

Article

Hydrogen Fuel Cell Electric Vehicles in Road Transport: Multi-Objective Optimization of Total Cost of Ownership and Well-to-Wheel Emissions

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Abstract

Traditional techno-economic assessments of zero-emission mobility frequently rely on static Total Cost of Ownership (TCO) models that fail to capture the concurrent evolution of economic and environmental parameters. To address this research gap, this study develops a novel dynamic multi-objective optimization framework that jointly assesses TCO and Well-to-Wheel (WTW) emissions across the period 2026–2060, capturing the non-linear trade-offs between cost minimization and lifecycle decarbonization. The model developed compares light-duty hydrogen Fuel Cell Electric Vehicles (FCEVs) with diesel, petrol, and battery-electric vehicles (EVs), incorporating time-varying Capital Expenditure (CAPEX) learning curves, fuel price trajectories, carbon pricing effects, and emissions-decay pathways. Hydrogen break-even prices are computed annually against each competing technology to identify the market conditions under which FCEVs become cost competitive. The results show that light-duty hydrogen FCEVs face a substantial entry barrier in 2026, with a TCO of approximately €275,000, far above diesel, petrol and EV alternatives. However, their relative competitiveness improves over time as hydrogen production costs decline and fossil-fuel vehicle costs increase due to the EU ETS2 and Eurovignette CO₂ surcharges. The analysis identifies two key inflection points, that is, light-duty hydrogen FCEVs become more cost effective than petrol vehicles in 2037 and reach parity with EVs in 2046. In emissions terms, light-duty FCEVs occupy a strong position on the low-WTW frontier, while EVs combine the lowest TCO with similarly favorable emissions performance. To bridge the intermediate cost-parity gap and mitigate infrastructure lock-in risks, targeted policy measures, such as carbon-weighted road toll exemptions, upstream fuel-tax subsidies under the EU ETS2 framework, and capital grants for localized commercial fleet refueling units, are essential to accelerate early-stage market industrialization and secure the economic viability of hydrogen mobility.



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Keywords: hydrogen FCEVs; total cost of ownership; well-to-wheel emissions; multi-objective optimization; break-even analysis; EU ETS2

1. Introduction

The global imperative for deep decarbonization of the transportation sector has catalyzed research into alternative propulsion systems, as it represents a formidable challenge in the global pursuit of net-zero emissions, accounting for approximately 16% of total anthropogenic greenhouse gas emissions as of 2025 [1]. While other sectors have successfully decoupled economic growth from carbon intensity, transport-related carbon dioxide

(CO₂) emissions have surged by nearly 80% since 1990 [1–4]. Road transport, in particular, remains the dominant contributor, responsible for approximately 73% of the sector’s total climate impact within the European Union (EU) [2]. Within this segment, heavy-duty vehicles represent a significant portion of these emissions; namely, almost a quarter of all transport-related emissions are attributed to heavy-duty vehicles [5]. Consequently, the EU has established ambitious, legally binding targets to drastically reduce transport emissions over the next two decades, aligning with the European Green Deal and the Fit for 55 legislative package [6,7]. Specifically, by 2035, emissions are targeted to be reduced by 100% for cars and vans, and for heavy-duty vehicles, 90% of emissions have to be reduced by 2040 [7].

Therefore, as international climate targets grow more stringent, the inherent limitations of current petroleum-based transport have catalyzed the development of alternative energy carriers, placing Fuel Cell Electric Vehicles (FCEVs) as a pivotal alternative to both traditional internal combustion engine vehicles and electric vehicles (EVs). Unlike conventional EVs that store energy in large lithium-ion batteries, FCEVs generate electricity on board via a fuel cell, illustrated in Figure 1, where compressed hydrogen and oxygen from the air react to produce water [8–10]. This process produces just water vapor and warm air as byproducts, classifying FCEVs as zero-emission vehicles [11–13]. In addition, another advantage of FCEVs is the high kinetic rate of energy transfer during refueling. While high-power DC fast-charging for EVs is constrained by lithium plating risks and resistive heating [14–17], hydrogen refueling utilizes a standardized high-pressure transfer that allows full refueling in minutes [18–21].

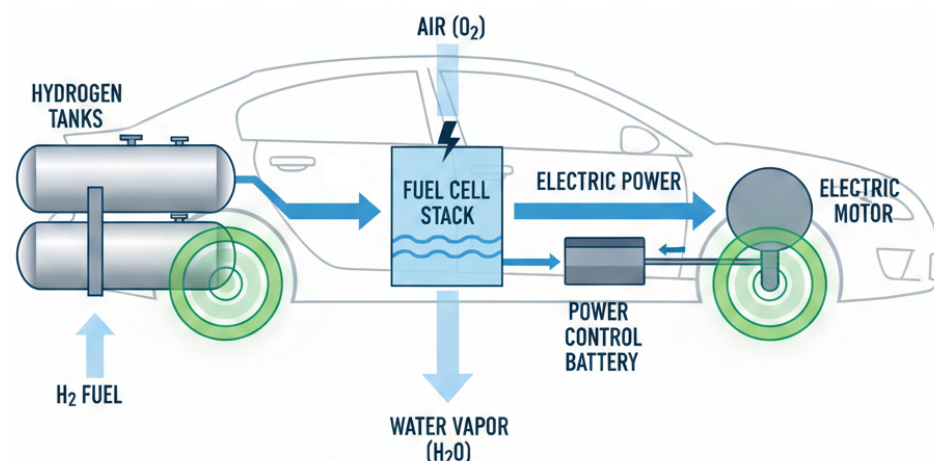


Figure 1. Simple schematic of a hydrogen FCEV.

The adoption of alternative propulsion systems is primarily governed by the Total Cost of Ownership (TCO), a comprehensive financial metric that extends beyond the initial Capital Expenditure (CAPEX), to encompass the entirety of a vehicle’s operational lifecycle [22–24]. Historically, TCO analysis has served as a static decision-making tool, used to compare the fiscal viability of diesel fleets against emerging low-carbon technologies. Recent literature focuses on fundamentally deterministic models, or even probabilistic frameworks to capture uncertainty, often remaining focused on identifying a single outcome or a range of cost [25–28]. This approach fails to account for the stochastic nature of energy prices, the impact of evolving carbon taxation and the technological learning curves that reduce hydrogen system costs over time. Consequently, while standard TCO provides a “snapshot” of current costs, it lacks the temporal flexibility required to navigate the complex economic transition toward 2060.

To address this research gap, the present study develops a dynamic parametric multi-objective optimization framework that integrates a 15-year vehicle lifecycle discounted TCO with time-decaying WTW emissions trajectories across the analysis horizon. The primary methodological contribution lies in the simultaneous evaluation of lifecycle TCO and WTW greenhouse gas emissions through a joint optimization lens, coupled with an annual hydrogen break-even price calculation framework. This approach systematically isolates the economic thresholds required to achieve cost-parity against three competing light-duty vehicle technologies, namely diesel, petrol, and battery-electric vehicles, and identifies Pareto-optimal technology sets across the analysis horizon. By doing so, this study explicitly maps the dynamic market conditions and threshold hydrogen prices under which hydrogen mobility emerges as the superior option, offering a robust decision-making tool for fleet transitions.

In Section 2, a comprehensive literature review is presented, outlining the key variables influencing the TCO and WTW emissions of the selected light-duty vehicle technologies. Section 3 develops the proposed mathematical model and formulates the lifecycle cost-benefit analysis. Section 4 presents the model implementation, including all parameters adopted for the analysis. Section 5 discusses the results, and Section 6 concludes the study by summarizing the principal findings and outlining directions for future research.

2. FCEVs Lifecycle Cost Competitiveness

The rapid evolution of zero-emission mobility has generated a vast body of scholarly work concerning the feasibility and optimization of FCEVs. While early 21st-century research focused primarily on the basic proof-of-concept for hydrogen propulsion [29–32], current literature (2020–2026) has pivoted toward solving specific technical bottlenecks related to electrochemical durability, volumetric storage density, and system-level energy management [33–37]. As these technical bottlenecks are resolved, TCO remains the definitive metric for evaluating the commercial readiness and competitiveness of zero-emission fleets. However, to capture true long-term viability, TCO must be formulated not as a static value, but as a dynamic, multi-dimensional function. This function must integrate a shifting spectrum of variables across the temporal horizon, including initial CAPEX for vehicle acquisition, time-variant Operational Expenditure (OPEX) driven by volatile energy prices, and the evolving fiscal penalties associated with carbon regulations.

