been followed (Eq. (1)).

$$capex = \frac{C_{PWT} + C_{ES} + C_G}{1 - GM} \quad (1)$$

Where C_{PWT} represents the cost of the powertrain (i.e., Engine, FC and Electric Motor, EM), C_{ES} refers to the energy storage (i.e., tanks and batteries), C_G to the glider and GM is the gross margin. The prices of powertrain and fuel tanks/batteries are influenced by the year of production due to the technological improvement [30,32,33]. Starting from these data and considering cost reduction scenarios the future costs of FCs and batteries have been derived [30–33].

2.2. Opex

As discussed in the *Introduction*, the opexes are the operational expenses, thus extremely influenced by the considered lifespan. As this work focuses on urban buses, a kilometric lifespan (km_{life}) equal to a million kilometers has been considered over 17 years ($year_{life}$).

The annual opex can be calculated following Eq. (2), where SFC represents the Specific Fuel Consumption (in kWh/km), C_{En} the energy cost, C_{Tn} the taxes expenses at and C_{In} the average insurance expenses at the n-th year [34].

$$opex_n = SFC \cdot \frac{km_{life}}{year_{life}} \cdot C_{En} + C_{In} + C_{Tn} \quad (2)$$

The SFCs of the considered vehicles have been derived from a previous work [3], while for the current and future non-household prices of electricity and hydrogen data have been derived from the literature [35–37]. As regards electricity generation, its cost could be influenced by political, economic, and social factors, therefore it is extremely difficult to accurately forecast its cost. For electricity cost, country-based non-household data have been imported from Eurostat [38]. Building on these data, electricity cost uncertainty is addressed through a scenario-based approach rather than through explicit probabilistic bounds. For the baseline year, observed Eurostat prices implicitly reflect the combined effects of political, economic and social conditions, including market regulation, fuel price volatility and policy interventions [38]. For 2030, country-specific electricity price trends are derived from literature-based projections that explore alternative policy-consistent scenarios, accounting for different levels of renewable deployment, CO_2 pricing and exposure to fossil fuel markets [39]. For 2050, given the substantially higher uncertainty associated with long-term socio-economic and political developments and the lack of robust country-level projections, a harmonized trend derived from averaged long-term scenarios is adopted to represent a representative decarbonization-oriented pathway while ensuring internal consistency of the modelling framework [40].

While for hydrogen, two different scenarios have been considered. In the first one, a mix of green, blue and grey hydrogen has been hypothesized for each EU Country, according to their current hydrogen production mixes, and considering the forecast of Hydrogen Mix (HM) evolution. The second option considers 100 % green hydrogen (100 GH) [3,23]. This 100 GH hypothesis could be considered representative as the bus recharges always at the depot where potentially a green hydrogen production station could be installed. This assumption is consistent with the operational characteristics of captive bus fleets, which refuel at a central depot, and with several real-world deployments where hydrogen refueling stations with on-site or locally integrated green hydrogen production are already implemented at bus depots (e.g., Aberdeen, SunLine, AC Transit, Ferrara [41–44]). Despite green hydrogen being the most expensive one (i.e., >8 €/kg), its cost is expected to decrease by 2030, and to reach a minimum close to 2 €/kg in 2050 [45]. On the contrary, grey hydrogen is expected to become more expensive (owing to carbon taxes), reaching up to average 2.6 €/kg in 2050 (in 2024 the considered price is close to 3.5 €/kg), while blue hydrogen is expected to show the lowest variation (its price is expected to remain always between 3.5 and 5 €/kg) [45]. Finally, both ownership taxes, and the insurance contribution have been kept into account [26]. Being the insurance contribution strongly dependent on many factors such as driver's age, vehicle type, location and accident history, it has been estimated as 1.5 % of the purchase price [28,46,47].

2.3. Maintenance

Maintenance costs have been calculated (Eq. (3)), considering the ordinary maintenance (i.e., lubricating oil change, for both engines and gearboxes, replacement of wheels, brakes, brake pads and filters over the entire life of the vehicle) and the extraordinary one, which involves specific major powertrain components (i.e., battery, FC, H_2ICE) replacement [30,46]. Focusing on the rationale behind the choice of the replacement rates of these specific major powertrain components, despite the fact that the replacements' frequency can vary among the different powertrain layouts as a function of operating conditions, it was assumed that, for any given scenario, all specific major powertrain components replacements occur the same number of times and at the same moments over the vehicle's lifetime. As for the specific rates chosen, regarding the battery, an expected life of 2′000 cycles can be taken as a reference [31,48]. Taking into account one recharge/day, around 60′000 km/year driven [31,49] with a mean of 200 km/day [31,50,51], the battery lasts between 400′000 and 600′000 km, depending on working conditions (i.e., external temperature and passengers' load, thus consumptions, depth of discharge and discharge rate). For FCs and H2ICEs, an estimated lifetime of 20′000 h [31,52] can be taken as a reference. Considering the mean speed of the cycle (22.5 km/h), an equivalent life of around 450′000 km can be calculated, which, with a vehicle lifetime mileage of 1 million km, justifies the choice on the investigated replacement rates of the specific major powertrain components.

$$maintenance = M_{ord} + M_{extra-ord} \quad (3)$$

2.4. Input data

The data adopted as input for the present analysis derive from previously developed models [3], where the performance of four different powertrain configurations (BEV, FCV, HH_2ICEV and H_2ICEV) have been assessed on the Braunschweig homologation cycle as a function of different external temperatures and passenger loads (curb weight of 9 and 12 ton). Table 1 summarizes the input data adopted in the present work, coupled with their respective references. The four configurations have been sized for a net 100 kW power output, while proper tanks and batteries sizes have been adopted with respect to vehicle weight (thus consumption, to guarantee a fixed autonomy). For all configurations, Nichel-Manganese–Cobalt (NMC) batteries have been considered as PEM for FCs. As regards specific costs, the most recent literature data [30,32,33] have been adopted for batteries and FCs to stick with current technological development, while detailed price reduction trajectories have been imposed [32,33]. Even SFC data are reported for the different configurations (9 ton and 12 ton of curb weight) for the different powertrains. Overall, SFCs show minimal values for BEVs, followed by FCVs and then by hybrid and conventional H_2ICEVs. Table 1 reports the minimum and maximum SFCs for a given configuration which is affected by passenger load and external temperature [3], which are fundamental aspects in considering feasible SFC for different countries, where characteristic external temperatures might significantly differ.

Focusing on energy sources, both hydrogen and electricity prices have been carefully evaluated. Fig. 1 displays the hydrogen prices of grey, blue and green hydrogen as a function of the three years

Table 1
Input parameters of the model.

