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Cost–Carbon Dual Assessment of Hydrogen Versus Battery-Electric Powertrains for Chinese Road Freight: Coupling Hydrogen Pathway Costs with Regional Grid Carbon Intensity

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Abstract

Choosing between battery-electric and hydrogen fuel-cell trucks to decarbonize Chinese road freight hinges on two upstream quantities rarely assessed jointly: delivered hydrogen cost and regional grid carbon intensity. This study couples pathway-resolved delivered hydrogen costs with charging-region grid carbon intensity in one vehicle-level cost–carbon evaluation. A literature-anchored parametric simulation links six hydrogen pathways, seven regional grid settings, two truck classes, and three powertrains. It evaluates total cost of ownership (TCO), fuel-chain well-to-wheel carbon intensity (CI, vehicle manufacturing excluded), Pareto fronts, and the critical carbon price p*, with one-at-a-time sensitivity and a 10,000-draw Monte Carlo analysis. Renewable electricity is purchased at 0.25 CNY/kWh (zero-purchase supply retained as a labelled scenario), placing delivered hydrogen at 33.0–54.3 CNY/kg. For 49 t long-haul duty, TCO is 5.31 CNY/km (diesel), 4.70 (battery-electric; 11.5% lower per kilometre yet about 4% higher per tonne-kilometre, governed by the payload capacity ratio), and 7.92 (renewable-hydrogen fuel-cell; 49.1% higher). Across the same option space, WTW carbon intensity ranges from 198 to 3578 gCO_2e/km. Eight finite critical carbon prices span 681.7–2936.4 CNY/tCO_2, up to roughly 28 times the 2024 market band of 60–105 CNY/tCO_2; parity probabilities remain near zero at current prices. Policy support should follow fuel carbon intensity and certified renewable-hydrogen siting, not vehicle purchases alone.

Keywords: total cost of ownership; hydrogen production pathway; well-to-wheel carbon intensity; grid carbon intensity; heavy-duty truck; critical carbon price; Chinese road freight

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1. Introduction

1.1. Motivation: Decarbonizing Chinese Road Freight with Hydrogen and Electricity

Road freight carries the bulk of China's physical logistics and runs almost entirely on diesel. Road transport is the country's largest source of transport CO_2 emissions, and freight trucks account for most of that total [1]. Decarbonizing this segment is therefore a structural rather than a marginal task, and Chinese policy has begun to treat it as such. New-energy vehicle promotion has reshaped the light-duty market, and fuel-cell electric vehicle (FCEV) demonstration city clusters now target commercial vehicles [2]. Hydrogen is positioned preferentially for heavy-duty and long-haul duty cycles that strain battery range and charging time [3]. Internationally, hydrogen for transport is likewise framed as complementary to direct electrification in hard-to-electrify segments [1].

The two electrification routes depend on different upstream systems, and that asymmetry is the crux of the comparison. A battery-electric truck's emissions track the regional grid it charges from: official operating-margin factors span 0.44–0.75 $kgCO_2/kWh$ across China's macro-regions against a national average of 0.5366 $kgCO_2/kWh$ in 2022 [4]. A fuel-cell truck's emissions and fuel cost both track the hydrogen production pathway and its delivery chain—today dominated by coal-based routes in China [3], with renewable electrolysis emerging in resource-rich provinces. The supply chain therefore decides both the economics and the climate outcome before the vehicle is ever purchased. Energy prices reinforce the asymmetry: diesel retail prices in the 7.2–7.7 CNY/L range anchor fossil economics [5], while charging tariffs [6] and hydrogen refuelling prices remain in flux.

Fleet purchasers weigh cost and carbon simultaneously, yet the analytical tools available to them usually treat the two separately: total cost of ownership (TCO) models take the energy price as given, and carbon studies take the vehicle as given. This paper develops a joint cost–carbon map for Chinese road freight (Figure 1). Within a single framework, hydrogen pathway costs and regional grid carbon intensities are coupled to powertrain economics for two duty-benchmarked vehicle classes: 4.5 t delivery vans and 49 t tractor-trailers. The results are simulation-based (indicative rather than definitive) and are meant to inform siting, procurement, and policy decisions rather than to forecast any specific fleet.

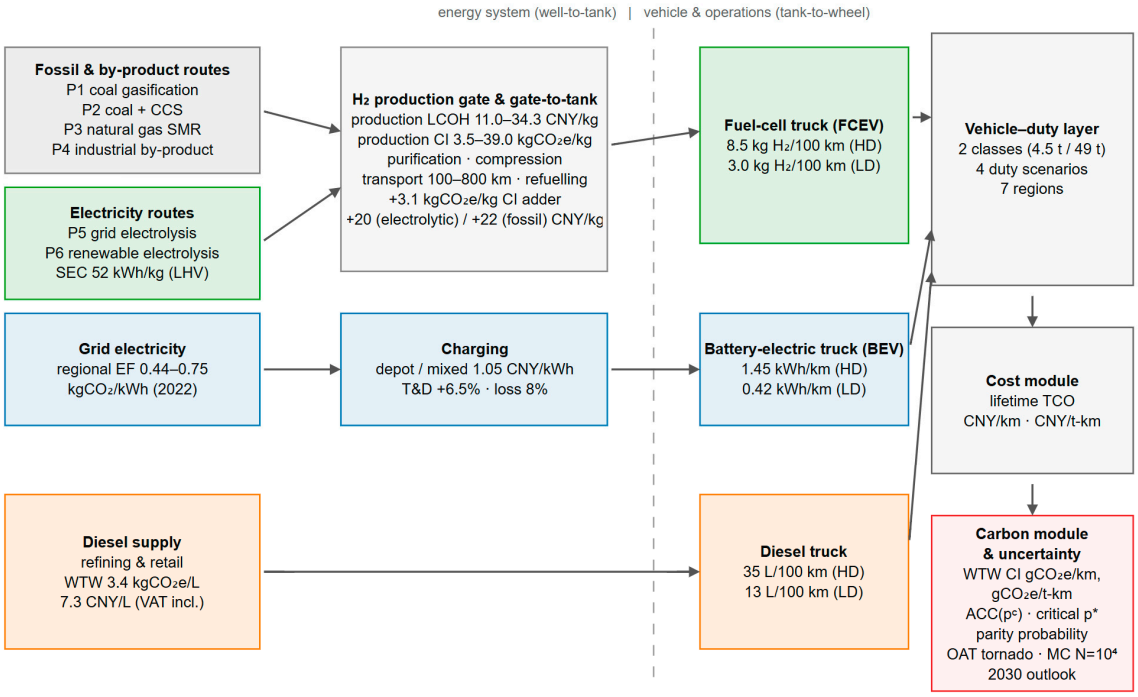


Figure 1. Assessment framework and system boundary. **Left**: hydrogen pathways P1–P6 and the gate-to-tank chain (purification, compression and transport, refuelling); **right**: the vehicle-duty layer coupled to the cost and carbon modules, closed by ACC(pc), the critical carbon price p*, and parity probability, and wrapped by the uncertainty layers (OAT, Monte Carlo, 2030 outlook). Colour coding: blue–green tones mark the hydrogen supply side (production pathways P1–P6 and the gate-to-tank chain); blue marks the cost module; red marks the carbon module. WTW boundary; CNY2024; single LHV basis.

1.2. Literature Review

Four bodies of literature bear on this question. We review each in turn and identify what it leaves unresolved.

1.2.1. TCO Comparisons of Fuel-Cell, Battery-Electric, and Diesel Trucks

TCO comparisons for zero-emission heavy-duty vehicles are best developed in Europe and North America. Component-based capital models feed TCO frameworks in which fuel price and annual mileage dominate the ranking of diesel, battery-electric, and fuel-cell trucks [7]. The component costs behind those models are battery packs at roughly 221 EUR/kWh, fuel-cell systems at 430 EUR/kW, and 700 bar tanks near 1211 EUR/kg-H_2, with the tank figure kept per kilogram of hydrogen to avoid a stored-energy unit trap. Within this structure, published parity crossovers cluster between 2025 and 2030, although their timing is sensitive to vehicle-price and usage assumptions [8–10]. Discount-rate choice reinforces the sensitivity: across a 5–12% range spanning freight hurdle rates and utility-weighted costs of capital, rankings can materially flip [11,12]. Closest to a joint cost–carbon treatment, Himona and Poullikkas [12] evaluate TCO and well-to-wheel emissions together within a dynamic multi-objective framework—though at the EU aggregate level, restricted to light-duty vehicles, over a four-technology option set with a single aggregated hydrogen pathway and a single grid intensity, and purely deterministically; the present study extends that joint perspective to Chinese road freight with a pathway- and region-resolved option space and an explicit uncertainty layer. China-specific evidence has strengthened recently but remains thin at the vehicle level. Most directly, the Asian Development Bank Institute's 2024 assessment of hydrogen-truck total cost of ownership in China [13] examines cost parity for fuel-cell trucks under Chinese price and policy settings—the most direct national-level anchor to date. Recent Chinese scenario studies quantify the cost, emission, and policy trade-offs of integrating hydrogen fuel-cell trucks into freight operations: multi-agent simulation finds adoption highly elastic to the dispensed price (a reduction from 35 to 20 CNY/kg roughly doubling 2035 adoption) [14], and the carbon-reduction value of fuel-cell commercial vehicles has been priced at 0.02–1.19 CNY per kilogram of hydrogen [15]. Green-hydrogen economics for China's road transport are themselves electricity-price-regime sensitive [16]. Earlier anchors remain dated: tractor TCO estimates rest on 2015-vintage data [17], fuel-cell truck prices reflect subsidy-era market conditions, and urban-delivery comparisons cover limited segments [18,19]. These crossover years are reported as deterministic point estimates, without confidence bounds or parity probabilities [8–10]; the discount-rate reversals are likewise scenario outcomes rather than probabilistic statements [11,12]. In most of these comparisons, the fuel price remains a single assumed number, never reconciled with the carbon accounts of the same supply chains.

1.2.2. Hydrogen Production Pathways and LCOH in China

Hydrogen production costs in China have been mapped at provincial resolution, and the reported spreads are wide. Coal gasification is generally the cheapest route at 7.2–17.2 CNY/kg [20], with coal plus carbon capture and storage at 11.2–19.4 CNY/kg, steam methane reforming at 9.1–25.2 CNY/kg, and industrial by-product hydrogen at 8–15.1 CNY/kg [21,22]. Electrolytic routes span an even broader band, from 20–55 CNY/kg on grid power to 5.3–104 CNY/kg for renewable electricity, depending chiefly on the electricity tariff and full-load hours [23–25]. Electricity purchases contribute 53.7–68.7% of electrolytic hydrogen cost in China depending on the power-price regime (68.7% at 2020 industrial tariffs, 53.7% under the 2030 curtailment scenario), which directs attention to valley and time-of-use tariffs, off-grid operation, and curtailed renewables [21]. Learning rates of 15–18% per doubling underpin projected electrolyzer cost declines [26]. These studies, however, disagree on system boundary: some report production-gate levelized costs, others at-pump or delivered values [21,23]. Comparing them therefore requires an explicit harmonization layer that adds purification, compression, transport, and refuelling in a declared

way; without it, no delivered cost by pathway and region is available as a consistent TCO input, which is precisely why downstream TCO comparisons collapse to a single assumed hydrogen price (Gap G1).