To ground this framework in current engineering realities, Table 1 summarizes the key parameters influencing TCO across the three vehicle categories considered in this study; namely, internal combustion engine vehicles, battery-electric vehicles, and hydrogen fuel cell electric vehicles. In particular, it captures the main technical, operational, and economic factors that shape lifecycle cost differences and therefore underpin the subsequent comparative analysis.

The upfront CAPEX remains a primary barrier to adoption across all vehicle segments, though the drivers vary significantly between light-duty and heavy-duty applications. For light-duty, FCEVs currently occupy a premium market niche. As of 2026, flagship models like the Toyota Mirai and Hyundai Nexo command purchase prices between €60,000 and €75,000, roughly 30–50% higher than their electric counterparts in the same luxury segment [38–40]. Unlike the EV market, which has seen a surge in more affordable models (closer to €40,000) due to the scaling of lithium iron phosphate battery chemistry and thus dropping the battery costs to approximately 100–130 €/kWh [41,42], FCEV costs remain tethered to low-volume production of 700-bar Type IV storage tanks and platinum-heavy proton exchange membrane fuel cell stacks [43–46]. However, proton exchange membrane fuel cell stacks are currently transitioning from prototype to serial production stages [44,46]. Specifically, literature suggests that as of 2026, the primary

research focus has pivoted from fundamental cost reduction to operational durability as the leading driver of lifetime value [47–50]. In the heavy-duty segment, CAPEX remains the most significant barrier to the commercial adoption of heavy-duty FCEVs. As of 2026, the purchase price of a heavy-duty fuel cell truck is estimated to be two to three times that of its diesel equivalent, primarily driven by the high cost of the fuel cell stack and high-pressure hydrogen storage systems [46]. Recent literature suggests that while target costs are moving toward 70 €/kW by 2030 for heavy-duty FCEVs, current 2026 market prices still reflect a “low-volume penalty,” necessitating a reliance on government subsidies to achieve initial fleet parity [46,51–56].

Table 1. Parameters influencing TCO and WTW emissions for Internal Combustion, Electric, and Hydrogen FCEVs.

Parameter	Internal Combustion Vehicles	EV	Hydrogen FCEV	Impact on TCO
Powertrain Mass	Baseline (Lowest)	High (3000–4000 kg for heavy-duty EV batteries)	Moderate (half the weight than a comparable light-duty EV battery)	Affects payload-adjusted revenue and efficiency.
Refueling Time	10–15 min	45–90 min	10–20 min	Influences downtime opportunity cost.
Operational Range	>1000 km	300–600 km	600–800 km	Defines the suitability gap for long-haul.
Tank/Storage Type	Steel/Atmospheric	Solid-state/Li-ion (Pack)	Type IV (350/700 bar)	High CAPEX for FCEV storage vs. EV battery.
Energy Density	High (Diesel)	Low (Wh/kg)	High (kWh/kg)	Determines the weight-neutrality of the vehicle.
Maintenance Profile	Mechanical (High)	Electrical (Low)	Hybrid (Mechanical & Electrical)	FCEVs require stack refurbishing vs. battery swap.

For light-duty FCEVs, durability targets have stabilized around 5000 to 8000 operational hours [57], but in the heavy-duty vehicle sector, the 2026 benchmark has moved toward 25,000 h to compete with the million-kilometer lifespan of diesel engines [58]. Recent studies emphasize that the economic end-of-life is reached when the stack experiences a 10% voltage degradation, a threshold that significantly impacts the vehicle’s resale or salvage value [59,60]. However, real-world degradation, which is notably accelerated by dynamic load cycling and sub-optimal thermal management, often results in earlier end-of-life thresholds [61–63]. Recent literature indicates that a stack reaching its 10% power-loss limit before the vehicle’s 10-year depreciation cycle significantly erodes residual value, as the replacement cost of a 200 kW stack can exceed 30% of the vehicle’s initial price [64–67]. Research also indicates that a degraded fuel cell stack can exhibit a fuel consumption increase of up to 14%, which simultaneously elevates the carbon footprint by 26%, and ultimately affects OPEX over the vehicle’s lifespan [68,69]. Furthermore, unlike batteries, which have an established secondary market for “second-life” stationary storage, FCEVs face uncertainty regarding the salvage value of the platinum catalyst, making the calculation of net depreciation a volatile variable in current TCO models. Interestingly, the recent literature explores a different salvage pathway for FCEVs: the high-value recovery of the platinum-group metals from the catalyst layers, which can recoup a significant portion of the initial stack cost compared to the more complex recycling processes required for lithium batteries [70–72].

A critical differentiator in TCO modeling is the “Energy System Mass”, defined as the total weight of the powertrain including fuel, tanks, and conversion hardware. For light-duty vehicles, this mass differential allows FCEVs to offer a “weight-neutral” long-range

alternative. While a battery EV with a 600 km range may carry a battery pack exceeding 600 kg, a comparable FCEV system weighs approximately 300 kg, preserving vehicle dynamics and improving efficiency in temperature-sensitive environments [73–76]. In the heavy-duty vehicle segment, this technical difference manifests as a structural payload-adjusted revenue gap [77–79]. For a standard 40 tonne tractor-trailer, the battery requirements for long-haul operations (>500 km) can reach 3000 to 4000 kg, directly displacing billable cargo capacity despite the EU's 2-tonne weight allowance for zero-emission vehicles [80–82]. Current research demonstrates that FCEVs, by utilizing high-pressure Type IV tanks, maintain a significant mass efficiency over battery EVs [83]. This allows for a higher revenue, as the ability to carry an additional tonnage can offset the higher per-kilogram cost of hydrogen fuel [73,84].

While the initial capital outlay defines the barrier to entry, the long-term economic viability of zero-emission fleets is dictated by the efficiency with which primary energy is converted into tractive effort. The OPEX of FCEVs is fundamentally defined by the thermodynamic WTW efficiency gap. Standard literature establishes a significant efficiency gap since, while EVs typically achieve a WTW efficiency of 70–90%, the hydrogen pathway (including electrolysis, compression, transport and fuel cell reconversion) reaches a systemic efficiency of only 30–40% [73,85]. As of early 2026, this thermodynamic penalty translates into a substantial fuel cost disparity. In the European market, the cost per kilometer for an FCEV is approximately three times higher than that of a battery EV [86,87]. However, for commercial operators, this issue is frequently weighed against the high cost of vehicle downtime. Specifically, the 15 min average refueling window for an FCEV mirrors traditional diesel workflows, whereas EVs cannot yet match these refueling times [73,88].

Moreover, while older TCO models often assumed an ubiquitous refueling network, the recent literature has introduced the issue of added costs due to infrastructure, to reflect the current sparse state of hydrogen refueling stations [89,90]. Unlike diesel, which benefits from an optimized refueling network, FCEV operators must often divert from the most efficient route to access fuel. Recent spatiotemporal models identify this as an additional issue, where the average distance to a refueling station can add to the total annual distance driven [91–93]. This extra mileage increases TCO in three ways: higher fuel consumption, accelerated vehicle depreciation and lost operational hours for the driver. However, research also highlights a pivot toward specific deployment strategies, where modular, on-site refueling units are placed at logistics hubs to eliminate route deviation costs [92,94,95].