Components Data

Powertrain	Parameter	Size (9 ton &12 ton)	Baseline Specific Cost	2030 Cost Variation w/r 2024	2050 Cost Variation w/r 2024
H_2ICEV	Glider	6 m	12500 €/m [31]	0 %	0 %
	Engine	100 kW	30 €/kW [30]	0 % [30]	0 % [30]
	Tank	36–42 kg	500 €/kg$_{H2}$	−50 % [30]	−60 % [30]
HH_2ICEV	Glider	6 m	12500 €/m [31]	0 %	0 %
	Engine	100 kW	30 €/kW [30]	0 % [30]	0 % [30]
	Tank	33–39 kg	500 €/kg$_{H2}$ [30]	−50 % [30]	−60 % [30]
	Battery	15 kWh	100 €/kWh [32]	−29 % [32]	−45 % [32]
	Motor & Inverter	100 kW	15 €/kW [30]	0 % [30]	0 % [30]
FCV	Glider	6 m	12500 €/m [31]	0 %	0 %
	FC	100 kW	440 €/kW [30]	−20 % [33]	−64 % [33]
	Tank	27–32 kg	500 €/kg$_{H2}$ [30]	−50 % [30]	−60 % [30]
	Battery	15 kWh	100 €/kWh [32]	−29 % [32]	−45 % [32]
	Motor & Inverter	100 kW	15 €/kW [30]	0 % [30]	0 % [30]
BEV	Glider	6 m	12500 €/m [31]	0 %	0 %
	Battery	550 kWh	100 €/kWh [32]	−29 % [32]	−45 % [32]
	Motor & Inverter	100 kW	15 €/kW [30]	0 % [30]	0 % [30]

Consumption Data [3]

Powertrain	**Configuration**	**Min SFC [kWh/km]**	**Max SFC [kWh/km]**
H_2ICEV	9 ton	2.35	4.27
	12 ton	2.85	4.71
HH_2ICEV	9 ton	1.99	3.95
	12 ton	2.53	4.40
FCV	9 ton	1.48	3.02
	12 ton	2.05	3.55
BEV	9 ton	0.92	1.47
	12 ton	1.03	1.58

Hydrogen Price [45,53]

Type	**Min Baseline [€/kg$_{H2}$]**	**Max Baseline [€/kg$_{H2}$]**	**2030 Cost Variation w/r 2024**	**2050 Cost Variation w/r 2024**
Grey	2.6	4.6	+5 %	+10 %
Blue	3.3	5.5	−2 %	−5 %
Green	4.3	9.4	−40 %	−58 %

Electricity Price [38–40]

Parameter	**Min Baseline [€/kWh]**	**Max Baseline [€/kWh]**	**2030 Cost Mean Variation w/r 2024**	**2050 Cost Mean Variation w/r 2024**
Value	0.1	0.3	−19 %	−19 %

considered [45,53] As visible in 2024, grey hydrogen is the least expensive one, with expected increase in 2050 due to carbon taxes; blue hydrogen is expected to remain almost constant across all EU. It is worth noticing that the highest prices are expected in the Scandinavian area. Finally, green hydrogen is expected to drop in price by 2050, reaching value slightly below 2 €/kg$_{H2}$. Overall, in EU by 2050 green hydrogen prices are expected to drop below 4 €/kg$_{H2}$, suggesting hydrogen as a suitable energy carrier as proposed by Peiretti Paradisi et al. [30], while for grey and blue, hydrogen prices are expected to remain above such threshold in the Scandinavian region.

However, the final hydrogen price (except for the 100 GH scenario), is the result of the combination of grey, blue and green hydrogen shares, as for electricity the final price is a function of the EGM. For this reason, Fig. 2 is provided, where the expected prices of electricity and hydrogen in the HM scenario are reported in the whole EU for the three scenarios investigated, considering the average price during the vehicle life (17 years).

Focusing on electricity prices, a minimum of 0.1 €/kWh is reported for Finland, while a maximum of 0.3 €/kWh for Cyprus. Detailed country-based 2030 price variations are modelled from Ref. [54], while for 2050 due to literature lack, a mean coefficient for all countries have been adopted, following the results presented in Ref. [40], considering the mean scenario among the reported ones. As visible the lowest electricity prices for non-household are reported in the Scandinavian area (between 8 and 10 c€/kWh), while the highest values are reported in central EU. Considering HM hydrogen price, as for grey and blue, the highest prices are reported in the Scandinavian area once again. Overall, prices below 3.2 €/kg$_{H2}$ are expected in 2050, while in 2024 and 2030 only in the central EU such levels are reached.

3. Results and Discussion

The TCO evaluations have been conducted in each country of the EU considering three different purchase years: 2024, 2030 and 2050 considering both HM and 100 GH scenarios. Furthermore, a sensitivity analysis has been conducted on the curb weight (two different curb weight masses have been investigated: 9 ton and 12 ton) and the number of powertrain swaps (single replacement and double replacement during the lifespan). Finally, the typical average external temperature of each country and a 66 % passenger load have been considered [55].

3.1. TCO breakdown

3.1.1. Capex

Capex values are mainly influenced by components' sizes and no dependency with the country is modelled here. Therefore, the only aspects that affect capexes are curb weight and production year.

Fig. 3 reports the capexes of the different configurations. FCV and BEV present the highest one (above 0.1 €/km). Thanks to projected components' price variation, capex price variation in 2030 and 2050 with respect to 2024 are provided. FCVs and BEVs experience the largest price reduction, accounting for more than 10 % for BEVs and close to 15 % for FCVs. Minimal differences with respect to the 12 ton case are expected, owing to slightly different HFVs tank capacities.