1.2.3. Grid Carbon Intensity and EV Lifecycle Emissions

Battery-electric emissions inherit the grid. Chinese provincial operating-margin emission factors span 0.095–1.092 $kgCO_2$/kWh [27], while the official national factors announced by the Ministry of Ecology and Environment stood at 0.5568 $kgCO_2$/kWh for 2021 and 0.5366 $kgCO_2$/kWh for 2022 [4]. Regional aggregation, however, remains largely unused in vehicle-level comparisons, which often still apply a single national number [24,28]. The battery-electric well-to-wheel chain is structurally simple—electricity consumption multiplied by the grid factor and inflated by transmission-and-distribution and charging losses—yet each multiplier is scenario-sensitive, and average factors can diverge from marginal ones when charging shifts in time [29–31]. Grid decarbonization trajectories, such as modelled national factors falling from roughly 468 gCO_2/kWh in 2030 to 263 gCO_2/kWh in 2050, are increasingly used in prospective vehicle assessments [32]; such trajectories belong to the scenario layer rather than to official factor sets [25]. The vehicle-level studies in this strand, however, are largely passenger-car or charging-scheduling analyses [27–31]; heavy-truck applications with their payload-normalized metrics have yet to draw on this regional heterogeneity, and the documented, time-stamped, and uncertainty-banded spread is still collapsed into a single national average.

1.2.4. WTW Carbon Intensity of Hydrogen for Chinese Logistics

The carbon intensity of hydrogen supply decides whether a fuel-cell truck is clean. Well-to-wheel intensities of 22–24 $kgCO_2e$/kg for coal-based hydrogen [25] and 9–14 $kgCO_2e$/kg for natural-gas reforming, contingent on the assumed methane-leakage rate [23], dominate Chinese production. By-product hydrogen sits near 10.9 $kgCO_2e$/kg subject to allocation conventions [33], while renewable electrolysis reaches 2.3–4.8 $kgCO_2e$/kg at the gate, plus a 2.9–3.1 $kgCO_2e$/kg gate-to-tank delivery adder [24]. The model adopts the band reported in [25], 3.1 [2.9–3.4] $kgCO_2e$/kg (Section 2.5), whose central value matches the top of this quoted range. Values quoted on a direct-emissions-only basis understate coal-route totals by 20–30%, and single-study floor cases should be treated cautiously [34]. Critically, grid-electrolytic hydrogen—specific electricity consumption multiplied by the grid factor—exceeds even coal-based hydrogen across the eight northern provinces, with only hydro-rich grids approaching competitiveness [24]. Certification thresholds sharpen the stakes: 3.38–4.4 $kgCO_2e$/kg under RFNBO-style rules [35,36], with grid electrolysis eligible only where the grid factor falls to roughly 83–99 gCO_2/kWh [26]. At the supply chain level, integrated optimization studies evaluate hydrogen production jointly with scope 3 emissions [37], but stop at the production gate rather than the vehicle layer. No study in this strand has yet connected these thresholds to region-resolved delivery chains or, ultimately, to vehicle-level carbon accounts for logistics operations.

Taken together, the four reviews expose two further, cross-cutting deficits that no single strand resolves on its own: the absence of a joint cost–carbon metric that ranks powertrains over the full pathway-by-grid option space for Chinese logistics, and the absence of any uncertainty quantification behind the resulting parity and certification claims. Combined with the pathway-opaque fuel cost and the national-average grid factor identified above, they amount to the four gaps formalized next.

1.3. Research Gaps and Objectives

Despite substantial and rapidly growing literature on truck TCO, hydrogen production economics, grid carbon intensity, and well-to-wheel assessment, these threads have developed largely in parallel. Joint cost-emission assessment has been demonstrated at the vehicle level for European light-duty transport [12], and China-specific cost and hydrogen-economics studies exist individually [13–23]; to our knowledge, however, no published framework combines the four elements simultaneously—China-specific road freight, pathway-resolved delivered hydrogen costs, region-resolved grid carbon intensity, and vehicle-level TCO/WTW integration under explicit uncertainty. China is where this coupling carries the most weight. Coal-based routes still dominate its hydrogen supply [3], official operating-margin grid factors differ markedly between macro-regions [4], and fuel-cell demonstration city clusters now target commercial fleets [2]. These contrasts make pathway- and region-resolved rankings directly actionable for fleet procurement and siting. Specifically, four gaps persist:

- G1—Pathway-opaque fuel cost in TCO. TCO comparisons typically import one hydrogen price, severing the link between production pathway, delivery distance, and vehicle economics; the fuel-cost spread embedded in the six-pathway by seven-region delivered-cost matrix (23.7–76.9 CNY/kg over the full literature parameter ranges, derived in Section 3.1) never reaches the vehicle layer.
- G2—National-average grid factors. A single national emission factor masks the 0.44–0.75 $kgCO_2$/kWh regional spread in official operating-margin factors, materially reordering battery-truck carbon accounts by charging location.
- G3—No joint cost–carbon metric. Pareto dominance (Equation (14)) and the critical carbon price p* at which a cleaner but costlier option overtakes a cheaper dirtier one (Equation (16)) are well defined, yet have not been applied across the full pathway-by-grid option space for Chinese logistics.
- G4—Deterministic point estimates [8–12]. Without uncertainty quantification, parity claims carry no probabilities, and green-hydrogen certification thresholds remain disconnected from the regional outcomes that determine eligibility.

Accordingly, the objectives of this study are threefold: (i) to harmonize literature-anchored parameters into single-source evidence bases—a six-pathway by seven-region delivered-hydrogen-cost matrix and a matching well-to-wheel carbon-intensity matrix—under declared boundaries and unit conventions (Sections 2.2, 2.3 and 2.5); (ii) to embed these supply-side matrices in class-resolved TCO and joint cost–carbon metrics, including Pareto fronts, the carbon-internalized average cost, and the critical carbon price p* (Sections 2.4 and 2.6); and (iii) to propagate parameter uncertainty through one-at-a-time sensitivity analysis and a 10,000-draw Monte Carlo simulation, yielding parity probabilities and robustness verdicts, with a 2030 outlook layer (Section 2.7).

Relative to the four literature streams reviewed above, and beyond the operational objectives (i)–(iii), this study's contribution is a coupled evidence-and-decision framework rather than another single-axis comparison. It harmonizes hydrogen pathway costs and regional grid carbon intensity for Chinese logistics. An explicit consistency ledger fixes the energy basis (a single lower-heating-value convention, Equation (1)), the cost boundary (a declared gate-to-tank build-up, Equation (2)), and the vintage of every emission factor. On that harmonized base sits a joint cost–carbon decision layer over the full option space of six pathways, seven regional grids, two vehicle classes, and three powertrains. That layer combines Pareto fronts, carbon-internalized average cost (ACC; Equation (15)), critical carbon prices (Equation (16)), and Monte Carlo parity probabilities—a combination that, to our knowledge, no published single-axis or single-region assessment reproduces for Chinese road freight. The framework then carries the simulated evidence into policy-

relevant guidance: a regional siting rule for hydrogen production, certification arithmetic for green-hydrogen eligibility, and a quantified gap between ranking-reversal carbon prices and China's current carbon market [38].

The remainder of the paper keeps Methods and Results parallel. Section 2 presents the framework and boundary (Section 2.1), data sources and harmonization (Section 2.2), the hydrogen delivery cost model (Section 2.3), the TCO model (Section 2.4), the well-to-wheel carbon-intensity model (Section 2.5), the coupling metrics (Section 2.6), and the sensitivity and uncertainty design (Section 2.7), closing with implementation details (Section 2.8). Section 3 presents the corresponding results (Sections 3.1–3.6), draws policy implications (Section 3.7), and then compares against the literature and states its limitations (Section 3.8). Section 4 concludes. All quantitative statements derive from the parametric simulation implemented in Python 3.12 with fixed random seeds. Monetary values are expressed in 2024 Chinese yuan, and the findings inherit the uncertainty of the published parameters on which they are anchored.

2. Materials and Methods

Each Methods block below maps onto the Results blocks it supports (Sections 2.3–2.7 feed Sections 3.1–3.6); in particular, the coupling metrics of Section 2.6 underlie both the Pareto-front results (Section 3.4) and the critical-carbon-price results (Section 3.5).

2.1. Analysis Framework, System Boundary, and Scenario Matrix

Figure 1 shows the analysis framework. Two supply-side layers—delivered hydrogen cost (Section 2.3) and regional grid carbon intensity (Section 2.5)—feed two vehicle-side layers, total cost of ownership (TCO) and well-to-wheel (WTW) carbon intensity (CI), for two vehicle classes and three powertrains (fuel cell electric vehicle, FCEV; battery electric vehicle, BEV; and reference diesel). Three coupling metrics close the layers: Pareto fronts over the joint cost–carbon plane, a carbon-internalized average cost (ACC), and the critical carbon price p* at which cost rankings flip (Section 2.6); one-at-a-time (OAT) sensitivity and a 10,000-draw Monte Carlo (MC) layer surround the deterministic core (Section 2.7).

Four boundary declarations were applied throughout. The carbon boundary was well-to-wheel: the well-to-tank (WTT) fuel chain plus tank-to-wheel conversion, with cradle-to-grave items—notably battery manufacturing (150–200 $kgCO_2e/kWh$ [9]) and photovoltaic embodied carbon (approximately 0.04 $kgCO_2e/kWh$ [24])—excluded from the headline CI and acknowledged as a boundary limitation in Section 4.2. The cost boundary was first-owner; externalities were excluded except where internalized through the ACC construct, and vehicle lifetimes were 8 years (heavy-duty, HD) and 10 years (light-duty, LD). Refuelling and charging infrastructure (hydrogen refuelling stations, HRS; depot chargers) entered only through the energy prices of Section 2.3 rather than as endogenous infrastructure capital. A single lower heating value (LHV) basis was declared once, via the unit-consistency check of Equation (1) in Section 2.2. The higher heating value (HHV), sometimes mislabeled as LHV in the sources, was then rejected (item L1 below).