The integration of emissions data into economic modeling is increasingly recognized as a critical carbon-cost nexus that determines the market viability of FCEVs. Therefore, a comprehensive evaluation of FCEVs necessitates an analytical boundary that extends beyond the vehicle's operation to encompass the entire WTW pathway. While FCEVs are categorized as zero-emission vehicles at the point of use, representing the Tank-to-Wheel (TTW) phase, their total environmental impact is inextricably linked to the Well-to-Tank (WTT) stage, which includes hydrogen production, compression and distribution [96,97]. Current literature emphasizes that the carbon intensity of the hydrogen feedstock, ranging from carbon-heavy steam methane reforming to renewably-powered electrolysis, is the primary determinant of the vehicle's lifecycle sustainability [96,98,99]. By integrating these two stages, a WTW framework allows for a transparent comparison between FCEVs and traditional internal combustion or electric alternatives, ensuring that WTT emissions are not overlooked in favor of operational efficiency. This holistic framework is particularly crucial when contrasting FCEVs against alternative electrified pathways like hybrid electric vehicles (HEVs/PHEVs). Modern hybrid architectures deploy advanced transient control frameworks, such as driver-oriented adaptive consumption minimization [100] or online

stochastic energy management using state-of-charge prediction [101], to maximize real-world fuel economy and reduce operational tailpipe emissions. However, because hybrids remain fundamentally tethered to fossil-fuel baselines, their long-term decarbonization potential faces an inescapable threshold floor. Conversely, while FCEVs shift the analytical challenge away from short-term onboard component control loops to fuel supply chain dynamics, they unlock complete WTW decarbonization when paired with a renewable feedstock supply. Additionally, the literature indicates that while grey hydrogen, produced via steam methane reforming, currently offers the lowest fuel-related TCO [102,103], it fails to meet long-term decarbonization targets, potentially exposing fleet operators to escalating financial risks through carbon taxes and the loss of low-carbon fuel credits [102,104,105]. Conversely, green hydrogen derived from electrolysis, presents a higher immediate TCO due to significant electricity costs and electrolyzer CAPEX [53–55], yet it offers a future-proof economic profile as carbon pricing mechanisms internalize the environmental externalities of fossil-based fuels.

Recent studies suggest that as carbon taxes globally trend upward of 800 €/tCO₂, the TCO gap between high-emission and zero-emission hydrogen pathways will narrow significantly [106]. Specifically, 2025 and 2026 mark a pivot point in price stabilization due to the European Hydrogen Bank auction mechanisms. Results from the 2024 and 2025 auctions have successfully lowered the entry price for renewable hydrogen by providing fixed premiums (ranging from 0.20 €/kg to 0.60 €/kg) to producers [107]. As of 2026, these subsidies have begun to stabilize pump prices for green hydrogen, with average retail prices narrowing from a prohibitive 12–15 €/kg toward a more competitive 5–8 €/kg [108,109]. Research indicates that for heavy-duty vehicles to reach TCO parity with diesel, hydrogen prices must fall within the 4–6 €/kg range [110,111]. While green hydrogen remains above this threshold in 2026, the inclusion of carbon-weighted road tolls and the expansion of the EU Emissions Trading System 2 (ETS2) are effectively lowering the parity threshold by inflating the operational cost of traditional internal combustion engines. In addition, with the 2026 implementation of the EU ETS2 and the Eurovignette CO₂ surcharges [112,113], the financial penalty for diesel operations has shifted from a theoretical projection to a tangible OPEX variable that requires updated quantification, both for light- and heavy-duty transport [23,114–116].

Beyond the immediate technical and energy costs, the TCO for road transport is increasingly dictated by external regulatory input and spatial constraints. As EU shifts from policy design to enforcement, the financial penalties associated with carbon-intensive propulsion are no longer theoretical. The 2026 fiscal landscape is defined by the preparatory phase of the EU ETS2, which expands carbon pricing to the road transport and building sectors. Unlike the original ETS1, the EU ETS2 operates as an upstream system, placing the compliance burden on fuel suppliers who are expected to pass these costs directly to the pump [117]. When integrated into a long-term TCO model, this carbon tax effectively increases the lifetime OPEX of a traditional diesel heavy-duty vehicles [77,118]. Furthermore, research in 2026 has begun to incorporate the social cost of carbon into corporate TCO assessments to reflect environmental, social, and governance requirements [119–121]. By increasing the value of carbon, the price of diesel and grey hydrogen can become the dominant TCO factor, making green hydrogen FCEVs economically competitive even at higher retail fuel prices [122–124].

Overall, despite the proliferation of techno-economic and environmental studies on alternative powertrains, a critical deficiency persists in how the existing literature couples life-cycle expenditures with environmental footprints. Extant TCO-WTW frameworks can be broadly segregated into two methodological paradigms, both of which exhibit substantial limitations when forecasting long-term market transitions. A vast majority of conventional

models evaluate cost and emissions performance based on a single baseline year or select static snapshots (e.g., 2026 vs. 2030 or 2050) [125–130]. These models treat initial capital outlays and operating costs as fixed inputs, effectively neglecting the continuous, non-linear trajectories of technological learning rates and manufacturing economies of scale that occur between milestones. In addition, while many models attempt to map TTW and WTT dynamics, they routinely apply static emission intensities to future fuel and electricity supply chains [131–133]. By utilizing a fixed grid or feedstock emission factor, these studies ignore the highly dynamic, exponential decay pathways of electricity and hydrogen supply chain decarbonization driven by regional infrastructure policies.

Crucially, existing coupled models overlook the structural impact of dynamic carbon pricing frameworks. While upcoming upstream mechanisms such as the EU ETS2 and evolving Eurovignette CO₂ surcharges are recognized qualitatively [112,113], prior optimization models rarely formalize them as time-dependent, escalating OPEX variables. Consequently, current literature tends to generate polarized, binary outcomes: either overestimating the short-term economic viability of hydrogen by disregarding early-stage low-volume penalties, or underestimating its long-term potential by failing to model the regulatory inflation applied to fossil fuels alongside the parallel cost decay of green hydrogen feedstocks.

3. Mathematical Modeling

The mathematical model developed is based on a parametric multi-objective optimization. The model performs a lifecycle cost–benefit analysis, comparing diesel, petrol, EVs and hydrogen light-duty FCEVs, computing parametric hydrogen break-even prices against each alternative technology on an annual basis, and deriving Pareto-optimal technology sets under simultaneous cost and emissions objectives. For a vehicle of technology type $j \in \{\text{diesel, petrol, EV, hydrogen FCEV}\}$ purchased in year y , the lifecycle TCO in € is given by

$$\text{TCO}_j(y) = \text{CAPEX}_j(y) + \sum_{t=0}^{T-1} \frac{\text{OPEX}_j(y+t)}{(1+r)^t}, \quad (1)$$

where $\text{CAPEX}_j(y)$ is the vehicle purchase price in year y in €, OPEX_j is the annual operating cost in year $y+t$ in €/year, r is the discount rate in %, $T = 15$ is the vehicle lifespan in years and t indexes the year within the vehicle's life (0 to 14).

The annual operating cost comprises five components:

$$\text{OPEX}_j(y) = C_{\text{fuel},j}(y) + C_{\text{maint},j} + C_{\text{insur},j} + C_{\text{reg},j} + C_{\text{tax},j}, \quad (2)$$

where $C_{\text{fuel},j}(y)$ is the annual fuel/energy cost in €/year, $C_{\text{maint},j}$ is the annual maintenance cost in €/year, $C_{\text{insur},j}$ is the annual insurance cost in €/year, $C_{\text{reg},j}$ is the annual registration cost in €/year and $C_{\text{tax},j}$ is the annual road tax cost in €/year. The fuel/energy cost is given by

$$C_{\text{fuel},j}(y) = \frac{\text{km}_{\text{annual}}}{e_j} \cdot p_j(y), \quad (3)$$

where $\text{km}_{\text{annual}}$ is set at 15,000 km/year, e_j is the fuel/energy efficiency in km/L for diesel and petrol vehicles, km/kWh for EV and km/kg_{H2} for hydrogen FCEV, and $p_j(y)$ is the annual fuel/energy price in €/L for diesel and petrol vehicles, €/kWh for EV and €/kg_{H2} for hydrogen FCEV. Fossil fuel and electricity retail prices are projected forward from their 2026 baseline values using a compound annual growth rate, reflecting the combined effect of underlying energy price inflation and the progressive pass-through of EU ETS2

compliance costs to fuel suppliers. The annual price for technology j in year y is therefore given by

$$p_j(y) = p_{j,0} \cdot (1 + g)^{y-y_0}, \quad (4)$$

where $p_{j,0}$ is the 2026 baseline price, $y_0 = 2026$ is the base year, and $g = 0.08$ is the uniform annual compound growth rate applied to diesel, petrol, and electricity prices. It should be noted that the model does not include a separate explicit carbon tax parameter. Instead, the financial effect of the EU Emissions Trading System 2 (ETS2) and the Eurovignette CO₂ surcharges, both of which entered their preparatory implementation phase in 2026, is captured implicitly through the fuel price growth rate applied to diesel and petrol. Under the ETS2 upstream mechanism, compliance costs are borne by fuel suppliers and passed through to retail pump prices. While the ETS2 framework includes an initial cost containment corridor to stabilize early market entry, post-2030 allowance pricing remains subject to significant regulatory and macroeconomic uncertainty. Consequently, rather than modeling a separate carbon allowance market, the annual compound growth rate, g , applied to fossil fuel prices in Equation (4) is calibrated as a smoothed, long-term representation of ascending regulatory costs. This cost escalation trajectory is consistent with the cost escalation trajectories reported in the literature [112–114,117,119,134]. Hydrogen FCEVs are excluded from ETS2 obligations in the model, as the hydrogen supply chain does not fall within the ETS2 upstream fuel scope as currently legislated.