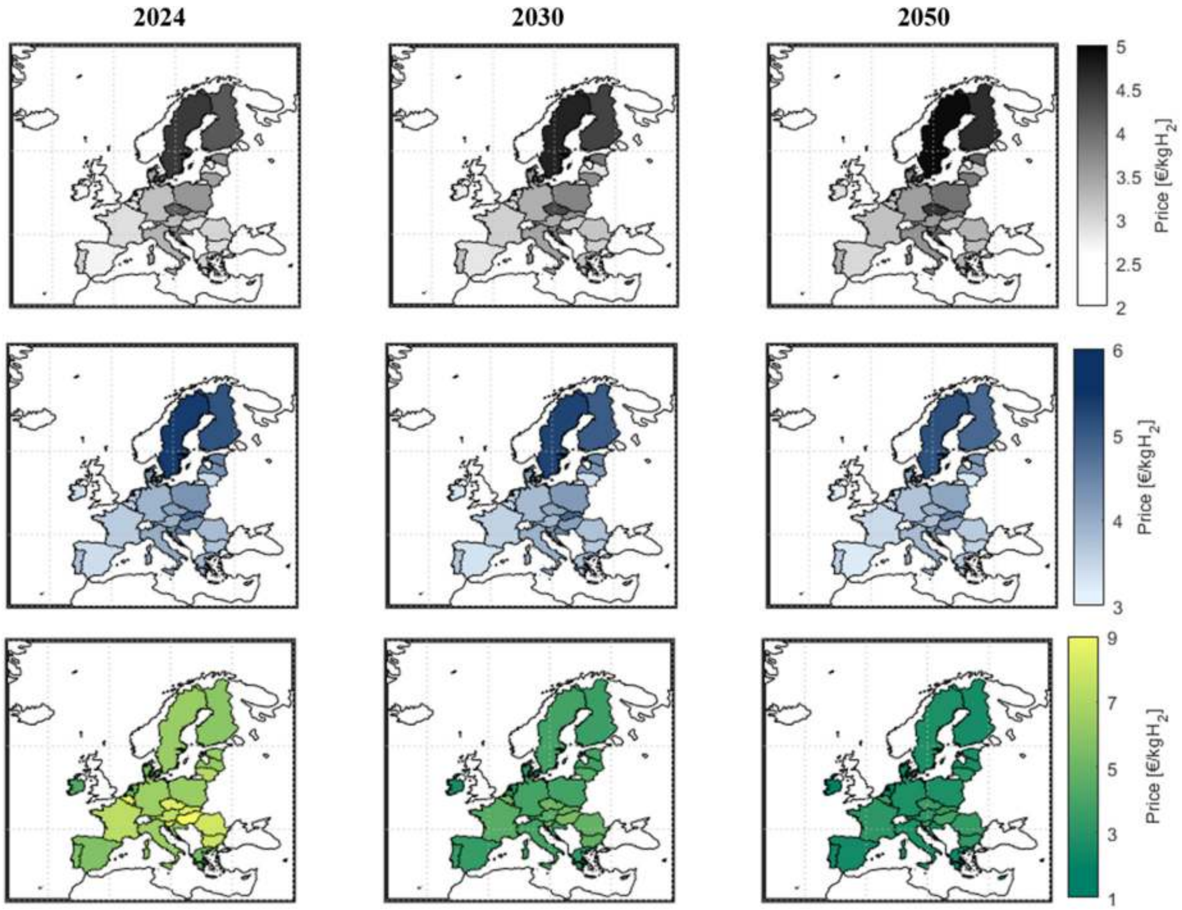

Fig. 1. Hydrogen prices for 2024, 2030 and 2050 for grey, blue and green hydrogen (elaborated from Refs. [45,53]). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

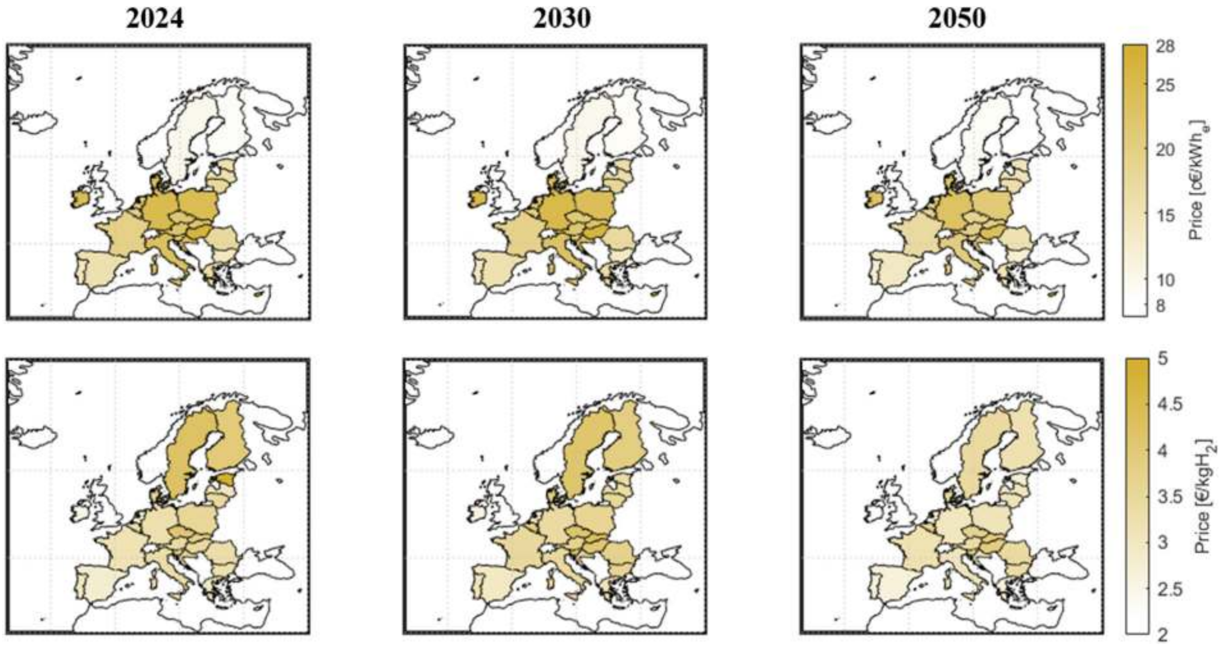

Fig. 2. Electricity and HM hydrogen prices for 2024, 2030 and 2050 (elaborated from Refs. [38–40,45,53]);

3.1.2. *Opex*

Fig. 4 reports the result in terms of opexes for the different considered cases. As visible in the considered scenario, H_2ICEVs always present the highest opexes, owing to lower powertrain efficiency thus higher consumption. When HM is considered, for lower curb weights, FCVs and BEVs present similar opexes, while the gap increases for the 12 ton cases.