The simulated scenario matrix combined six hydrogen production pathways (P1 coal gasification; P2 coal gasification with 80% carbon capture and storage; P3 natural gas steam methane reforming, SMR; P4 industrial by-product; P5 grid electrolysis; P6 dedicated renewable electrolysis) with six regional deployment grids (North, Northeast, East, Central, Northwest, South) plus a national-average reference row. On the vehicle side, two vehicle classes were modelled (4.5 t gross vehicle weight LD delivery truck, payload basis 1.8 t; 49 t gross combination weight HD tractor-trailer, payload basis 30 t), together with three powertrains and four duty scenarios (LD urban 30,000 km/year at 30 km/h; LD regional 60,000 at 50; HD regional 100,000 at 50; HD long-haul 160,000 at 70; Table 1). The

baseline year was 2024, expressed in real CNY2024. A 2030 outlook was computed as a clearly labelled scenario layer only, with reduced vehicle prices (HD BEV 750,000 CNY; HD FCEV 950,000 CNY; LD FCEV 450,000 CNY), a 20% lower renewable-electrolyzer capital cost (2800 CNY/kW), and regional grid factors scaled by 0.80. The carbon price was swept from 0 to 1000 CNY/tCO_2 in 25 CNY/tCO_2 steps, with benchmark markers at 0, 60, and 105 CNY/tCO_2 (the 2024 low and high of the China carbon market [38]) and at 540 CNY/tCO_2 (the 2024 EU ETS average converted at the declared 8.3 CNY/EUR rate); this sweep applies to the ACC and parity curves, whereas the critical carbon price is evaluated analytically from Equation (16) on the wider [0, 3000] CNY/tCO_2 interval (Section 2.6). All computations were performed in Python 3.12 (NumPy, Pandas, SciPy, Plotly) under a fixed global seed of 20240924; implementation and validation details are deferred to Section 2.8.

2.2. Data Sources and Parameter Harmonization

Because the study is a parametric simulation, every parameter carries a central value, a low-high range, a source, and a vintage (documented in Tables 2 and 3, with full provenance for all parameters—including those of Tables 1 and 4—consolidated in Appendix A, Table A1). Sources comprise peer-reviewed Chinese and European techno-economic studies [7–11,15–18,20–29,32–34,37,39], and official Chinese announcements on grid emission factors [4], diesel retail prices [5], charging tariffs [6], carbon market prices [38], and vehicle catelogue data [40]. Currency vintages span USD 2007/2015/2020/2023, EUR 2023/2024, and RMB 2021/2022. All monetary values were converted to CNY at the declared fixed rates (8.3 CNY/EUR; 7.1 CNY/USD—one rate per currency applied to every vintage, so cross-year comparability is carried by the deflator rather than by the exchange rate) and were then deflated to the 2024 price level using China's GDP deflator (National Bureau of Statistics of China; GDP at current prices divided by GDP at constant prices; index rebased to 2024 = 100).

A single energy basis was enforced first: all vehicle-energy arithmetic was written in one LHV-consistent form, converting each powertrain's energy carrier to a common MJ/km basis,

$$E_d = (b_d)/(100)\rho_d LHV_d;\ E_B = 3.6e_B;\ EH_2 = (mH_2)/(100)\ LHVH_2\ (MJ/km) \quad (1)$$

where b_d is the diesel consumption (L/100 km); ρ_d is the diesel density (0.832 kg/L); LHV_d is the diesel LHV, stated on one consistent triple as 42.6 MJ/kg = 35.4 MJ/L at ρ_d = 0.832 kg/L = 9.84 kWh/L; e_B is the electricity consumption (kWh/km), so the factor 3.6 converts kWh to MJ; mH_2 is the hydrogen consumption (kg/100 km); and $LHVH_2$ = 33.33 kWh/kg = 120.0 MJ/kg. Ed, EB, and EH_2 denote the per-km energy content (MJ/km) of diesel fuel, electricity, and hydrogen, respectively, all on the single LHV basis. The three are not equal in tractive energy per kilometre at the duty consumptions of Table 1 (HD long-haul: approximately 12.4 MJ/km of diesel fuel energy vs. 5.2 MJ/km of electricity and 10.2 MJ/km of hydrogen, the difference reflecting powertrain efficiency). The 140.4 MJ/kg value reported as "LHV" in [20] is an HHV and was rejected as a basis.

Table 1. Vehicle specifications and duty scenarios. Panel (**a**): vehicle specifications; panel (**b**): duty scenarios (lifetime and payload columns of panel (**a**) apply per class).

(a) Vehicle Specifications.

Vehicle	Class	Purchase Price [10^4 CNY]	Purchase Price Low	Purchase Price High	Energy Consumption	Unit	Consumption Low	Consumption High	Maintenance [CNY/km]	Insurance [% of Price/year]	Lifetime [yr]	Payload Basis [t]	Payload Ratio vs. Diesel [-]
HD Diesel	HD	40	35	48	0.35	L/km	0.32	0.38	1.3	4	8	30	1
HD BEV	HD	95	75	120	1.45	kWh/km	1.3	1.6	0.95	4	8	30	0.85
HD FCEV	HD	125	95	160	0.085	kg/km	0.075	0.095	1.25	4	8	30	0.96
LD Diesel	LD	12	10	14	0.13	L/km	0.11	0.15	0.55	3.5	10	1.8	1
LD BEV	LD	23	18	28	0.42	kWh/km	0.36	0.48	0.38	3.5	10	1.8	0.9
LD FCEV	LD	65	50	85	0.03	kg/km	0.025	0.035	0.5	3.5	10	1.8	0.97

(b) Duty Scenarios.

Duty Scenario	Class	Annual Activity [km/year]	Average Speed [km/h]
LD urban	LD	30,000	30
LD regional	LD	60,000	50
HD regional	HD	100,000	50
HD long-haul	HD	160,000	70

Note: Purchase prices in 10^4 CNY, CNY2024; class-level energy consumptions; payload bases and powertrain capacity ratios.

Table 2. TCO and hydrogen delivery-chain parameters.

Parameter	Unit	Base Value	Low Bound	High Bound	Source
discount rate	fraction/year	0.07	0.05	0.12	[11,12]; base 7% (OAT: 5–12%); uniform in MC
diesel retail 0# VAT incl.	CNY/L	7.3	6.8	8	[5]
BEV charging tariff (depot/mixed + service)	CNY/kWh	1.05	0.75	1.5	[6]
H_2 market anchor (Figure 2 comparison band only; not swept)	CNY/kg	35	35	40	[14]; authors' band
residual share at end of life	fraction	0.2	0.15	0.25	authors' re-estimation [7,8]
payload utilization u	fraction	0.7	0.6	0.8	[11]
payload capacity ratio, FCEV (HD/LD)	fraction	0.96/0.97	0.92/0.93	1.00/1.00	[11,41]; near-diesel packaging of the fuel-cell system

Table 2. *Cont.*

Parameter	Unit	Base Value	Low Bound	High Bound	Source
payload capacity ratio, BEV (HD/LD)	fraction	0.85/0.90	0.80/0.85	0.95/1.00	[11,41]; packaging penalty of the traction battery
driver cost (HD)	CNY/year	150,000	130,000	170,000	authors' re-estimation [7,18,39]
driver cost (LD)	CNY/year	80,000	70,000	90,000	authors' re-estimation [7,18,39]
other fixed (HD) (inspection/parking/admin)	CNY/year	8000	—	—	authors' assumption
other fixed (LD)	CNY/year	4000	—	—	authors' assumption
HD BEV battery replacement (year 6)	CNY	180,000	140,000	230,000	authors' assumption [7]
LD BEV battery replacement	-	none (warranty)	—	—	authors' assumption
FC system share	fraction	0.35	0.3	0.4	authors' assumption [7,8]
stack replacement trigger	cumulative hours	15,000	—	—	authors' assumption [8]
stack replacement cost	fraction of FC share x price	0.3	—	—	authors' assumption [7,8]
insurance rate (HD)	fraction/year	0.04	—	—	authors' re-estimation [7,18,39]
insurance rate (LD)	fraction/year	0.035	—	—	authors' re-estimation [7,18,39]
electricity T&D factor	fraction	0.065	0.05	0.08	[27]; uniform in MC
charging loss	fraction	0.08	0.05	0.15	[29]; uniform in MC
diesel WTW EF (derived)	$kgCO_2e/L$	3.4	3.1	3.7	derived: combustion 2.66–2.68 [10,17,42] + declared upstream uplift (Section 2.5); uniform in MC
gate-to-tank H_2 CI adder	$kgCO_2e/kg$	3.1	2.9	3.4	[25]
purification adder (P1–P4)	CNY/kg	2	1.5	2.5	[21]
compression + transport 200 km	CNY/kg	10	7	14	[22]
refuelling station adder	CNY/kg	10	8	13	[25]
SEC alkaline electrolyzer (LHV)	kWh/kg	52	50	55	authors' harmonization [23,24]
P6 electrolyzer CAPEX (2024)	CNY/kW	3500	2800	4500	authors' assumption [26]
P6 electricity purchase price (curtailed/dedicated PPA)	CNY/kWh	0.25	0.2	0.31	[26]; cost dominance per [21]
P6 fixed O&M	fraction of CAPEX/year	0.025	—	—	authors' assumption
P6 system life/r	year/fraction	20/7%	—	—	authors' assumption

Note: Central values with low-high ranges, CNY2024. An em dash in the low/high columns denotes a parameter held fixed (not varied) in the sensitivity analysis. Full provenance, including vintages, is consolidated in Appendix A (Table A1).

Table 3. Delivered hydrogen cost build-up by pathway and region. Panel (**a**): purchased-power base; panel (**b**): producer-owned variant of the P6 delivered cost with lower bounds on component-cost anchors (PV module 240 USD/kWp; wind turbine 400 USD/kW; 20-year life at 7%; no balance-of-system, no fixed O&M—declared lower bounds, Section 2.3).

(a) Purchased-Power Base.