The hydrogen retail price follows a compound annual decay trajectory, calibrated to decline from the 2026 baseline, $p_{H_2,0} = 8.00$ €/kg, to the 2060 target, $p_{H_2,T} = 1.78$ €/kg, consistent with European Hydrogen Bank auction outcomes and IEA Net Zero scenario projections [135–137]. The implied annual decay rate g_{H_2} is derived from

$$g_{H_2} = \left(\frac{p_{H_2,T}}{p_{H_2,0}} \right)^{\frac{1}{y_T - y_0}} - 1, \quad (5)$$

which yields $g_{H_2} \approx -0.043$, corresponding to an annual decline of approximately 4.3%. The hydrogen price in any year y is then

$$p_{H_2}(y) = p_{H_2,0} \cdot (1 + g_{H_2})^{y-y_0}. \quad (6)$$

The remaining fixed annual costs $C_{\text{fixed},j}$ in €/year are given by

$$C_{\text{fixed},j} = C_{\text{maint},j} + C_{\text{insur},j} + C_{\text{reg},j} + C_{\text{tax},j}. \quad (7)$$

In terms of CAPEX, vehicle purchase prices follow exponential learning curves, given as

$$\text{CAPEX}_j(y) = \text{CAPEX}_{j,0} \cdot \exp[\lambda_j \cdot (y - y_0)], \quad (8)$$

where $\text{CAPEX}_{j,0}$ is the baseline purchase price in year $y_0 = 2026$ in €, λ_j is the technology-specific learning rate and y is the target year.

For each vehicle technology, j , the WTW emissions intensity follows a time-varying trajectory:

$$I_j(y) = I_{\text{min},j} + (I_{2026,j} - I_{\text{min},j}) \cdot \exp[-k_j \cdot (y - 2026)], \quad (9)$$

where $I_j(y)$ is the WTW emissions intensity for year y in gCO₂ per unit fuel/energy, $I_{\text{min},j}$ is the long-run decarbonization floor, $I_{2026,j}$ is the baseline WTW intensity in 2026 and k_j is the decarbonization speed.

For each purchase year y , a two-objective minimization problem is then defined over the discrete set of vehicle technologies:

$$\min_{j \in J} [\text{TCO}_j(y), \text{WTW}_j(y)], \quad (10)$$

where $J = \{\text{diesel}, \text{petrol}, \text{EV}, \text{hydrogen FCEV}\}$. A technology j is Pareto-optimal if there exists no other technology $j' \neq j$ such that

$$\text{TCO}_{j'}(y) \leq \text{TCO}_j(y) \quad \text{and} \quad \text{WTW}_{j'}(y) \leq \text{WTW}_j(y), \quad (11)$$

with at least one strict inequality. For each year y , the Pareto set $P(y)$ is the collection of all non-dominated technologies:

$$P(y) = \{j \in J : \nexists j' \in J \text{ such that } (j' \prec j)\}, \quad (12)$$

where $j' \prec j$ denotes Pareto dominance.

The multi-objective optimization problem defined in Equations (10)–(12) is solved by exhaustive enumeration and pairwise Pareto dominance screening, which is the exact and complete solution method for a discrete feasible set of finite cardinality $|J| = 4$. The procedure is executed independently for each purchase year $y \in \{2026, \dots, 2060\}$ and consists of the following steps:

Step 1: Objective evaluation. For each technology $j \in J$ and purchase year y , compute the two objective values: (a) $\text{TCO}_j(y)$ via Equations (1)–(8), using the NPV of all lifecycle costs over the 15-year vehicle life and (b) $\text{WTW}_j(y)$ as the lifecycle-average emissions intensity:

$$\text{WTW}_j(y) = \frac{1}{T} \sum_{t=0}^{T-1} \frac{k_{m,\text{annual}}}{e_j} \cdot I_j(y+t), \quad (13)$$

where $I_j(y+t)$ is the time-varying WTW intensity from Equation (6).

Step 2: Pareto dominance screening. For each candidate technology $j \in J$, check whether it is dominated by any other technology $j' \in J$, $j' \neq j$, i.e., whether there exists j' that satisfies Equation (11), with at least one strict inequality. Since $|J| = 4$, this requires at most 6 pairwise comparisons per year. Technology j is added to the Pareto set $P(y)$ if and only if no such dominating j' exists.

Step 3: Break-even price optimization. For each purchase year y and each competing technology $j \in \{\text{diesel}, \text{petrol}, \text{EV}\}$, the break-even hydrogen price $p_{\text{H}_2,j}^*(y)$ is found by solving the single-variable minimization:

$$\min_{p_{\text{H}_2}} |\text{TCO}_{\text{FCEV}}(y, p_{\text{H}_2}) - \text{TCO}_j(y)|, \quad (14)$$

subject to the bounds $p_{\text{H}_2} \in [p_{\text{lb}}, p_{\text{ub}}]$. Since TCO_{FCEV} is strictly monotone and linear in p_{H_2} through the fuel cost term of Equation (3), the objective function is convex and the solution is unique. This sub-problem is solved using the constrained non-linear optimizer `fmincon` in MATLAB with a tolerance of 10^{-4} .

Step 4: Annual iteration. Steps 1–3 are repeated for all $y \in \{2026, \dots, 2060\}$, yielding the time-evolving Pareto set $P(y)$.

4. Model Implementation

As presented in Figure 2, the model developed is implemented in MATLAB and performs a lifecycle TCO and WTW optimization for diesel, petrol, EV and hydrogen light-duty FCEV vehicles over the period 2026–2060. The implementation follows a sequential

procedure that combines annual cost and emission trajectories, discounted lifecycle cost calculations, and Pareto screening to identify the non-dominated technology set for each purchase year. In addition, the model computes parametric hydrogen break-even prices relative to each competing technology, thereby quantifying the hydrogen price levels required for cost parity under varying market conditions.

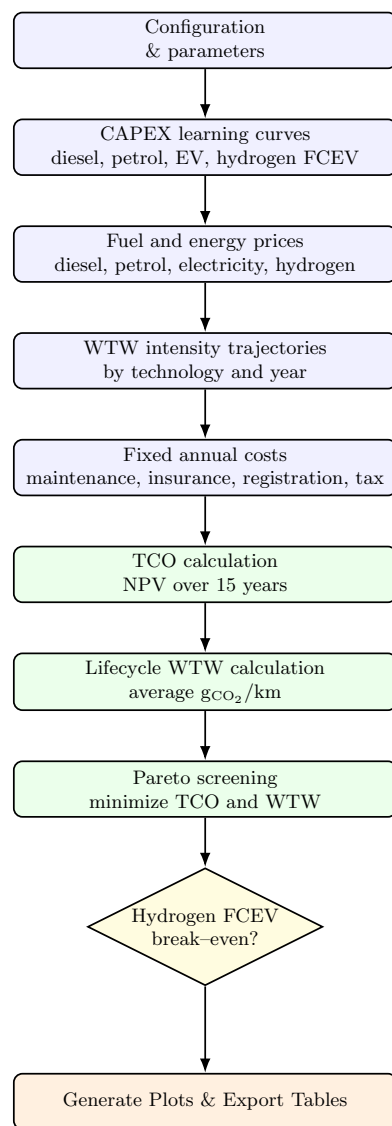


Figure 2. Optimization model logic diagram.

Table 2 summarizes the key technical, economic, and environmental inputs used in the MATLAB R2026a implementation, including the analysis horizon, discount rate, annual mileage, vehicle efficiencies, baseline CAPEX values, learning rates, fuel and electricity prices, and WTW emissions trajectories for all four light-duty vehicle technologies [11,38–40,114,135–163]. Crucially, the quantitative boundaries of this techno-economic assessment are strictly restricted to light-duty vehicles. Heavier logistics or long-haul transport segments feature entirely different operational patterns, higher annual utilization rates, and distinct payload constraints, and are therefore excluded from the numerical modeling. Table 2 also groups the fixed annual operating costs and the emissions-decay parameters so that the full lifecycle TCO and WTW calculations can be reproduced consistently for diesel, petrol, EV, and hydrogen FCEV cases.