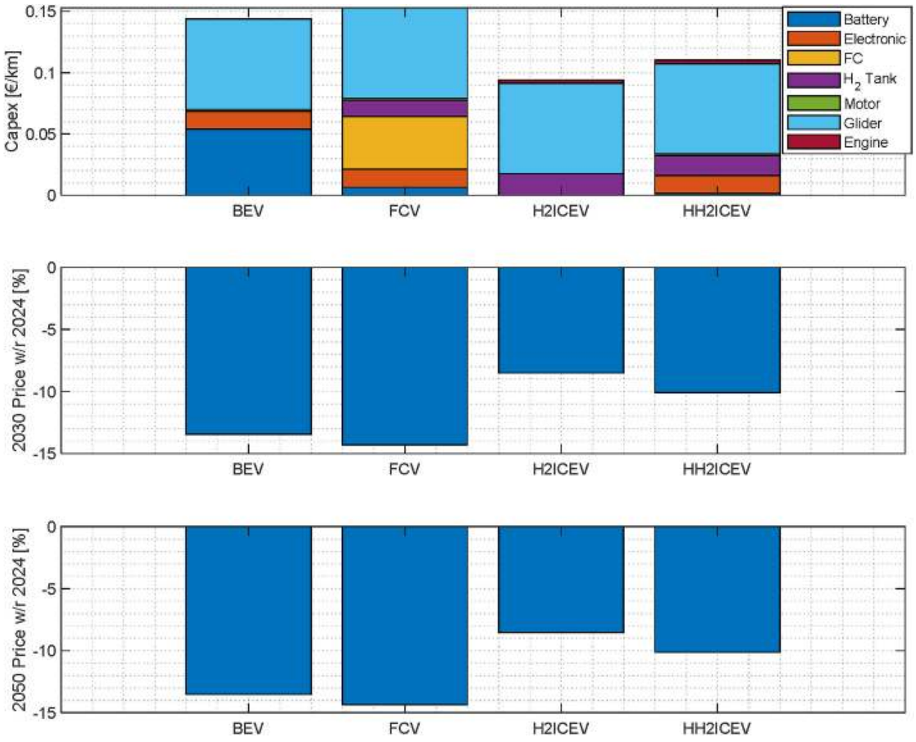

Fig. 3. Capex for different configurations and effect of the purchase year.

Considering 100 GH BEVs always report the lowest opexes (true in general), with great gaps with respect to HFVs, except in 2050, especially for the 9 ton case (see Fig. 4).

3.1.3. *Maintenance*

The maintenance TCO component here is modelled only as a function of vehicle purchase year, as it happens for capexes, since the only time-based effect considered is the cost of the replacement (extraordinary maintenance) given a certain year of purchase, while the ordinary maintenance cost is kept constant with the year but different among the different powertrain configurations (as mentioned in the previous chapter).

As visible, the extraordinary maintenance covers a substantial portion for FCVs and BEVs, while it shows minimal contribution for H_2ICE-powered vehicles. Considering the forecasted price reduction of the components modelled, in 2030 BEVs are expected to show the greatest reduction, close to −6 %, while FCVs would reach −4.9 %. Conversely, in 2050, FCVs would expect a reduction up to −15 %, while BEVs a more limited one, being −9 %.

3.2. *Overall results*

3.2.1. *Current scenario*

Fig. 6 summarizes the results in the whole EU for 2024, showing the least expensive powertrain configuration in each country for each of the considered scenarios.

The results in the whole EU underscore an extremely heterogeneous situation among the different scenarios. Focusing on the 9 ton results, single swap HM scenario, H_2ICEVs and FCVs represent the best solutions in most of the countries. When double major powertrain components replacement is considered, FCVs disappear from the results, owing to expensive FC costs. Instead, BEVs are generally the best solution when 100 GH is considered. Interestingly, for higher curb weights, FCVs are partially convenient only under single swap HM, while in all other cases either BEVs or H_2ICE-powered vehicles are the most promising option. It is worth pointing out that, for all scenarios considered, only in the Scandinavian region and Ireland the best configurations remain unaltered (BEVs and H_2ICEVs respectively). These results underscore that, generally, 100 GH is still a premature option in 2024, owing to expensive hydrogen prices.

3.2.2. *Future scenarios*

Given the forecast of market penetration of HFVs and electricity prices in the next decades, future scenarios have been assessed, to provide valuable information for stakeholders, considering 2030 and 2050 as a purchase year.

Fig. 7 shows the least expensive powertrain configurations in each EU country in 2030 for all considered scenarios.

Generally speaking, BEVs are the best solutions for the 100 GH cases (with some FCVs exceptions), owing to expensive hydrogen prices coupled with expensive FC costs. For HM scenarios, either FCVs or H_2ICEVs/HH_2ICEVs represent the best option, depending on whether single or double major powertrain components replacement is considered respectively. As it was for 2024, in the Scandinavian area BEVs remain always the optimal solution among all scenarios.

Analyzing the best configuration for each scenario in 2050 (Fig. 8) it is evident that due to technological developments and hydrogen price drops, FCVs have become the best solution in most countries in each scenario. In some countries, the double major powertrain components replacement is more favorable to H_2ICEVs (i.e., Spain, Ireland). It is confirmed that BEVs remain the best solution for the Scandinavian area once again, promoting BEVs as the optimal configuration (in terms of TCO) for the Scandinavian area, independently of the considered scenario.

3.3. *Broader view: LCA vs TCO*

Focusing on the analysis just on the TCO alone may overlook environmental factors that are not directly reflected in economic metrics. For this reason, a Life Cycle Assessment (LCA) perspective [27,40–43,56] is introduced as a complementary analytical tool, aimed at providing additional insight into the environmental implications of the considered