Pathway	Pathway Name	Region	Production LCOH [CNY/kg H_2]	Purification Adder [CNY/kg H_2]	Compression + Transport (200 km) [CNY/kg H_2]	Refuelling Station Adder [CNY/kg H_2]	Delivered LCOH [CNY/kg H_2]	Delivered LCOH Low [CNY/kg H_2]	Delivered LCOH High [CNY/kg H_2]
P1	coal gasification	all regions (invariant)	11	2	10	10	33	23.7	46.7
P2	coal + CCS	all regions (invariant)	15	2	10	10	37	27.7	48.9
P3	natural gas SMR	all regions (invariant)	12.5	2	10	10	34.5	25.6	54.7
P4	industrial by-product	all regions (invariant)	11	2	10	10	33	24.5	44.6
P5	grid electrolysis	North	31.2	0	10	10	51.2	41	64.4
P5	grid electrolysis	Northeast	29.12	0	10	10	49.12	39	62.2
P5	grid electrolysis	East	34.32	0	10	10	54.32	44	67.7
P5	grid electrolysis	Central	30.68	0	10	10	50.68	40.5	63.85
P5	grid electrolysis	Northwest	22.36	0	10	10	42.36	33.5	54.5
P5	grid electrolysis	South	31.72	0	10	10	51.72	41.5	64.95
P5	grid electrolysis	National average	31.2	0	10	10	51.2	41	64.4
P6	renewable electrolysis	North	27.49	0	10	10	47.49	34.55	66.78
P6	renewable electrolysis	Northeast	26.17	0	10	10	46.17	33.57	65.16
P6	renewable electrolysis	East	32.75	0	10	10	52.75	37.86	75.16
P6	renewable electrolysis	Central	33.7	0	10	10	53.7	38.37	76.88
P6	renewable electrolysis	Northwest	24.14	0	10	10	44.14	31.96	62.52
P6	renewable electrolysis	South	31.9	0	10	10	51.9	37.38	74.2
P6	renewable electrolysis	National average	28.52	0	10	10	48.52	35.85	67.5

Table 3. *Cont.*

(b) Producer-Owned Variant of the P6 Delivered Cost (Lower-Bound Anchors).						
Region	**FLH [h/year]**	**LCOE PV [CNY/kWh]**	**LCOE Wind [CNY/kWh]**	**P6 PV-Own [CNY/kg]**	**P6 Wind-Own [CNY/kg]**	**P6 PPA [CNY/kg]**
North	1500	0.107	0.179	40.1	43.8	47.5
Northeast	1650	0.098	0.163	38.2	41.6	46.2
East	1100	0.146	0.244	47.4	52.4	52.8
Central	1050	0.153	0.255	48.7	54.0	53.7
Northwest	1950	0.083	0.138	35.4	38.3	44.1
South	1150	0.140	0.233	46.2	51.0	51.9
National average	1400	0.115	0.192	41.5	45.5	48.5

Note: Central values with low-high ranges, CNY2024. An em dash in the low/high columns denotes a parameter held fixed (not varied) in the sensitivity analysis. Full provenance, including vintages, is consolidated in Appendix A (Table A1).

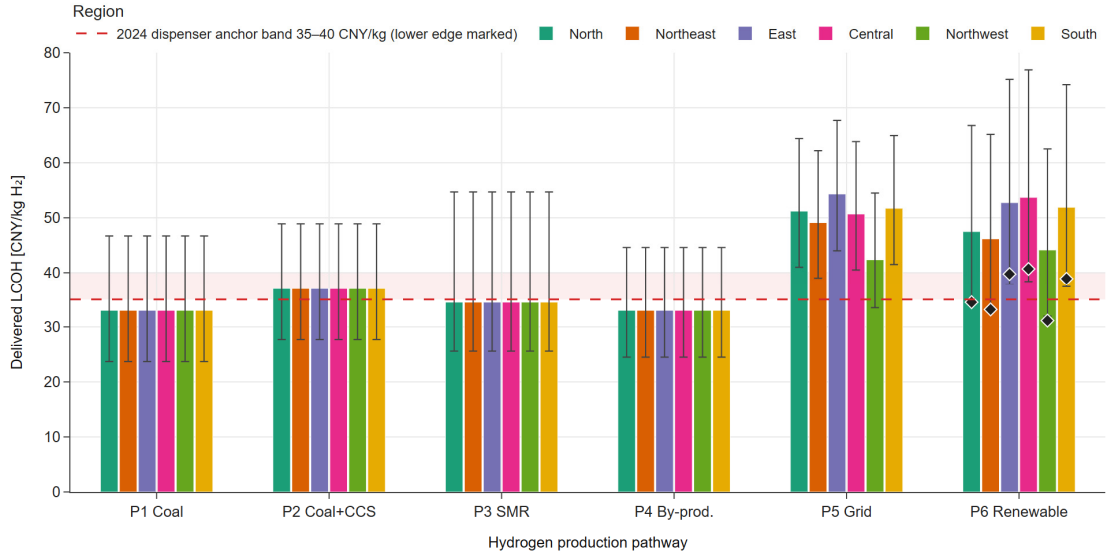


Figure 2. Delivered hydrogen cost (CNY/kg) by pathway and region, purchased-power base (P6 at p_e = 0.25 CNY/kWh; diamonds: zero-purchase S0). Bars: base; whiskers: low–high envelope; shaded band: 35–40 CNY/kg 2024 market anchor [14] (dashed: lower edge). P1–P4 are region-invariant; the national-average row is tabulated (Table 5).

Table 4. Production-to-tank carbon intensity of the hydrogen pathways by region (WTT production basis plus the G2T adder).

Pathway	Pathway Name	Region	Production CI [$kgCO_2e/kg\ H_2$]	Gate-to-Tank Adder [$kgCO_2e/kg\ H_2$]	Production-to-Tank CI [$kgCO_2e/kg\ H_2$]
P1	coal gasification	all regions (invariant)	22.8	3.1	25.9
P2	coal + CCS	all regions (invariant)	11.8	3.1	14.9
P3	natural gas SMR	all regions (invariant)	11.5	3.1	14.6
P4	industrial by-product	all regions (invariant)	10.9	3.1	14
P5	grid electrolysis	North	39	3.1	42.1
P5	grid electrolysis	Northeast	32.76	3.1	35.86
P5	grid electrolysis	East	30.16	3.1	33.26
P5	grid electrolysis	Central	24.44	3.1	27.54
P5	grid electrolysis	Northwest	29.64	3.1	32.74
P5	grid electrolysis	South	22.88	3.1	25.98
P5	grid electrolysis	National average	27.9	3.1	31
P6	renewable electrolysis	North	3.5	3.1	6.6
P6	renewable electrolysis	Northeast	3.5	3.1	6.6
P6	renewable electrolysis	East	3.5	3.1	6.6
P6	renewable electrolysis	Central	3.5	3.1	6.6
P6	renewable electrolysis	Northwest	3.5	3.1	6.6
P6	renewable electrolysis	South	3.5	3.1	6.6
P6	renewable electrolysis	National average	3.5	3.1	6.6

Note: WTT-WTW production basis plus the G2T adder; certification arithmetic of Section 3.7 uses the production-to-tank column. P1–P4 are region-invariant and collapsed to one row each.

Table 5. Regional grid parameters.

Region	Grid EF 2022 [$kgCO_2/kWh$]	Grid EF Low [$kgCO_2/kWh$]	Grid EF High [$kgCO_2/kWh$]	Industrial Tariff [CNY/kWh]	Industrial Tariff Low [CNY/kWh]	Industrial Tariff High [CNY/kWh]	Valley Tariff [CNY/kWh]	Valley Tariff Low [CNY/kWh]	Valley Tariff High [CNY/kWh]	Renewable FLH [h/year]	Renewable FLH Low [h/year]	Renewable FLH High [h/year]
North	0.75	0.68	0.83	0.6	0.52	0.68	0.32	0.25	0.4	1500	1300	1750
Northeast	0.63	0.56	0.7	0.56	0.48	0.64	0.3	0.24	0.37	1650	1400	1950
East	0.58	0.52	0.64	0.66	0.58	0.74	0.35	0.28	0.42	1100	950	1300
Central	0.47	0.42	0.52	0.59	0.51	0.67	0.32	0.25	0.39	1050	900	1250
Northwest	0.57	0.51	0.63	0.43	0.37	0.5	0.24	0.19	0.3	1950	1600	2400
South	0.44	0.39	0.49	0.61	0.53	0.69	0.33	0.26	0.4	1150	980	1350
National average	0.5366	0.4829	0.5903	0.6	0.52	0.68	0.32	0.25	0.4	1400	1260	1540

Note: 2022 operating-margin grid factors (published 2024), industrial and valley tariffs, and renewable full-load hours. The National average row is a reference blend, not a seventh deployment region: its grid factor is the official MEE national factor (0.5366 $kgCO_2/kWh$), its tariff entries reuse the North-grid catalogue values (0.60/0.32 CNY/kWh), and its *FLH* entry is a 1400 h/year national reference value; these are fixed reference inputs, not weighted regional blends. Its low/high columns are the ±10% Monte Carlo bands of Section 2.7, not source uncertainty ranges. Compiled-only inputs, declared as an authors' compilation rather than cited references: the provincial industrial/valley tariffs consolidate 2024 provincial catalogue and trading prices, and the renewable *FLH* values follow a CABEE/IRENA-based provincial wind + PV blend; no single citable document reports either set.

Because the source literature disagrees on system boundaries, units, and accounting conventions, twenty consistency issues were logged during extraction and resolved explicitly before any parameter entered the model:

- L1 LHV vs. HHV. A single LHV basis (Equation (1)) governed electrolyzer consumption, efficiency, and per-km energy; the 140.4 MJ/kg value labelled LHV in [20] is in fact an HHV and was rejected.
- L2 LCOH system boundaries. Production-gate, delivered, and at-the-pump levelized costs of hydrogen (LCOH) reported in the sources were harmonized to a single at-the-tank basis through the explicit purification, compression-and-transport, and refuelling layers of Equation (2); boundary-raw values were never compared directly.
- L3 contradictions within a single source. Inconsistent table values (two coal-gasification cost variants in [23]) and typographical values ([21,41]) were absorbed into the declared ranges rather than resolved arbitrarily.
- L4 coal and SMR CI basis. Only WTT-WTW production factors were used (coal 22.8 [20.0–25.0]; SMR 11.5 [9.0–14.0] $kgCO_2e/kg$); direct-only values, which understate coal-route WTW CI by 20–30%, were excluded.
- L5 SMR methane-leakage band. The wide SMR CI band was tied to a declared upstream CH_4-leakage assumption, its high end consistent with severe leakage at a 20-year GWP of 85 [24]; the band is propagated rather than collapsed in the uncertainty layer.
- L6 tank-cost units. 700 bar storage costs were admitted only per kg H_2 (1211 EUR/kg [7]); a per-kWh figure of roughly 690 USD/kWh of stored capacity [9] was not reused. Converting it at the hydrogen LHV basis gives 690 × 33.33 kWh/kg ≈ 23,000 USD per kg of stored H_2 (USD, vintage as in [9]), a physically implausible unit basis for the tank.
- L7 currency vintages. All monetary values were deflated to CNY2024 and converted at the declared rates; foreign-currency values were never mixed raw.
- L8 China–EU efficiency gap. European heavy-truck consumption (approximately 29–31 L/100 km) was not transplanted; the China 49 t fleet was set at 35 [15,35–40] L/100 km [17].
- L9 grid-factor basis. The headline matrix uses official MEE operating-margin factors (2022 values, published 2024) [4]; IAM trajectories [32] were confined to the 2030 outlook, and every factor carries its year stamp.
- L10 battery-cost definitions. Pack manufacturing, pack system, and retail-embedded battery costs were labelled separately; only retail-embedded prices enter the TCO, with component costs serving as cross-checks.
- L11 dispenser-price anchor. The 2024 dispensed-hydrogen anchor of 35–40 CNY/kg [14] served the comparison panel only; the approximately 80 CNY/kg benchmark of [15] was retained as a cited early-market outlier, not a model input.
- L12 subsidy-era vehicle prices. Early-market Chinese FCEV prices [16] were not mixed with the 2024 price set; catalogue-consistent prices were used and flagged as low-confidence [40].
- L13 discount-rate spread. The 5–12% spread that can flip rankings was handled with a 7% base case, an OAT sweep, and a uniform MC distribution rather than a single point value [11,12].
- L14 floor-case outlier. The near-zero FCV CI of [34] (5.59 gCO_2/km (direct CO_2), nuclear-electrolytic supply) was used only as a discussion lower bound, never in the pathway matrix.
- L15 LD FCEV consumption. With no direct 4.5 t FCEV source, a scaled 3.0 [2.5–3.5] kg/100 km was adopted from bus and passenger-car brackets and flagged as low-confidence [40].