It should be noted that, while this study provides a deterministic baseline for the energy transition pathway up to 2060, a key limitation is the inherent uncertainty associated with long-term economic forecasting. Key parameters, including hydrogen and electricity prices, vehicle capital costs, and regulatory penalties, are subject to shifting market dynamics. While a full sensitivity analysis is beyond the immediate scope of this work, the comprehensive data compiled in Table 2 establishes a transparent baseline. This framework is intentionally structured to serve as a foundation for future research, where these parameters can be systematically varied to explore diverse socio-economic scenarios.

Table 2. Model parameters used in the TCO and WTW analysis for light-duty vehicles.

Parameter	Symbol/Unit	Value	Description
Analysis period	y_0, y_T	2026, 2060	Start and end years of the study.
Vehicle lifetime	T (years)	15	Economic analysis horizon for each vehicle.
Discount rate	r	0.05	Real discount rate used for NPV calculations.
Annual mileage	$\text{km}_{\text{annual}}$ (km/year)	15,000	Annual vehicle usage.
H ₂ efficiency	e_{H_2} (km/kg)	5.0	Hydrogen fuel cell vehicle efficiency.
Diesel efficiency	e_d (km/L)	15.0	Diesel vehicle efficiency.
Petrol efficiency	e_p (km/L)	12.0	Petrol vehicle efficiency.
EV efficiency	e_e (km/kWh)	5.0	Battery-electric vehicle efficiency.
H ₂ FCEV CAPEX, 2026	$\text{CAPEX}_{h,0}$ (€)	55,000	Initial purchase price for FCEV.
Diesel CAPEX, 2026	$\text{CAPEX}_{d,0}$ (€)	25,000	Initial purchase price for diesel vehicle.
Petrol CAPEX, 2026	$\text{CAPEX}_{p,0}$ (€)	24,000	Initial purchase price for petrol vehicle.
EV CAPEX, 2026	$\text{CAPEX}_{e,0}$ (€)	40,000	Initial purchase price for EV.
H ₂ learning rate	λ_h	−0.25	CAPEX learning rate for FCEVs.
Diesel learning rate	λ_d	−0.015	CAPEX learning rate for diesel vehicles.
Petrol learning rate	λ_p	−0.015	CAPEX learning rate for petrol vehicles.
EV learning rate	λ_e	−0.15	CAPEX learning rate for EVs.
H ₂ price, 2026	$p_{\text{H}_2,0}$ (€/kg)	8.00	Baseline hydrogen retail price in 2026.
H ₂ price, 2060	$p_{\text{H}_2,T}$ (€/kg)	1.78	Target hydrogen price in 2060.
Diesel price, 2026	$p_{d,0}$ (€/L)	1.80	Baseline diesel price.
Petrol price, 2026	$p_{p,0}$ (€/L)	1.90	Baseline petrol price.
Electricity price, 2026	$p_{e,0}$ (€/kWh)	0.320	Baseline electricity price.
H ₂ WTW intensity, 2026	I_{2026,H_2} (gCO ₂ /kg)	450	Initial WTW intensity for hydrogen.
Diesel WTW intensity, 2026	$I_{2026,d}$ (gCO ₂ /L)	3200	Initial WTW intensity for diesel.
Petrol WTW intensity, 2026	$I_{2026,p}$ (gCO ₂ /L)	3000	Initial WTW intensity for petrol.
EV WTW intensity, 2026	$I_{2026,e}$ (gCO ₂ /kWh)	450	Initial WTW intensity for EV electricity.
H ₂ WTW floor	$I_{\text{min},\text{H}_2}$ (gCO ₂ /kg)	20	Long-run emissions floor for hydrogen.
Diesel WTW floor	$I_{\text{min},d}$ (gCO ₂ /L)	400	Long-run emissions floor for diesel.
Petrol WTW floor	$I_{\text{min},p}$ (gCO ₂ /L)	400	Long-run emissions floor for petrol.
EV WTW floor	$I_{\text{min},e}$ (gCO ₂ /kWh)	20	Long-run emissions floor for EV electricity.
H ₂ decay rate	k_{H_2}	0.090	Decarbonization speed for hydrogen.
Diesel decay rate	k_d	0.020	Decarbonization speed for diesel.
Petrol decay rate	k_p	0.020	Decarbonization speed for petrol.
EV decay rate	k_e	0.070	Decarbonization speed for EV electricity.
Maintenance cost	C_{maint} (€/year)	[500, 800, 750, 500]	H ₂ FCEV, diesel, petrol, EV.
Insurance cost	C_{insur} (€/year)	[800, 750, 750, 800]	H ₂ FCEV, diesel, petrol, EV.
Registration cost	C_{reg} (€/year)	[200, 180, 180, 200]	H ₂ FCEV, diesel, petrol, EV.
Road tax	C_{tax} (€/year)	[0, 150, 150, 0]	H ₂ FCEV, diesel, petrol, EV.

The implementation begins by constructing the CAPEX learning curves, fuel and electricity price trajectories and WTW emissions intensity paths for all light-duty vehicle types. Fixed annual costs, including maintenance, insurance, registration, and road tax, are next incorporated to complete the lifecycle operating cost structure. For each purchase year, the model evaluates the discounted TCO over the full vehicle lifetime and calculates the corresponding lifecycle-average WTW emissions. These results are then used to determine the Pareto-optimal set of technologies with respect to cost and emissions minimization. Finally, the model performs a break-even analysis for hydrogen by comparing the FCEV

TCO against diesel, petrol, and EV alternatives, and exports the results in tabular form for further interpretation.

5. Results and Discussion

Figure 3 illustrates the TCO, for the year 2026, across the four light-duty vehicle technologies considered in this study. This baseline comparison includes all evaluated technology alternatives prior to multi-objective optimization. The results reveal a severe cost discrepancy between hydrogen FCEVs and the more established alternative powertrains. With a TCO of approximately €275,000, the FCEV is more than three times more expensive than its competitors. This baseline uncompetitiveness is structurally rooted in the high initial vehicle purchase price (€55,000) and a substantial retail hydrogen price (8.00 €/kg), which amplify both the fixed and variable cost components in the absence of capital subsidies. In contrast, diesel, petrol, and EVs are confined to a considerably narrower TCO range of roughly €75,000–€90,000. EVs deliver the lowest baseline TCO, capitalizing on lower initial operating costs (0.320 €/kWh) and high powertrain efficiency (5.0 km/kWh). The difference between the FCEV and the lowest-cost alternative defines the net economic barrier that must be neutralized by technological scaling or fiscal intervention.

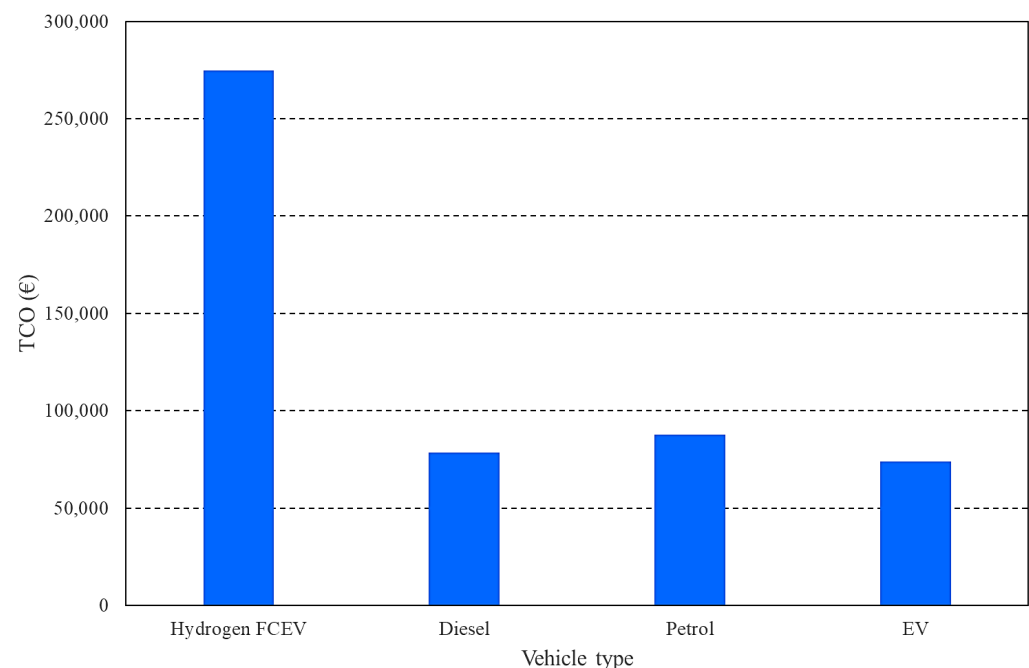


Figure 3. Baseline comparison of the total lifecycle TCO across all four individual vehicle technologies evaluated for a purchase year of 2026.