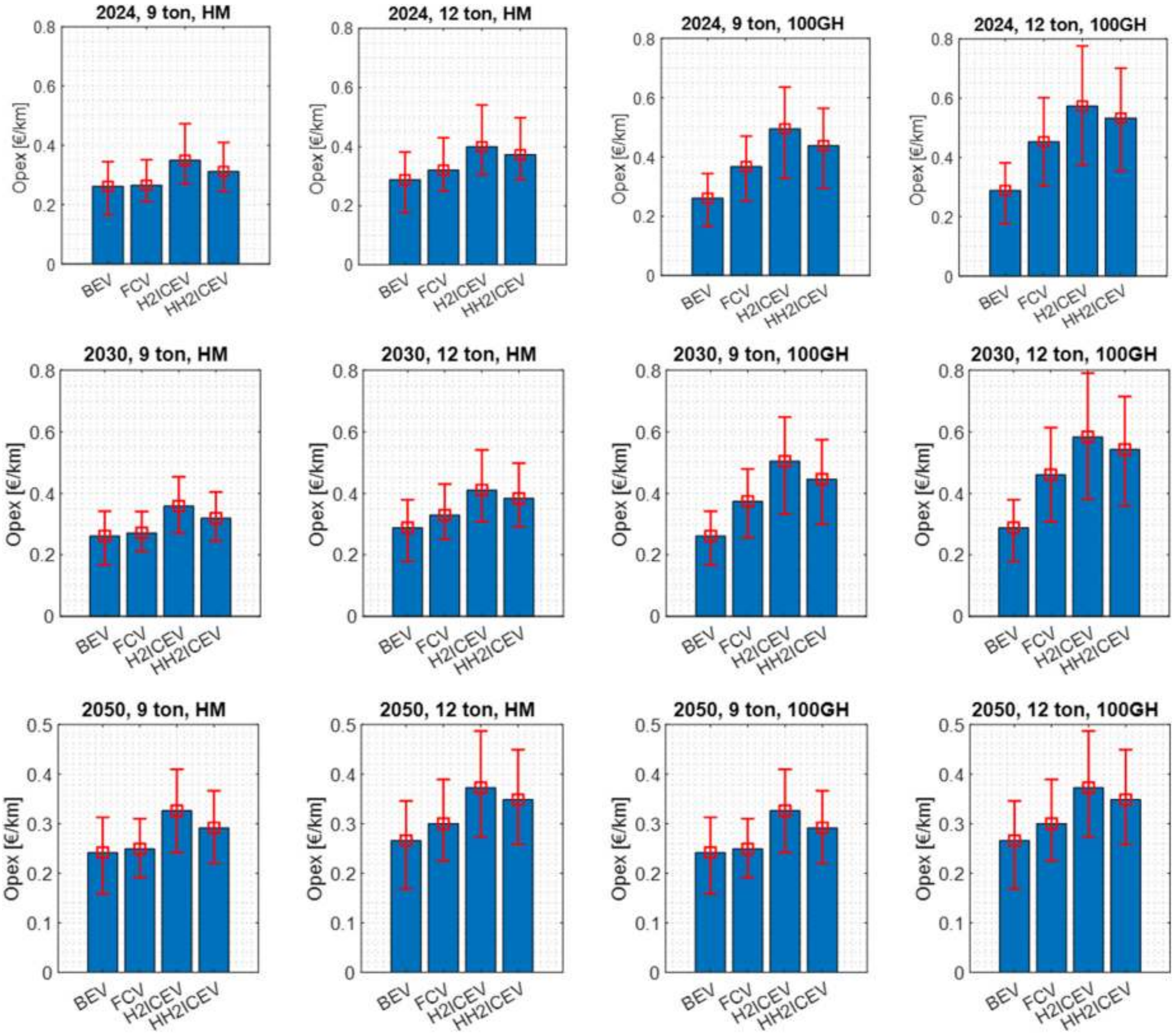

Fig. 4. Capex for different configurations and effect of the considered scenario, error bar represents variations among different countries.

solutions in short, medium and long terms and to identify the best compromise. By taking a Cradle-to-Grave (CtG) perspective, LCA allows to quantify the overall equivalent CO_2 emissions of a product over its whole life cycle, from raw material extraction to final recycling or end-of-use disposal [27,40,42], including energy (i.e., hydrogen and electricity) production and consumption, as well as chassis and powertrain components manufacturing, supporting the interpretation of the economic results without being directly integrated into the TCO framework. Figs. 9–11 show a comparison of these novel powertrains for the 2024, 2030, and 2050 scenarios respectively, considering both TCO and LCA. As for the LCA results, data were taken from a focalized study [3].

As it can be clearly seen, BEVs are characterized by the largest dispersion in terms of LCA, due to higher variety in EGMs with respect to hydrogen production mixes across EU countries.

Starting from Fig. 9, with the introduction of total CO_2 emissions based on LCA evaluation, the most favorable powertrains may differ from the ones obtained by looking at TCOs alone. In particular, BEVs are characterized by more dispersed and relatively lower (on average) total CO_2 emissions. On the other hand, in the HM scenarios, all HFVs show relatively similar TCOs, but H_2ICEVs and HH_2ICEVs are characterized by the highest total CO_2 emissions, followed by FCVs, which shows the lowest singular total CO_2 emissions overall. Interesting to notice the low LCA CO_2 emissions of Estonia even in HM scenario (separated from the others HFVs).

The trend is overturned when moving to the 100 GH scenarios. In these cases, HFVs average TCOs significantly increase, becoming even noticeably worse than BEVs' values (the gap is slightly recovered in the double major powertrain component replacement scenarios), while their total CO_2 emissions drop, with H_2ICEVs and HH_2ICEVs becoming the best compromise between total CO_2 emissions and TCO, with FCVs still boasting the lowest total CO_2 emissions. Interestingly, H_2ICEVs reach more than 1 €/km for double replacement scenarios.

Fig. 10 shows the comparison between economic viability and environmental impact in the 2030 scenarios. In the HM scenarios, with respect to the corresponding 2024 ones, overall total CO_2 emissions and TCOs have been reduced. As far as TCOs are concerned, however, HFVs still show lowest values overall, with total CO_2 emissions which are not too far from BEVs' ones. Shifting the focus on the 100 GH scenarios, TCOs become more overlapped across different solutions, but BEVs are still characterized by the lowest TCOs on average. In the case of a single major powertrain component replacement, with a 12-ton curb weight, BEVs represent the solution with both the lowest TCO and LCA values.

Finally, Fig. 11 shows the comparison in the 2050 scenarios. The expected total CO_2 emissions drop to noticeably lower values for all the different alternatives. In the HM scenarios, HFVs fully recover the gap with BEVs in terms of total CO_2 emissions, becoming a more competitive solution with respect to BEVs. FCVs on average become the best compromise between total CO_2 emissions and TCO, despite BEVs still showing very low total CO_2 emissions, but higher TCOs. On the other

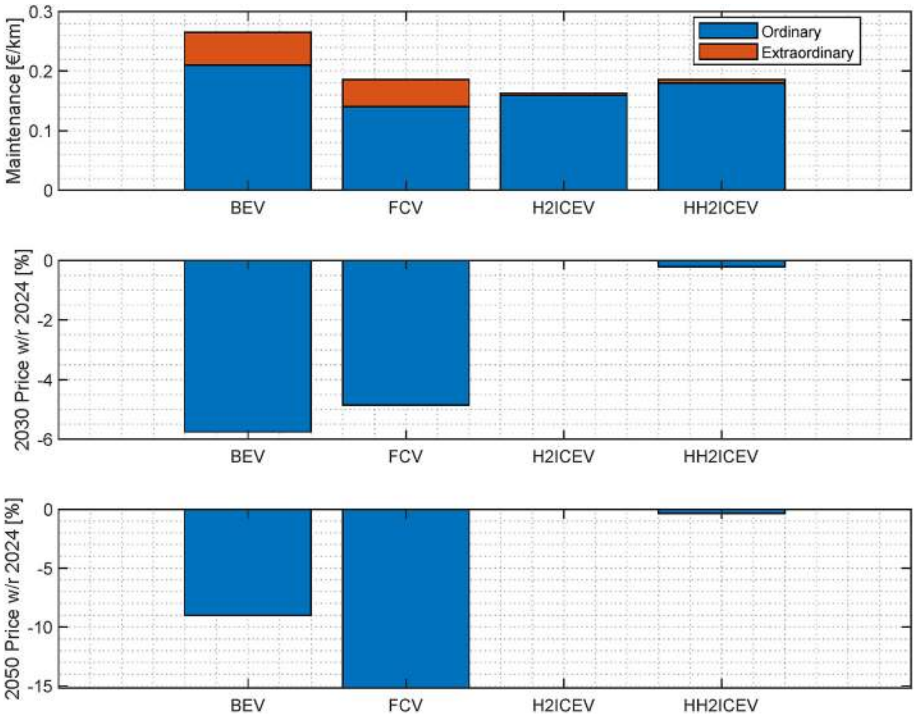

Fig. 5. Maintenance for different configurations and effect of the purchase year.