- L16 study-specific grid factors. City and "traditional-grid" factors in [25] served only to corroborate the regional spread, never as headline inputs.
- L17 factor vintage and margin basis. Every grid factor carries its year and operating-margin basis, and the average-versus-marginal caveat for emission factors is stated explicitly [28–30].
- L18 payload normalization. One payload basis per class (30 t HD; 1.8 t LD) was defined, with explicit capacity ratios (BEV 0.85 HD/0.90 LD; FCEV 0.96 HD/0.97 LD) instead of heterogeneous source-specific factors [11,41].
- L19 diesel CI scope labels. The diesel factor was admitted only with its scope label: 3.4 [3.1–3.7] $kgCO_2e/L$ as WTW—derived as the combustion-only 2.66–2.68 $kgCO_2e/L$ [10,17,42] plus a declared upstream well-to-tank term (Section 2.5)—and never mixed with the combustion-only basis.
- L20 insurance and driver costs. Because insurance and wage shares differ sharply by market, Chinese-consistent values were re-estimated (4.0% and 3.5%/year of purchase price; 150,000 and 80,000 CNY/year) rather than importing EU or UK shares [7,18,39].

Residual data gaps were filled from the intended official sources: regional grid factors from MEE announcements [4]; the 0# diesel retail price from NDRC notices [5]; charging tariffs [6]; carbon market prices [38]; catalogue consumptions and prices [40]; wages, insurance, and residual curves from national statistics and market reports.

2.3. Hydrogen Delivery Cost Model

Six production pathways were modelled (Table 5). P1–P4 were anchored to literature production-gate costs in CNY2024: P1 coal gasification 11 [7.2–17.2] CNY/kg, P2 coal + CCS 15 [11.2–19.4] CNY/kg, P3 SMR 12.5 [9.1–25.2] CNY/kg, and P4 by-product 11 [8.0–15.1] CNY/kg [20–24]. All delivered prices were then harmonized to a single at-the-tank basis,

$$pH_2(g,r) = C_{prod}(g) + \Delta C_{pur}(g) + \Delta C_{trans}(r) + \Delta C_{ref} \quad (2)$$

where $pH_2(g,r)$ is the delivered hydrogen price for pathway g in region r (CNY/kg); C_{prod} is the production-gate cost; ΔC_{pur} is the pressure-swing-adsorption purification adder to GB/T 37244 fuel grade, applied to fossil routes P1–P4 only (2.0 [1.5–2.5] CNY/kg) [21]; ΔC_{trans} is the compression and transport adder, 10 [7–12,16,17] CNY/kg at the 200 km base distance [22]; and ΔC_{ref} is the refuelling-station adder, 10 [8–12,17] CNY/kg [25]. A distance curve, $7 + 0.015 \times (d - 100)$ CNY/kg for $d \in [100, 800]$ km, was implemented for the distance sensitivity only (liquid-hydrogen crossover near 500 km [21]). The base case uses the explicit +10 CNY/kg adder. The transport and refuelling adders enter every pathway's delivered price identically—unlike the fossil-only purification adder—so those two adders act as a common cost shift and inter-pathway delivered-cost rankings are invariant to the assumed delivery distance by construction; the delivery-chain uncertainty that does reach the results is therefore carried by the adders' literature ranges (Table 2) rather than by any single point value. What the adder set does not represent is mode structure—compression staging, tube-trailer vs. liquid vs. pipeline transport, station capacity and utilization—which is why the distance curve above serves only as a sensitivity device and the simplification is acknowledged among the limitations (Section 3.8).

Electrolytic production costs were built bottom-up for P6 as an annualized capital-and-O&M charge per kilogram,

$$C_{prod,el} = [(c_{el}CRF_{el} + c_{OM,el})/(FLH) + p_e]\,(SEC) \quad (3)$$

where c_{el} is the alkaline electrolyzer system capital cost (3500 [2800–4500] CNY/kW in 2024); CRF_{el} is the capital recovery factor at r = 7% over a 20-year plant life (Equation (4)); $c_{OM,el}$ is the fixed O&M (2.5% of c_{el} per year); SEC is the specific electricity consumption

(52 [50–55] kWh/kg, LHV basis); *FLH* is the regional full-load hours of the renewable resource (1050–1950 h/year across the deployment regions, 900–2400 h/year over the low–high ranges; Table 3); and p_e is the purchased-renewable electricity price, 0.25 [0.20–0.31] CNY/kWh, taken from the curtailed-power price band of [26]. In the base case, P6 electricity is purchased at p_e, which explicitly remunerates the generating plant; the purchase term $p_e \times SEC$ is deliberately not divided by *FLH*, because the electrolyzer's capital charge—not its energy purchase—is what scales with utilization. Electricity purchases contribute roughly 70–80% of electrolytic hydrogen cost in the Chinese literature [21], so treating electricity as free would systematically favour P6; the purchased-price base removes that bias, while a zero-marginal-cost, fully curtailed or dedicated-supply specification (S0) is retained as a clearly labelled sensitivity scenario (S0, Section 3.6), constrained by the finite national curtailment resource. A producer-owned variant addresses the mirror-image concern that the P6 capital charge covers the electrolyzer but not the renewable plant itself: the generating asset is costed symmetrically with the electrolyzer as LCOEren = (cren CRFren + cOM,ren)/FLHren × *SEC*, where cren is the region's dominant-resource plant capital cost (photovoltaic for most grids, wind for the Northwest and North; Table A1) sharing the same regional *FLH*, under the declared direct-coupling assumption that no grid backfill or storage is modelled. Because both capital terms then divide by the same *FLH*, the regional resource gradient enters P6 through one consistent channel, and the variant brackets the PPA base from the ownership side (Section 3.1). For P5, the production term is the product of the regional industrial electricity tariff (Table 3; 0.43–0.66 CNY/kWh across the deployment grids, 0.60 CNY/kWh at the national average) and the specific consumption, $p_{e,r} \times SEC$. Its production carbon intensity remains the grid-factor product $SEC \times EF_r$ (Equation (9)). Unlike P6, this production term covers purchased electricity only: no electrolyzer capital or fixedO&M charge enters P5. Tables 2 and A1 therefore carry a P6 electrolyzer CAPEX row but no P5 counterpart. The omitted charge can be bounded analytically on the P6 parameter basis as (3500 CNY/kW × CRF + 2.5% of CAPEX) × 52 kWh/kg divided by the annual operating hours. It then amounts to approximately 3.6–5.4 CNY/kg over 4000–6000 full-load hours (about 4.3 CNY/kg at 5000 h/year). The P5 rows of Table 5 and the 42.4–54.3 CNY/kg P5 band of Section 3.1 are therefore electricity-only quantities. Comparisons with the capital-inclusive P6 costs and with the 20–55 CNY/kg literature band [23] are boundary-asymmetric and must be read under this declaration. Grid-electrolysis cost and carbon are thus driven by different regional quantities—power-market geography and grid carbon intensity, respectively—and P1–P4 remain region-invariant in the base case. The resulting pathway-by-region delivered-cost matrix is reported in Table 5 and visualized in Figure 2 (Section 3.1); S0 values are tabulated alongside.

2.4. Total Cost of Ownership Model

Capital costs were annualized with the capital recovery factor,

$$\mathrm{CRF}(r, N) = (r(1+r)^N)/((1+r)^N - 1) \quad (4)$$

where r is the discount rate (0.07 base; 0.05–0.12 range), and N is the ownership lifetime (8 years HD; 10 years LD). The annualized capital charge includes midlife replacements and a discounted residual,

$$C_{cap} = [P + R_{batt}(1+r)^{-tb} + R_{stack}(1+r)^{-ts} - RV(1+r)^{-N}]\,\mathrm{CRF}(r,N) \quad (5)$$

where P is the purchase price; R_{batt} is the HD BEV midlife battery-pack replacement (one pack at year 6, 180,000 [140,000–230,000] CNY; none within the LD warranty); R_{stack} is the FCEV stack replacement, costed at 30% of the fuel-cell system share (35% [30–40%] of the purchase price) and triggered at 15,000 cumulative operating hours (annual km divided

by duty average speed); t_b and t_s are the replacement years; and RV is the residual value (0.20 [0.15–0.25] of P) [7,8]. The hour trigger fires in both HD duties (years 6.6–7.5 of the 8-year life) but not within the LD life.