Figure 4 maps the multi-objective design space and the resulting Pareto optimal solutions evaluating the trade-off between lifecycle cost and emissions for the year 2026. The plot displays all evaluated vehicle technologies to illustrate the broader solution space alongside the non-dominated boundaries. light-duty diesel and petrol vehicles cluster in the high-emission region of the diagram, exhibiting WTW intensities of approximately 200–230 gCO₂/km. While conventional architectures benefit from a mature supply chain that keeps baseline CAPEX low (€24,000–€25,000), their performance is fundamentally constrained by the carbon intensity of liquid fossil fuels (3200 gCO₂/L and 3000 gCO₂/L). This establishes a clear conflict between short-term cost minimization and long-term environmental targets.

Conversely, hydrogen FCEVs operate at the opposite pole of the trade-off space, as seen in Figure 4. While they eliminate tailpipe (TTW) greenhouse gases, their total WTW footprint (approx. 60 gCO₂/km, given $e_{H_2} = 5.0$ km/kg) is heavily penalized by early-stage WTT supply chain emissions (e.g., hydrogen production method, compression, storage, and distribution), reflecting a 2026 baseline intensity of 450 gCO₂/kg. Consequently, FCEVs occupy a non-dominated position on the emissions-minimization frontier but suffer a severe TCO penalty. EVs dominate the 2026 solution space by minimizing both objectives simultaneously; they leverage a highly efficient grid-to-wheel conversion path that pairs low TCO with low lifecycle emissions, operating close to the FCEV emissions boundary due to an equivalent initial electricity grid intensity. Effectively, light-duty FCEVs are not yet the most cost-effective option, but they already occupy an emissions-competitive position on the frontier that becomes more meaningful as their costs decline over time.

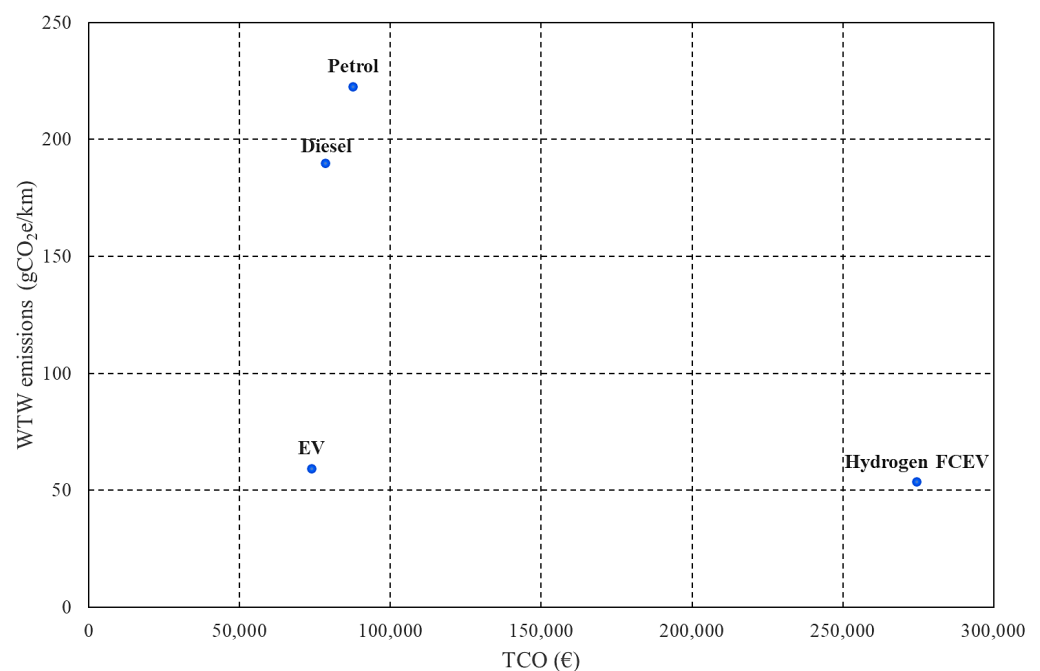


Figure 4. Multi-objective design space showing all four evaluated vehicle technologies, for a purchase year of 2026.

Figure 5 projects the temporal evolution of TCO up to 2046, illustrating a profound structural reconfiguration of market competitiveness driven by technology learning rates and escalating regulatory penalties. This projection maps the individual lifecycle trajectories of all four independent technology choices to evaluate how baseline costs evolve prior to multi-objective screening. Conventional petrol and diesel platforms exhibit a sharp upward cost trajectory, with petrol lifecycle costs rising toward €250,000 by 2046. This inflation is driven by the phase-in of the upstream EU ETS2 carbon pricing mechanism which directly penalizes the low efficiency and high fossil-emissions profile of ICEVs over time. By shifting the compliance burden upstream to fuel suppliers, these measures are expected to translate into higher pump prices over time, thereby eroding the cost advantage of conventional propulsion systems.

In contrast, FCEVs undergo accelerated economic optimization. Because hydrogen systems are unexposed to carbon compliance penalties, their long-term OPEX remains structurally protected. More importantly, the high learning rate assigned to hydrogen systems (−0.25) drives a steady compression of vehicle CAPEX, while hydrogen fuel prices decay exponentially from 8.00 €/kg toward the 1.78 €/kg target. As a result of this dual mechanism, the FCEV TCO intersects and falls below petrol in 2037, ultimately achieving

full parity with mature EV systems by 2046 at approximately €100,000. The EV TCO trajectory displays a moderate post-2030 increase, capturing the systemic transition from early-stage public subsidization to mature infrastructure conditions characterized by grid reinforcement costs and localized demand-response pricing. Overall, Figure 5 shows that light-duty hydrogen mobility only becomes competitive once its declining fuel-production costs coincide with the rising fiscal burden on fossil fuels and the partial leveling-off of EV cost advantages.

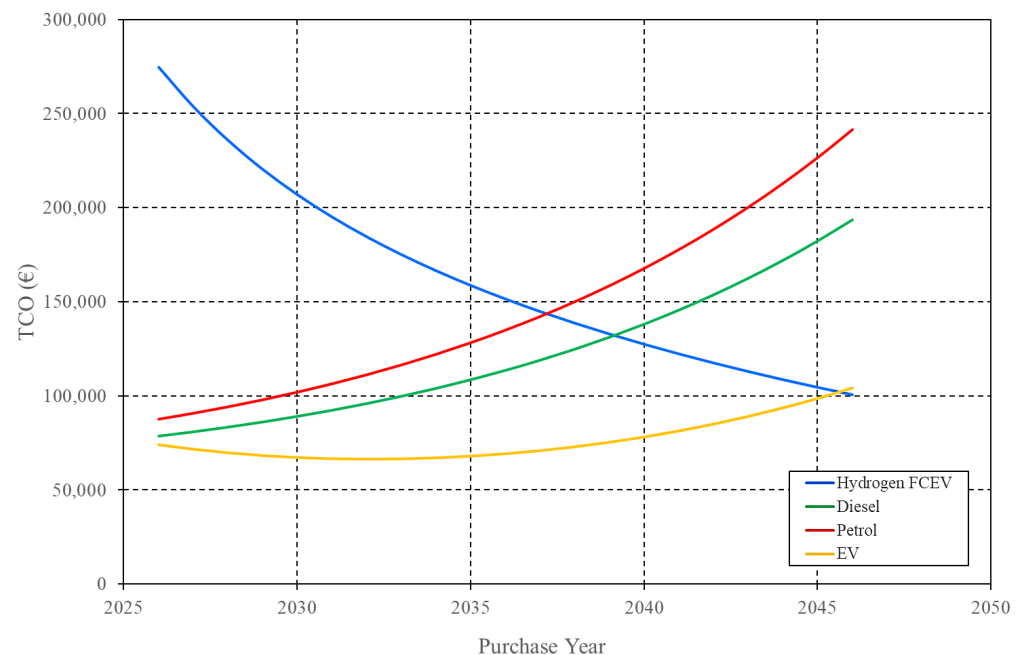


Figure 5. Temporal evolution of TCO for each individual vehicle technology across the purchase year horizon.