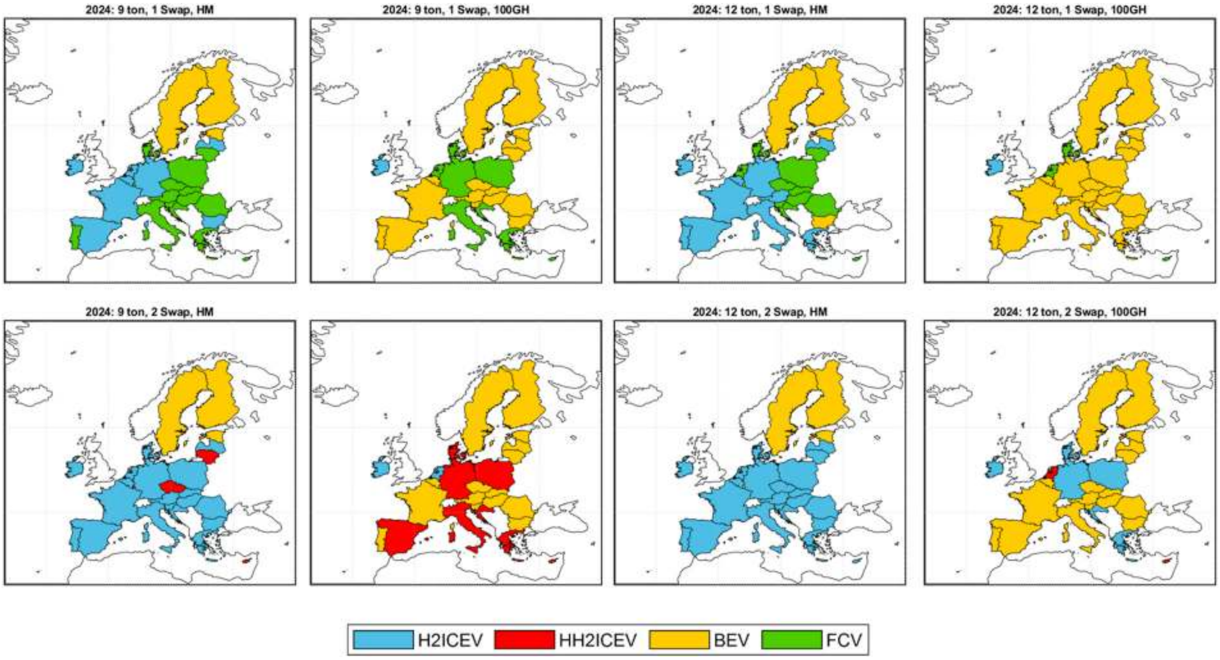

Fig. 6. Least expensive powertrain configuration for EU countries in the different 2024 scenarios.

hand, in the 100 GH cases, HFVs almost halve their values with respect to the corresponding HM scenarios in terms of total CO_2 emissions. From the TCO perspective, its increment due to 100 GH is more limited due to lower green hydrogen cost with respect to the previous scenarios. It is interesting to notice that the lowest LCA value overall is always reported for BEVs (except in the double major powertrain component replacement, 9 ton, 100 GH scenario), while, in terms of TCO, the lowest value is boasted by FCVs and H_2ICEVs.

From the results shown in the different scenarios, it is self-evident that there is not a single powertrain solution able to minimize both total CO_2 emissions and TCO at the same time in all the scenarios investigated. Moreover, the specific scenario considered in the evaluations heavily affects the results obtained. Therefore, the main result of this paper is to underline the need for specific country-based solutions to really achieve economic and environmental sustainability.

4. Conclusions & future developments

In this study, a Total Cost of Ownership (TCO) model was developed to assess the lifetime costs of innovative urban mobility solutions, such

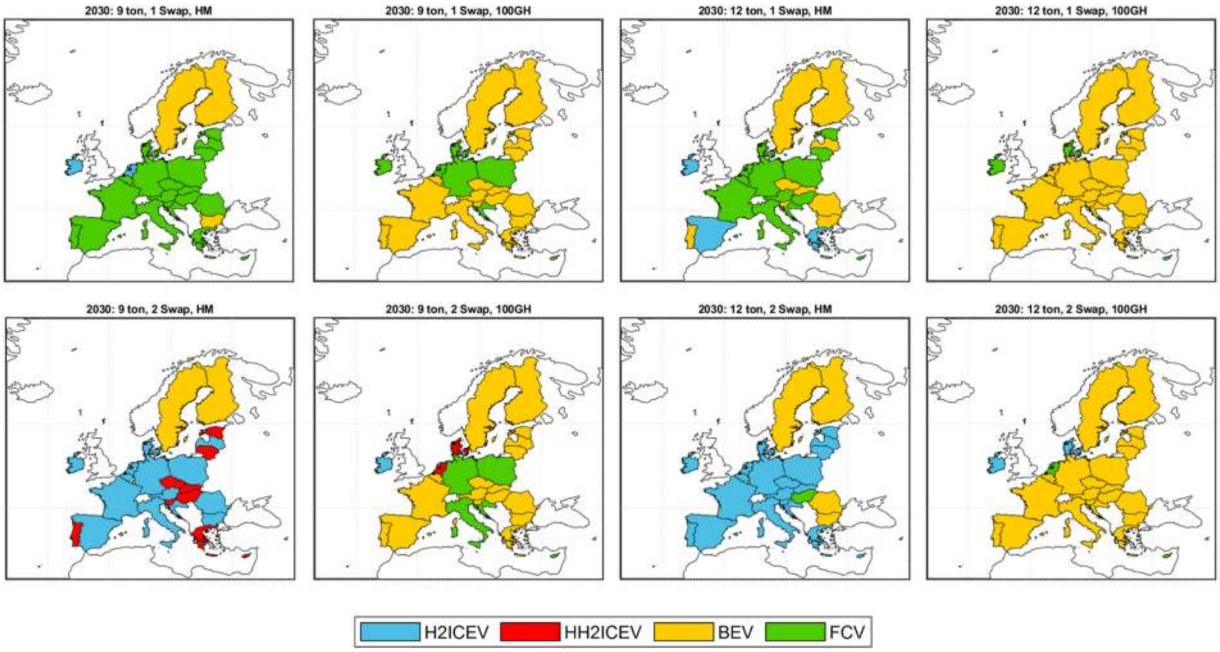

Fig. 7. Least expensive powertrain configuration for EU countries in the different 2030 scenarios.