Purchase prices were set at China-catalogue-consistent CNY2024 levels (HD: 400,000 [350,000–480,000] diesel, 950,000 [750,000–1,200,000] BEV, 1,250,000 [950,000–1,600,000] FCEV; LD: 120,000/230,000/650,000 CNY), below the EU component-cost build-ups of [7] (roughly 2.9 and 4.0 million CNY), consistent with the 20–40% China–EU retail gap. These medium-confidence inputs are swept widely in Section 2.7 (Table 2). Operating costs comprise maintenance (HD: 1.30/0.95/1.25 CNY/km for diesel/BEV/FCEV; LD: 0.55/0.38/0.50 CNY/km, re-expressed from European and UK anchors [7,8,18]), insurance (4.0%/year HD, 3.5%/year LD of purchase price), driver wages including social charges (150,000 [130,000–170,000] CNY/year HD; 80,000 [70,000–90,000] CNY/year LD), and other fixed costs (8000 CNY/year HD; 4000 CNY/year LD). The TCO per kilometre was then assembled as

$$TCO = (C_{cap} + C_{mnt} + C_{ins} + C_{drv} + C_{oth})/(KM) + c_{fuel} \quad (6)$$

where C_{mnt}, C_{ins}, C_{drv}, and C_{oth} are the annual maintenance, insurance, driver, and other fixed costs (CNY/year), and KM is the annual mileage of the duty scenario (km/year). The fuel cost per kilometre is powertrain-specific,

$$c_{fuel} = (p_d b_d)/(100) = p_e{}^v e_B = (pH_2 mH_2)/(100) \quad (7)$$

where p_d is the diesel pump price (7.3 [6.8–8.0] CNY/L, VAT included [5]); $p_e{}^v$ is the vehicle-side charging tariff (1.05 [0.75–1.50] CNY/kWh, electricity plus service fee [6]); and pH_2 is the pathway-resolved delivered price from Equation (2), with the 35–40 CNY/kg 2024 dispenser band reserved for the comparison panel only (item L11). For payload-sensitive comparison, the TCO was normalized to tonne-kilometres,

$$TCO_{tkm} = (TCO)/(m_{pay} u) \quad (8)$$

where m_{pay} is the effective payload, i.e., the class payload basis multiplied by the powertrain capacity ratio (Table 1), and u is the average load utilization, 0.70 [0.60–0.80], applied identically to all options [11]. Both per-km and per-t-km results are reported (Section 3.2). The two normalization parameters affect the results in fundamentally different ways, and both are now swept explicitly (Section 2.7). Because u enters Equations (8) and (13) as a common divisor for every powertrain, it cancels exactly from all cross-powertrain quantities—TCO and CI ratios, Pareto dominance, the critical carbon prices of Equation (16), and the parity probabilities of Equation (18)—and scales the per-tonne-kilometre levels only (its [0.60–0.80] range shifts absolute CNY/t-km by roughly ±17% around the 1/0.70 factor). The capacity ratios, by contrast, are powertrain-specific: they reflect the packaging penalty of the traction battery (BEV 0.85 HD/0.90 LD) against the near-diesel packaging of the fuel-cell system (FCEV 0.96 HD/0.97 LD) [11,41], and they do not cancel—the BEV capacity ratio alone decides whether a per-kilometre cost advantage survives the per-tonne-kilometre normalization (Section 3.2), which is why both ratios are swept in Section 2.7 and propagated in the Monte Carlo.

2.5. Well-to-Wheel Carbon Intensity Model

For grid electrolysis, the production-stage CI was computed regionally as

$$CI_{prod,P5}(r) = SEC \times EF_r \quad (9)$$

where EF_r is the regional grid operating-margin emission factor ($kgCO_2$/kWh; MEE 2022 official basis, published 2024 [4]) and *SEC* is as in Equation (3). Transmission and distribution

losses are applied explicitly on the BEV chain (Equation (11)); the P5 production factor is deliberately conservative in not compounding a second loss term. Pathway production CIs were taken as WTT-WTW values on the operational fuel-chain basis, vehicle-manufacturing emissions excluded (Section 2.1) (Table 4): P1 22.8 [20.0–25.0]; P2 11.8 [10.6–13.1]; P3 11.5 [9.0–14.0] with the declared CH_4-leakage basis; P4 10.9 [8.0–13.0] under economic allocation; and P6 3.5 [2.3–4.8] $kgCO_2e/kg$ [23–25,33]. The vehicle-level FCEV CI is

$$CI_{FCEV}(g,r) = (mH_2)/(100)(CI_{prod,g} + \Delta CI_{G2T}) \times 1000 \quad (10)$$

where $CI_{prod,g}$ is the pathway production CI ($kgCO_2e/kg$), ΔCI_{G2T} is the gate-to-tank (G2T) adder of 3.1 [2.9–3.4] $kgCO_2e/kg$ covering transmission, compression, and refuelling [25], mH_2 is in kg/100 km, and the result is in gCO_2e/km. Dividing the tank-side CI by an efficiency in km/kg is algebraically identical; the multiplication by the consumption was retained for dimensional explicitness.

The BEV chain applied the regional grid factor with transmission–distribution and charging losses,

$$CI_{BEV}(r) = e_B \times EF_r \times (1 + L_{TD})/(1 - L_{ch}) \times 1000 \quad (11)$$

where e_B is in kWh/km, EF_r in $kgCO_2/kWh$, L_{TD} is the transmission and distribution loss fraction (0.065 [0.05–0.08]) [27], L_{ch} is the charging loss fraction (0.08 [0.05–0.15]) [29], and the factor 1000 converts the resulting $kgCO_2e/km$ to gCO_2e/km (e.g., national average: $0.5366 \times 1.45 \times 1.065/0.92 \times 1000 = 900.7$ gCO_2e/km, Table 1 consumptions). The grid factors are officially stated on a CO_2 basis; entering the composite WTW chain, they are treated as CO_2-equivalent, consistent with the MEE operating-margin convention [4]. Diesel was treated with a scope-labelled WTW factor,

$$CI_D = (b_d)/(100) \times EF_{WTW,d} \times 1000 \quad (12)$$

where $EF_{WTW,d}$ = 3.4 [3.1–3.7] $kgCO_2e/L$ is the WTW emission factor. This factor is derived rather than imported from a single WTW source: it is the combustion-only value of 2.66–2.68 $kgCO_2e/L$ [10,17,42] plus a declared upstream well-to-tank term of 0.44–1.0 $kgCO_2e/L$ (central 0.7, i.e., a 17–38% uplift on combustion, centrally about 27%). The combinations span the tabulated 3.1–3.7 range; [42] supplies the combustion-stage basis only. For payload-normalized comparison, the same effective payload as in Equation (8) was applied,

$$CI_{tkm} = (CI_{km})/(m_{pay}u) \quad (13)$$

with both per-km and per-t-km metrics retained throughout, embodied emissions excluded as declared in Section 2.1, and every factor time-stamped (items L9, L17, and L19). The resulting CI matrix appears in Tables 3 and 4 (Section 3.3).

2.6. Cost–Carbon Coupling: Pareto Fronts and Critical Carbon Price

Options were compared jointly on cost and carbon. Option i Pareto-dominates option j if and only if

$$TCO_i \leq TCO_j \wedge CI_i \leq CI_j \wedge (TCO_i < TCO_j \vee CI_i < CI_j) \quad (14)$$

and the Pareto front is the non-dominated set over all pathway-region-powertrain options within a vehicle class, computed on both the per-km and per-t-km bases. To internalize carbon linearly, the carbon-internalized average cost (ACC) was defined as

$$ACC_i(p_c) = TCO_i + p_c \times CI_i \times 10^{-6} \quad (15)$$

where p_c is the carbon price (CNY/tCO_2), CI_i is in gCO_2e/km (or per t-km), and 10^{-6} converts to tCO_2 per unit distance; this flat internalization is applied identically across

options. The 10^{-6} factor presumes that CIi carries the same normalization as the TCO it is added to—gCO_2e per kilometre with TCO in CNY/km, or per tonne-kilometre with TCO in CNY/t-km (Equations (8) and (13)). Mixing the two bases would rescale p* by the payload factor—the unit trap guarded against throughout. The critical carbon price for a pair (cheaper-but-dirtier X, pricier-but-cleaner Y) follows from equating both ACCs,

$$p^*(X \to Y) = (TCO_X - TCO_Y)/((CI_Y - CI_X) \times 10^{-6}) \quad (16)$$

defined for TCOX < TCOY and CIX > CIY; for pc > p* the ACC ranking flips, so p* is the exchange rate between cost and avoided carbon at parity. Equation (16) is evaluated analytically and reported on [0, 3000] CNY/tCO_2. The ACC and parity probabilities of Equations (15) and (18) are tabulated on the 0–1000 CNY/tCO_2 grid of Section 2.1; because ACC is linear in pc, the pairwise ACC difference curves of Section 3.5 are drawn over the full [0, 3000] CNY/tCO_2 reporting interval without computing any new model output. Four outcome categories are distinguished, with the same convention in Methods and Results: (i) p* = 0 with status "already dominant", where the cleaner option already has the lower TCO, so no carbon price is needed; (ii) a positive finite p*, where the curves cross within the reporting bound; (iii) status "n/a", where the target is not cleaner than the source on the metric basis, so no crossing exists; and (iv) status ">3000", where a crossing exists but lies beyond the reporting bound. Category (iv) is labelled, not censored to a numeric value. Four ordered pairs were evaluated per class, duty, and region: diesel-to-BEV; diesel-to-FCEV (the best clean pathway per region being the minimum delivered LCOH among P2, P4, and P6); BEV-to-FCEV(P6); and the reverse FCEV(P6)-to-BEV. Section 3.5 benchmarks the computed p* values against independent literature crossovers of 170–360 CNY/tCO_2 [23] and cost-regime thresholds of [21], the 2024 China carbon market band of 60–105 CNY/tCO_2 [38], and the FCCV-style carbon value of 0.02–1.19 CNY/kg H_2 [15].

2.7. Sensitivity and Uncertainty Analysis

Deterministic sensitivity was assessed one factor at a time. For each driver θi, it was swept between its low and high values (Tables 2–4), with all others at base,

$$d_i^M = M(\theta_i^{high}) - M(\theta_i^{low}) \quad (17)$$

where M is the response metric (TCO or CI for the focal HD long-haul duty, with per-t-km variants stored) and d_i^M is the swing in the unit of M. Twenty drivers were swept, covering purchase prices, consumptions, energy prices (including the P6 electricity purchase price p_e), discount rate, utilization, the two payload capacity ratios, replacement costs, grid and diesel WTW factors, P6 capital cost and CI, and the gate-to-tank adder. Results are reported as tornado diagrams in Section 3.6. Electrolyzer full-load hours were not swept as an independent driver: the regional *FLH* variation in Table 3 (1050–1950 h/year base, 900–2400 h/year over the ranges) spans the plausible resource spread and therefore serves as the implicit, region-indexed sensitivity of P6 to resource quality (Section 3.1). Because p_e enters Equation (3) as $p_e \times SEC$, its OAT swing translates one-for-one into the delivered P6 cost (5.7 CNY/kg over [0.20, 0.31] CNY/kWh, or 16.1 CNY/kg over the full [0, 0.31] interval, at SEC = 52 kWh/kg), and the zero-purchase-price scenario S0 is reported alongside the base case throughout (Sections 3.1 and 3.6).