To isolate the precise fuel market thresholds required to trigger these transitions, Figure 6 details the dynamic break-even hydrogen prices required to achieve absolute TCO parity against each competing technology. The break-even curves plot the maximum allowable retail hydrogen price that maintains economic equivalence. FCEVs achieve cost parity the moment the projected baseline market price drops below a specific technology's break-even curve. Due to mounting carbon taxes on liquid fuels, hydrogen outcompetes petrol first in 2037 at a threshold price of 4.90 €/kg, followed closely by diesel in 2039 at 4.40 €/kg. The EV curve remains the lowest across the horizon, bottoming out at a highly stringent break-even target of 3.40 €/kg in 2046. This confirms that light-duty EV platforms represent the most formidable economic benchmark for hydrogen mobility, owing to their sustained volumetric efficiency advantages.

Figure 7 quantifies the net financial gap between light-duty hydrogen FCEVs and the most cost-effective alternative at any given point in time, isolating the net present value (NPV) penalty or bonus of hydrogen adoption. In 2026, early adopters face an economic penalty of approximately −€200,000 relative to a baseline EV or diesel fleet. This supports the findings presented in Figure 3. Choosing a hydrogen vehicle today is a massive financial loss compared to buying an EV or diesel vehicle. This deficit contracts continuously as manufacturing economies of scale yield down-market cost reductions. A critical milestone occurs in 2037: while absolute parity with the overall market leader is deferred until 2046, the FCEV crosses the zero-cost delta relative to petrol platforms by 2037. This indicates that light-duty FCEVs will transition into a pragmatically viable replacement for conventional liquid-fuel fleets nearly a decade before they challenge EV dominance.

However, the extended timeline to cross the absolute zero axis in 2046 introduces a severe risk of technology lock-in or path dependency favoring EV infrastructure, suggesting that long-term deployment mandates or targeted fuel-tax subsidies are mandatory to sustain the hydrogen investment pathway during the intermediate transition period.

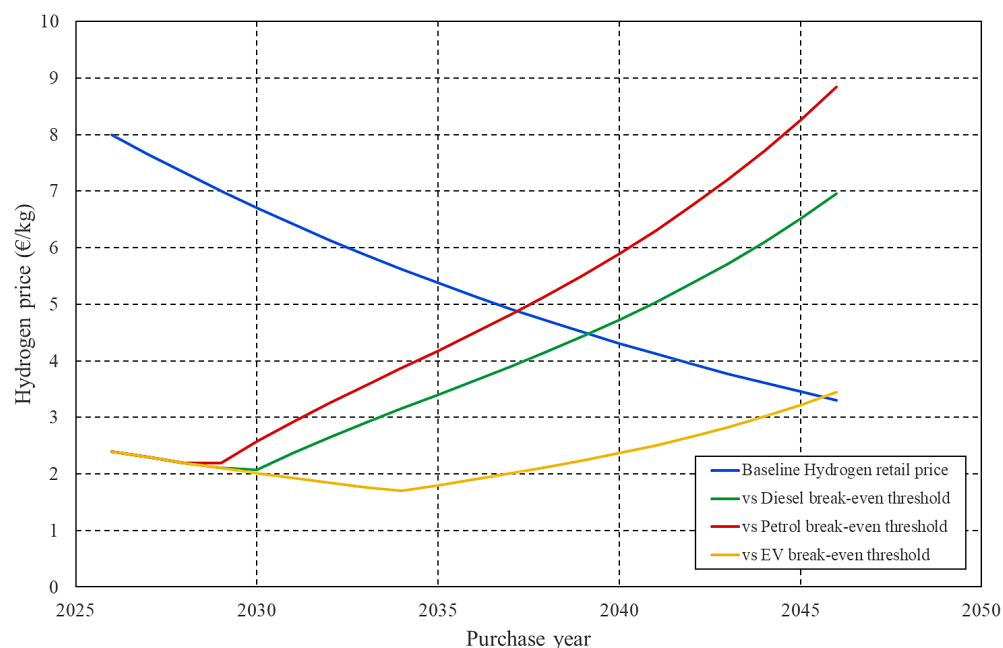


Figure 6. Parametric hydrogen break-even prices required to achieve TCO parity against competing vehicle technologies over the purchase year horizon compared against the baseline projected hydrogen retail price path, starting at 8€/kg in 2026.

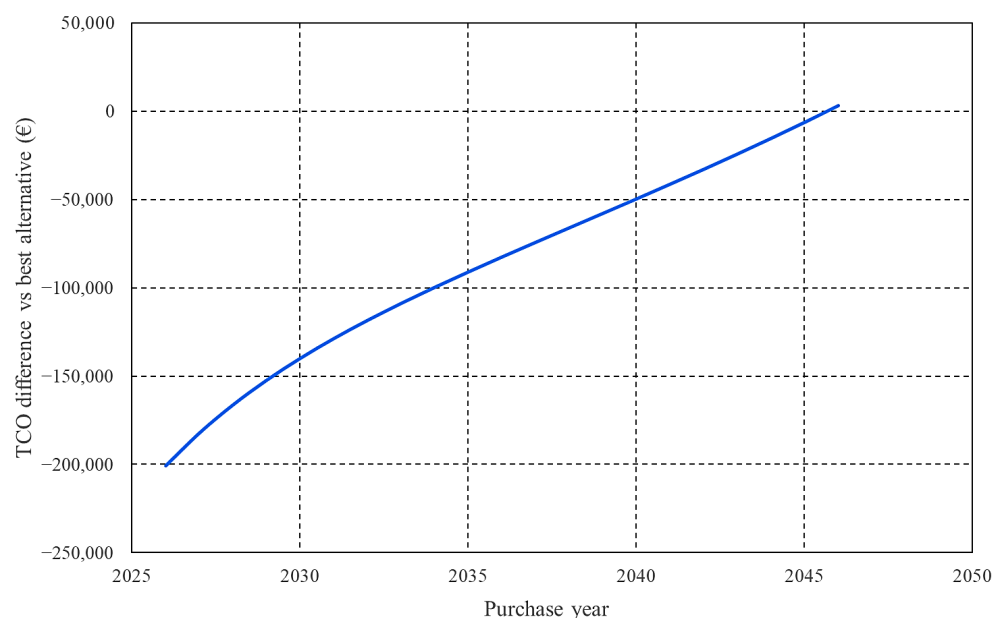


Figure 7. TCO difference between hydrogen FCEV and the best alternative over the purchase year horizon.

When contrasted with conventional European techno-economic transport literature, which often utilizes single-objective cost minimization to project FCEV parity even post-2040 for commercial and passenger vehicles [164–169], the parity horizons identified in this work (2037 and 2046) present distinct structural nuances. This study's dynamic multi-

objective framework optimizes simultaneously across a dual-axis of 15-year discounted TCO and time-decaying WTW emissions trajectories. Consequently, technologies enter the Pareto-optimal frontier not merely by matching raw capital costs, but by offering optimal environmental-economic trade-offs under evolving market conditions. Furthermore, taking in consideration progressive EU ETS2 carbon penalties, the model demonstrates how regulatory pressures shift the economic break-even thresholds over time by directly affecting fuel prices, establishing 2037 as the true multi-objective compromise milestone and 2046 as the long-term unsubsidized parity year.

Figure 8 traces the complete continuous migration of the Pareto-optimal frontier across the temporal horizon. Rather than portraying static trade-offs, this multi-objective optimization framework illustrates how the non-dominated frontier shifts over time. Simultaneously, it displays the underlying light-duty technology clouds containing all evaluated individual alternatives, as they drift through the TCO-WTW space under simultaneous learning effects and grid/feedstock decarbonization.