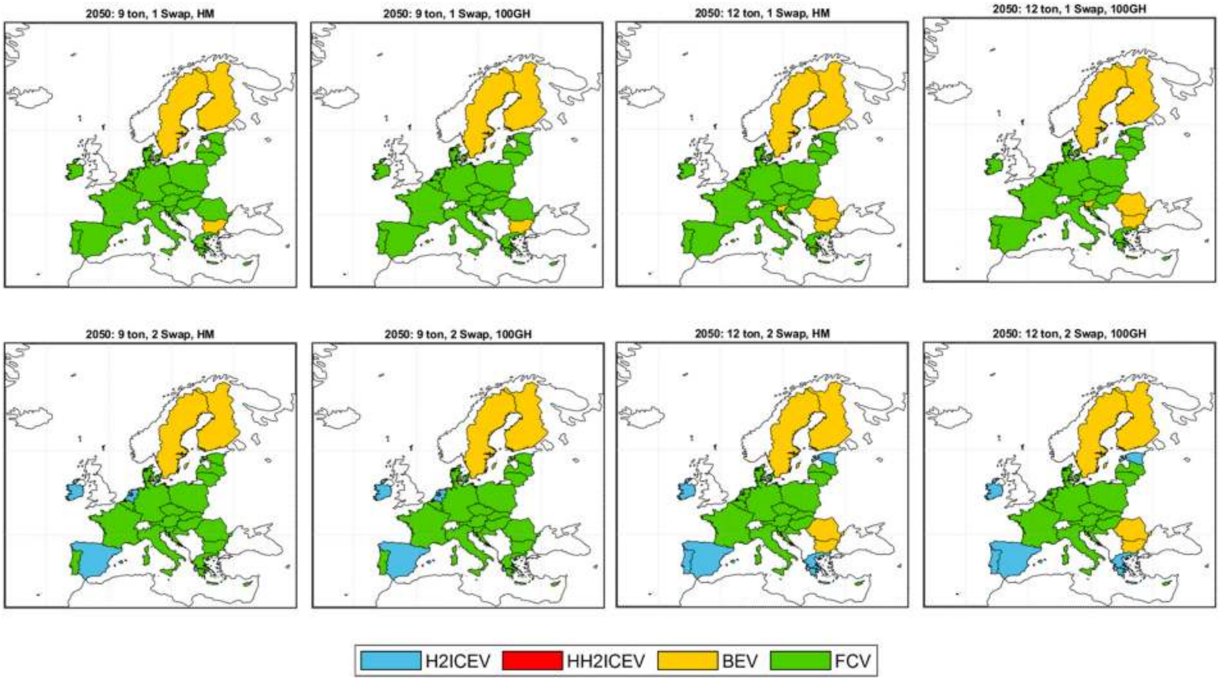

Fig. 8. Least expensive powertrain configuration for EU countries in the different 2050 scenarios.

as battery-electric and hydrogen-fuelled buses in the whole European Union (EU). Results were analysed across three purchase scenarios (2024, 2030, and 2050), considering grid electricity price and both mixed hydrogen (HM), and 100 % green hydrogen (100 GH) options, with a sensitivity analysis on bus curb weight and number of powertrain replacements. Detailed price evolution modelling of hydrogen and electricity have been integrated into the framework, as well as the most recent technological price trajectory curves for the main powertrain components.

The findings highlight the potential cost dynamics of these technologies under different adoption timelines, providing valuable insights for policymakers and industry stakeholders.

The main results can be summarized as follows.

1. Both BEVs and Fuel Cell Vehicles (FCVs) are significantly affected by potential additional maintenance costs, such as the replacement of fuel cells (FCs) and batteries.
2. For a given scenario, hydrogen vehicles present similar TCOs among them.
3. Scenario 2024 is characterized by the most heterogeneous result, with BEV and Hydrogen Internal Combustion Engine Vehicle (H_2ICEV) being the best solution (for 100 GH and HM respectively). This suggests that H_2ICE-powered vehicles could provide a more economically viable option for urban mobility, particularly in the

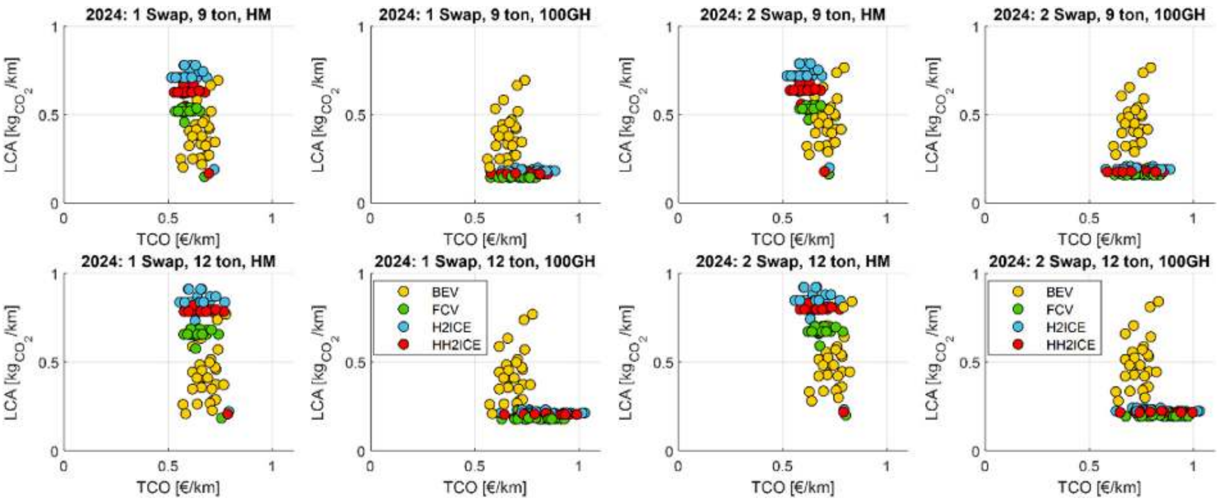

Fig. 9. LCA vs. TCO for EU countries in the different 2024 scenarios.