Stochastic uncertainty was propagated with a 10,000-draw Latin Hypercube Monte Carlo,

$$\left(TCO^{(s)}, CI^{(s)}\right) = F\left(\theta^{(s)}\right), \hat{P}\left(X \prec Y \backslash mid\ p_c\right) = (1)/(S)\Sigma_{s=1}{}^{S}\ 1\left[ACC_X{}^{(S)}\left(p_c\right) < ACC_Y{}^{(S)}\left(p_c\right)\right] \quad (18)$$

where θ(s) is the parameter vector of draw s (S = 10,000) and 1[·] is the parity indicator on the carbon-price grid. Most parameters were sampled as triangular distributions over

their low-base-high ranges; regional grid factors as uniform ±10% bands around their table values; and the discount rate (5–12%), transmission–distribution losses (5–8%), charging losses (5–15%), and the diesel WTW factor (3.1–3.7 $kgCO_2e/L$) as uniform distributions (Table A1; per-parameter notes in Table 2). The sampled vector includes the P6 electricity price, triangular on [0.20, 0.25, 0.31] CNY/kWh, and the four payload capacity ratios, triangular on their Table 2 ranges; these five variates are drawn from an independent stream seeded identically (20240924) and are combined with the archived draws, so the extended design conditions on rather than re-samples the base uncertainty set. Common random numbers were shared across powertrains within a draw so that paired differences are unbiased; the national-average reference row, fixed in the specification, was given ±10% bands for the MC only. Outputs comprise joint TCO-CI clouds, Pareto-membership frequencies, and parity probabilities on the carbon-price grid (Section 3.6). Pareto-membership frequencies are summarized qualitatively (Section 3.4) rather than as numeric statistics, because membership counts of a discrete front are sensitive to option-grid density—a limitation the authors accept by design. Convergence was checked through the running mean of the focal FCEV–BEV per-tonne-kilometre gap across doubling draw counts: at 1000 draws it was already within 0.1% of its 10,000-draw value (Section 3.6).

2.8. Model Implementation, Validation, and Reproducibility

The full pipeline was implemented in Python 3.12 (NumPy 2.5, Pandas 3.0, SciPy 1.16, Plotly 7.1) as two scripts: a simulation script generating the deterministic matrices (Tables 3–8), the OAT and MC layers, and a machine-readable headline summary; and a figure script rendering Figures 1–8. All stochastic elements were drawn from a single fixed seed (20240924), and all parameters were taken from one canonical parameter file recording every value's unit, base, range, source, vintage, and confidence. The implemented specification and the manuscript therefore share a single source of truth.

Six validation checks were executed automatically at the end of each run. The energy-closure check confirmed that the implied electrolyzer efficiency (LHV), $33.33/SEC = 64.1\%$, lies inside the plausible 62–74% window. Three delivered-price anchors were reproduced: coal-route P1 at 33.0 CNY/kg (window ± 5), renewable P6 in the Northwest at 44.1 CNY/kg under the purchased-power base (31.1 [14,15,28–40,42] CNY/kg under S0), and grid-electrolysis P5 at the national average at 51.2 [40–65] CNY/kg. The BEV HD CI at the national-average grid reproduced at 900.7 gCO_2e/km, within 1% of the analytical expectation of approximately 902 gCO_2e/km. The p*-bounds check passed, with 8 positive crossings (maximum 2936.4 CNY/tCO_2) and 7 already-dominant $p^* = 0$ values inside [0, 3000] CNY/tCO_2, and the remaining 97 pair–class–duty–region combinations labelled n/a (target not cleaner per tonne-kilometre; 46) or >3000 (crossing beyond the reporting bound; 51), as tabulated in Section 3.5; the S0 specification retains the original 13/7/44/48 counts. Unit tests asserted the single LHV basis, the absence of any foreign-basis hydrogen value, and FX use only with year tags. One check, the diesel HD TCO window of [2.5, 4.5] CNY/km, returned a documented deviation: the window is inconsistent with the specification's own parameters, whose component sketch already includes the driver cost (0.94 CNY/km) and sums to 4.4–4.8 CNY/km, above the window's own 4.5 upper bound. The formula result of 5.31 CNY/km was retained, and the deviation is disclosed here and in the deposited validation log rather than silently absorbed.

Read as a whole, the estimates that follow are internally consistent scenario outputs: the absolute numbers inherit the uncertainty of their literature anchors, while the regional and pathway contrasts that the coupling analysis targets are preserved by construction.

Table 6. First-owner TCO decomposition by class, duty scenario, and powertrain (CNY/km; FCEV fuelled with national-average renewable hydrogen at 48.5 CNY/kg under purchased power). FC stack replacement year = 15,000 cumulative operating hours divided by annual operating hours (annual km divided by duty average speed: 2286 h/year HD long-haul, 2000 h/year HD regional, 1200 h/year LD regional, 1000 h/year LD urban, e.g., 15,000/2286 = 6.5625 years); entries beyond the vehicle lifetime (LD: 10 yr) are marked "beyond life" and are not costed.

Class	Duty Scenario	Powertrain	Capital [CNY/km]	Residual Value [CNY/km]	Midlife Replacement [CNY/km]	Fuel [CNY/km]	Maintenance [CNY/km]	Driver [CNY/km]	Insurance [CNY/km]	Other Fixed [CNY/km]	TCO [CNY/km]	Tonne-km Intensity [t-km/km]	TCO [CNY/t-km]	FC Stack Replace-ment Year [yr]
HD	HD regional	Diesel	0.67	−0.078	0	2.555	1.3	1.5	0.16	0.08	6.187	21	0.295	—
HD	HD regional	BEV	1.591	−0.185	0.201	1.522	0.95	1.5	0.38	0.08	6.039	17.85	0.338	—
HD	HD regional	FCEV	2.093	−0.244	0.132	4.124	1.25	1.5	0.5	0.08	9.436	20.16	0.468	7.5
HD	HD long-haul	Diesel	0.419	−0.049	0	2.555	1.3	0.938	0.1	0.05	5.312	21	0.253	—
HD	HD long-haul	BEV	0.994	−0.116	0.126	1.522	0.95	0.938	0.238	0.05	4.702	17.85	0.263	—
HD	HD long-haul	FCEV	1.308	−0.152	0.088	4.124	1.25	0.938	0.312	0.05	7.918	20.16	0.393	6.5625
LD	LD urban	Diesel	0.57	−0.058	0	0.949	0.55	2.667	0.14	0.133	4.951	1.26	3.929	—
LD	LD urban	BEV	1.092	−0.111	0	0.441	0.38	2.667	0.268	0.133	4.87	1.13	4.294	—
LD	LD urban	FCEV	3.085	−0.314	0	1.456	0.5	2.667	0.758	0.133	8.285	1.22	6.78	15 (beyond life)
LD	LD regional	Diesel	0.285	−0.029	0	0.949	0.55	1.333	0.07	0.067	3.225	1.26	2.559	—
LD	LD regional	BEV	0.546	−0.055	0	0.441	0.38	1.333	0.134	0.067	2.845	1.13	2.509	—
LD	LD regional	FCEV	1.542	−0.157	0	1.456	0.5	1.333	0.379	0.067	5.12	1.22	4.19	12.5 (beyond life)

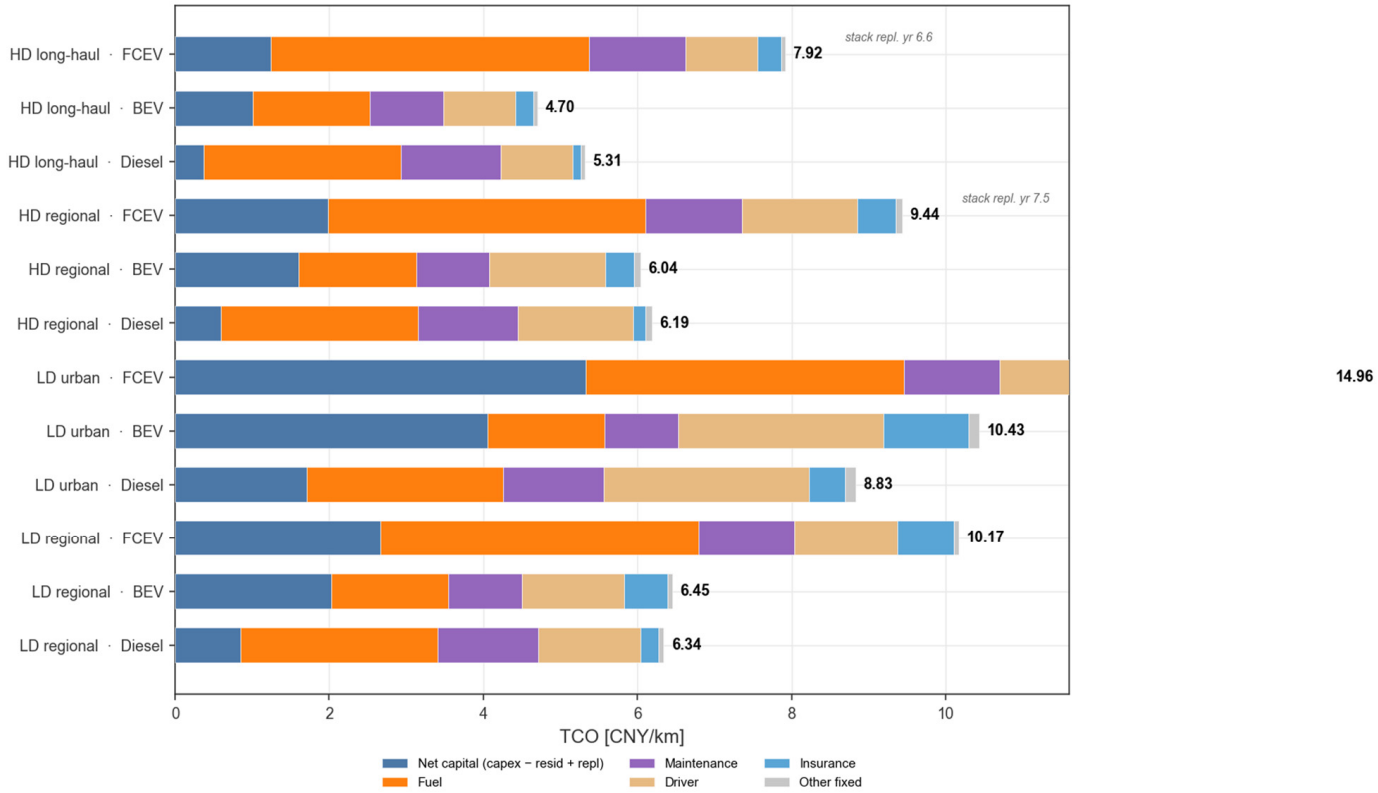


Figure 3. First-owner TCO and components (CNY/km) by class, duty, and powertrain at the 2024 baseline (FCEV at national-average renewable H_2, 48.5 CNY/kg). Stacked segments: net capital, fuel, maintenance, driver, insurance, other; right-hand labels: total CNY/km; stack-replacement years marked where triggered (HD duties only).