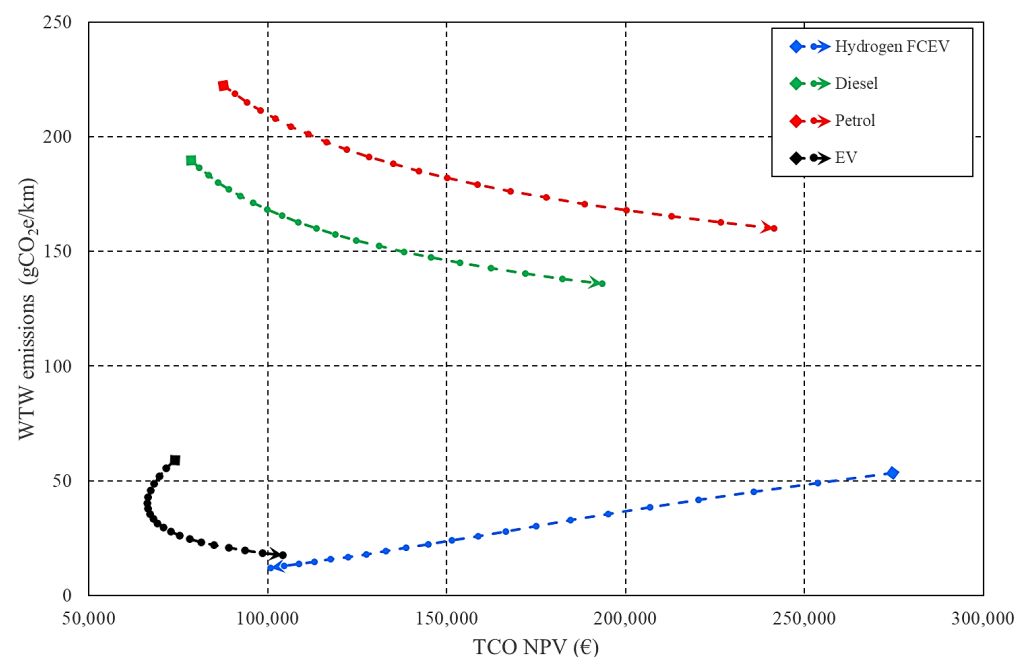


Figure 8. Pareto-optimal solutions for the evolution of TCO and WTW emissions for hydrogen FCEVs, diesel, petrol, and EVs over the purchase year horizon.

The hydrogen FCEV curve begins at the highest TCO level in the early years, but it gradually moves downward and to the left as the analysis progresses, indicating improving competitiveness over time. This decline is driven by falling hydrogen production costs, learning effects in fuel-cell systems, and the absence of direct exposure to fossil-fuel carbon surcharges. At the same time, its WTW emissions also decrease, due to the continued decarbonization of the hydrogen supply pathway. As a result, hydrogen FCEVs shift closer to the low-emission frontier and become increasingly relevant in later years, even though they remain expensive at the start of the horizon. Diesel and petrol follow a very different pattern. Their TCO increases steadily over time, while their WTW emissions remain much higher than those of EVs and hydrogen FCEVs throughout the full period. This upward cost movement reflects the growing effect of carbon pricing, fuel taxation, and regulatory penalties, which progressively erode the financial appeal of fossil-fuel propulsion. Both technologies therefore drift upward and remain far from the Pareto-efficient low-emissions region, which illustrates why conventional ICEVs become less attractive as the policy environment tightens. The EV curve occupies the most favorable

position overall because it combines low TCO with relatively low WTW emissions. Its cost profile improves in the early years and then flattens or rises only slightly later on, reflecting a mature technology that benefits from learning effects but also begins to face higher charging, grid, and infrastructure-related costs over time. On the emissions side, EVs remain consistently low because the electricity supply is assumed to decarbonize gradually. This keeps EVs near the bottom-left region of the figure for much of the timeline, which explains why they dominate the cost-minimization objective and appear frequently on the Pareto frontier.

The plotted results map exactly where a given technology-year combination represents a non-dominated alternative that optimizes the trade-off between cost and emissions. In the early years, these points are concentrated around the EV and hydrogen FCEV regions, because those technologies offer the most favorable environmental performance. As time advances, the hydrogen FCEV cloud moves closer to the efficient region, showing that hydrogen becomes progressively more attractive as its cost falls and its emissions profile improves. Overall, Figure 8 demonstrates that the four technologies do not merely differ in their starting positions since they follow distinct trajectories through the cost-emissions space, and these trajectories explain why EVs dominate in the near term while hydrogen FCEV becomes more competitive in the longer term.

The Pareto-optimality analysis indicates that, in 2026, the solution space is clearly divided with EVs dominating the cost-minimization objective, whereas EVs and hydrogen FCEVs share the emissions-minimization frontier. However, the steep decline in the FCEV cost curve suggests that this Pareto gap is narrowing more rapidly than initially expected. In particular, the intersection with petrol TCO in 2037 marks an important inflection point, at which hydrogen transitions from being primarily an environmental option to a pragmatically superior alternative to fossil-fuel propulsion. Full parity with battery-electric systems is then reached nine years later, in 2046, highlighting the progressively stronger long-term case for hydrogen mobility.

6. Conclusions

This study developed a novel multi-objective optimization framework to assess the long-term economic and environmental performance of light-duty hydrogen FCEVs relative to diesel, petrol, and EVs over the period 2026–2060. By shifting from traditional static techno-economic models to a dynamic framework combining discounted TCO calculations with time-dependent WTW emissions trajectories, the model successfully captured the non-linear interaction between technological learning, fuel price evolution, and regulatory cost escalation. The results provide a rigorous roadmap of when hydrogen mobility transitions from a policy-supported option to a self-sustaining, commercially competitive technology.

The analysis shows that light-duty hydrogen FCEVs face an intensive entry barrier in the baseline year 2026, with a TCO of approximately €275,000, that is nearly three times higher than alternative powertrains. This economic disparity is structurally driven by the low-volume penalty of proton exchange membrane fuel cell stacks, high hydrogen retail prices and the current immaturity of the supporting supply chain. Concurrently, the model reveals that hydrogen FCEV costs decline steadily over time, while diesel and petrol encounter sharp upward cost trajectories under the escalating regulatory pressure of EU ETS2 carbon pricing. While EVs maintain the lowest TCO for much of the analysis period due to superior volumetric efficiency, their cost advantage narrows post-2030 as infrastructure scaling and grid reinforcement costs phase in.

Two distinct structural inflection points emerge from the dynamic horizon. First, light-duty hydrogen FCEVs are projected to become more cost effective than petrol vehicles in 2037, indicating that hydrogen can emerge as a practical substitute for internal

combustion propulsion nearly a decade before full parity with EVs is achieved. Second, FCEVs reach parity with EVs in 2046, which marks the point at which hydrogen becomes economically competitive with the best available alternative in the model. These crossover points confirm that while the near-term economic case for hydrogen remains weak, its long-term competitiveness is robustly anchored by technological scaling and liquid-fuel decarbonization constraints.

The Pareto multi-objective optimization analysis further confirms that light-duty EVs dominate the cost-minimization objective in 2026, while EVs and FCEVs occupy the low-emissions frontier as feedstock supply chains decarbonize. This means that hydrogen does not currently offer a combined cost and emissions advantage, but it does offer a strong environmental profile and a plausible long-term pathway for sectors where battery mass, range, and refueling time remain limiting factors. While the quantitative economic constraints modeled reflect light-duty transport dynamics, they may offer a conservative qualitative framework for considering heavier transport segments. Because battery mass, payload capacity, and refueling downtime present severe operational bottlenecks in long-haul trucking, it is plausible that the competitive TCO thresholds identified in this study could shift significantly in heavier applications. Consequently, where battery scalability faces physical and economic limits, FCEVs are frequently highlighted in the literature as a highly attractive alternative, though confirming this would require dedicated quantitative modeling tailored to heavy-duty operational profiles.

Ultimately, this study indicates that light-duty hydrogen FCEVs can achieve market industrialization only if current cost trajectories are sustained alongside stringent regulatory pressure on fossil fuels. To bridge the critical intermediate cost-parity gap before 2037 and mitigate the risk of premature infrastructure lock-in, immediate and targeted policy interventions are mandatory. Commercial fleet operators and urban delivery managers require actionable fiscal support, including carbon-weighted road toll exemptions, upstream fuel-tax subsidies under the EU ETS2 framework, and direct capital grants to develop localized commercial fleet refueling stations. Sustained reductions in hydrogen production costs, alongside these targeted policy frameworks, represent the definitive pathway to accelerate commercial market adoption and secure deep transport decarbonization.

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