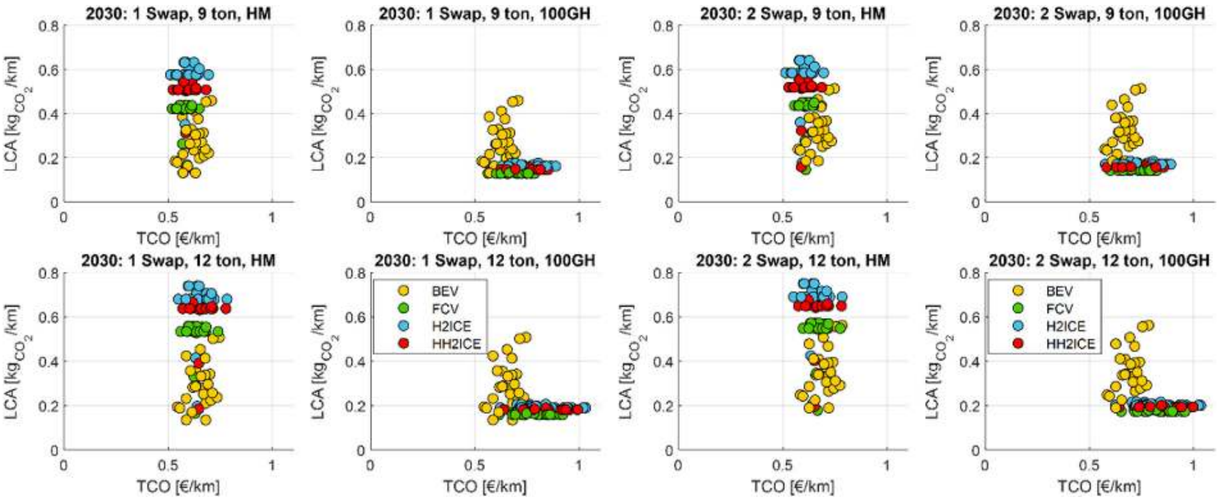

Fig. 10. LCA vs. TCO for EU countries in the different 2030 scenarios.

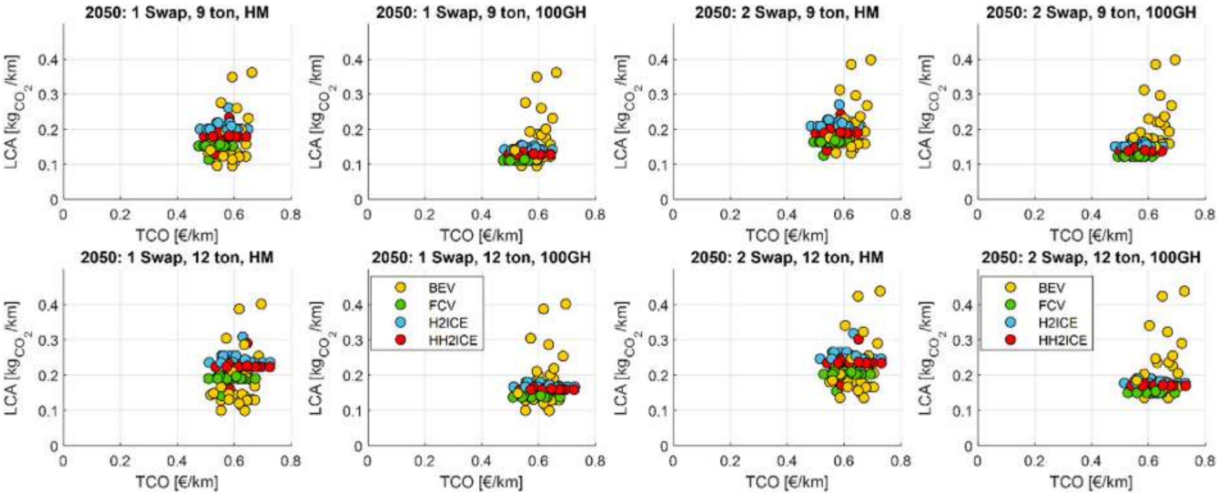

Fig. 11. LCA vs. TCO for EU countries in the different 2050 scenarios.

mid-to long-term, given the current trends in energy costs and vehicle maintenance.

4. Focusing on 2030, FCVs start to become more competitive, especially for single replacement and HM scenarios, while H_2ICEVs remain interesting for the double replacement HM one (confirming the

H_2ICEV as a feasible short-mid term solution). BEV still represent the most competitive solution for single replacement and 100 GH.

5. In 2050, due to technological development and hydrogen price reduction, FCVs become the best solution in most of the countries, with minimal exceptions: Scandinavian aera characterized by optimal BEV as solution and for double replacement Ireland and mediterranean countries (Greece and Spain) for H_2ICEVs.
6. In all scenarios analysed, BEVs are the best solution in the Scandinavian area, suggesting BEV as the optimal solution overall in that area (from TCO point of view).
7. When considerations on the Lifecycle Assessment (LCA) of CO_2 emissions of these novel powertrains are included as a complementary tool for a broader view in the several scenarios, results showed that, there is not a single solution that would minimize both LCA and TCO in all scenarios. As time passes, the gap for Hydrogen Fuelled Vehicles (HFVs) between HM and 100 GH scenarios becomes tighter, due to expected technological developments and progressive decarbonization, promoting HFVs, with FCVs emerging as the best compromise.

Nonetheless, even LCA analyses face limitations due to the complexity of real-world systems, which leads to the impossibility of considering all possible factors and thus to rely on assumptions to address data gaps. These assumptions, while necessary, can impact results and vary across studies. Transparency in documenting assumptions, methodologies, and data sources is critical to help stakeholders understand limitations and biases. LCA outcomes are highly context-dependent, influenced by factors like regional energy mixes and manufacturing practices. Acknowledging these limitations emphasizes the need for ongoing refinement in LCA methodologies to improve reliability and relevance while ensuring balanced and informed interpretations.

CRediT authorship contribution statement

Pier Paolo Brancaleoni: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Andrea Nicolò Damiani Ferretti:** Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Enrico Corti:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition. **Francesco Bellucci:** Visualization. **Davide Moro:** Resources, Project administration, Funding acquisition.

Funding

This research has been partially funded by Ministero dell'Istruzione, dell'Università e della ricerca (MIUR) (2020R92Y3Z) and partially supported by the European Union - NextGenerationEU - National Sustainable Mobility Center CN00000023, Italian Ministry of University and Research Decree n. 1033–17/06/2022, Spoke 2, CUP J33C22001120001.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Enrico Corti, Davide Moro reports financial support was provided by Ministry of University and Research, Italy. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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