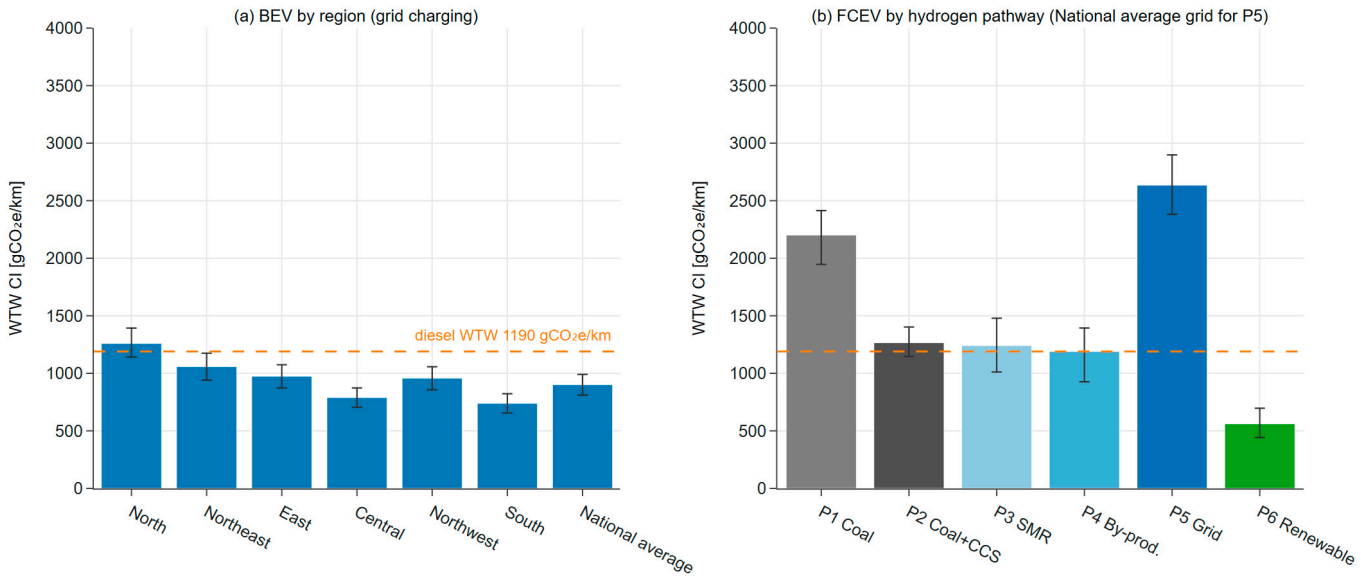


Figure 4. WTW carbon intensity (gCO_2e/km) of HD long-haul trucks (2022 operating-margin factors [4]): (**a**) BEV by charging region, whiskers spanning the grid-factor ranges, dashed line: diesel reference (1190 gCO_2e/km); (**b**) FCEV by production pathway, whiskers spanning the production-CI, grid-factor, and gate-to-tank ranges.

Table 7. Critical carbon prices p* (CNY/tCO_2) on the per-tonne-kilometre ACC basis of Equation (15), condensed from the full 112-combination matrix (Appendix B, Table A2). Panel (**a**): all positive finite crossings. Panel (**b**): already-dominant pairs (p* = 0). Category counts across the full matrix: 8 positive crossings, 7 already-dominant (p* = 0), 46 n/a (target not cleaner than source per tonne-kilometre), 51 > 3000 (crossing beyond the reporting bound).

(a) Class	Duty	Region	Pair (Source → Target)	p* [CNY/tCO_2]
HD	HD long-haul	South	Diesel → BEV	681.7
HD	HD long-haul	Central	Diesel → BEV	835.9
HD	HD long-haul	National average	Diesel → BEV	1679.3
HD	HD regional	South	Diesel → BEV	2858.7
LD	LD urban	South	Diesel → BEV	2253.5
LD	LD urban	Central	Diesel → BEV	2447.7
HD	HD long-haul	North	BEV → FCEV (P6)	2927.9
HD	HD regional	North	BEV → FCEV (P6)	2936.4
(b) Class	**Duty**	**Region**	**Pair (Source → Target)**	**p* [CNY/tCO_2]**
LD	LD regional	all seven regions	Diesel → BEV	0 (already dominant)

Table 8. One-at-a-time sensitivity of the BEV–diesel gap, HD long-haul duty (swings computed as |response (high)—response (low)| over each driver's Tables 2 and 3 range; percentages relative to the respective base gap).

Driver (Range)	TCO Gap Swing [CNY/km]	% of TCO Gap	CI Gap Swing [gCO_2e/km]	% of CI Gap
BEV charging tariff (0.75–1.5 CNY/kWh)	1.088	178.1	—	—
BEV purchase price (750,000–1,200,000 CNY)	0.529	86.6	—	—
Diesel consumption (0.32–0.38 L/km)	0.438	71.7	204.0	70.5
Diesel retail price (6.8–8.0 CNY/L)	0.420	68.8	—	—
Diesel WTW EF (3.1–3.7 $kgCO_2e$/L)	—	—	210.0	72.6
BEV consumption (1.3–1.6 kWh/km)	0.315	51.6	186.4	64.4
Grid EF, National average (0.483–0.590 $kgCO_2$/kWh)	—	—	180.1	62.3
Discount rate (5–12%)	0.161	26.4	—	—
HD BEV battery replacement (140,000–230,000 CNY)	0.063	10.3	—	—

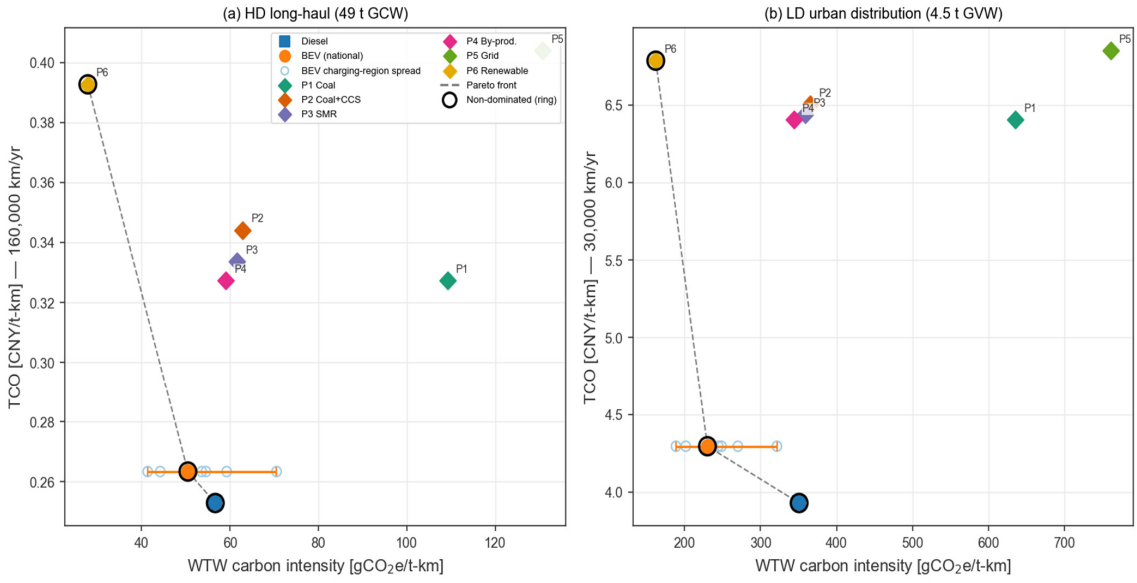


Figure 5. Joint cost–carbon position of all powertrain–fuel options per tonne-kilometre: (**a**) HD long-haul; (**b**) LD urban. Axes: WTW CI (gCO_2e/t-km) vs. TCO (CNY/t-km). Filled markers: national-average representatives; open circles: BEV charging-region spread; whiskers: min–max of the regional CI spread; open rings and dotted line: Pareto-non-dominated options and front.

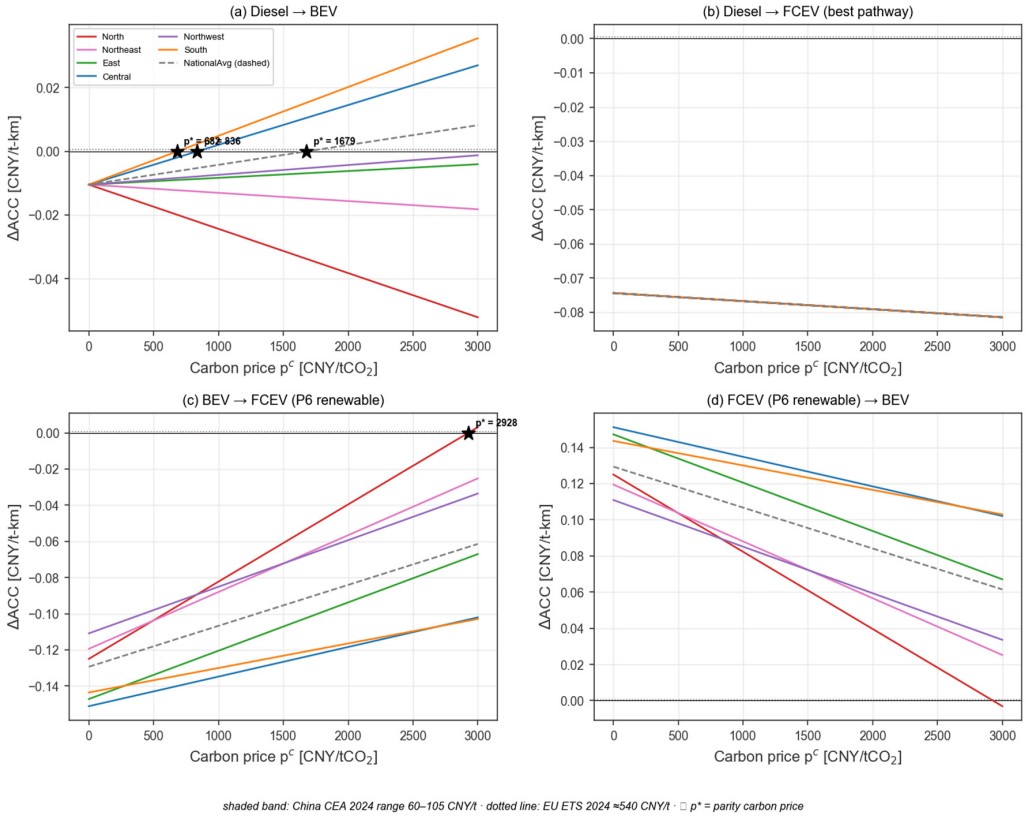


Figure 6. Carbon-internalized cost difference ΔACC = ACC(target) − ACC(source) vs. carbon price (HD long-haul, per tonne-kilometre): (**a**) Diesel → BEV; (**b**) Diesel → FCEV (best); (**c**) BEV → FCEV (P6); (**d**) FCEV (P6) → BEV. Negative ΔACC: target cheaper (stars mark finite p*). Shaded band: China CEA 2024 range (60–105 CNY/tCO_2 [38]); dotted line: EU ETS 2024 average (≈540 CNY/tCO_2).

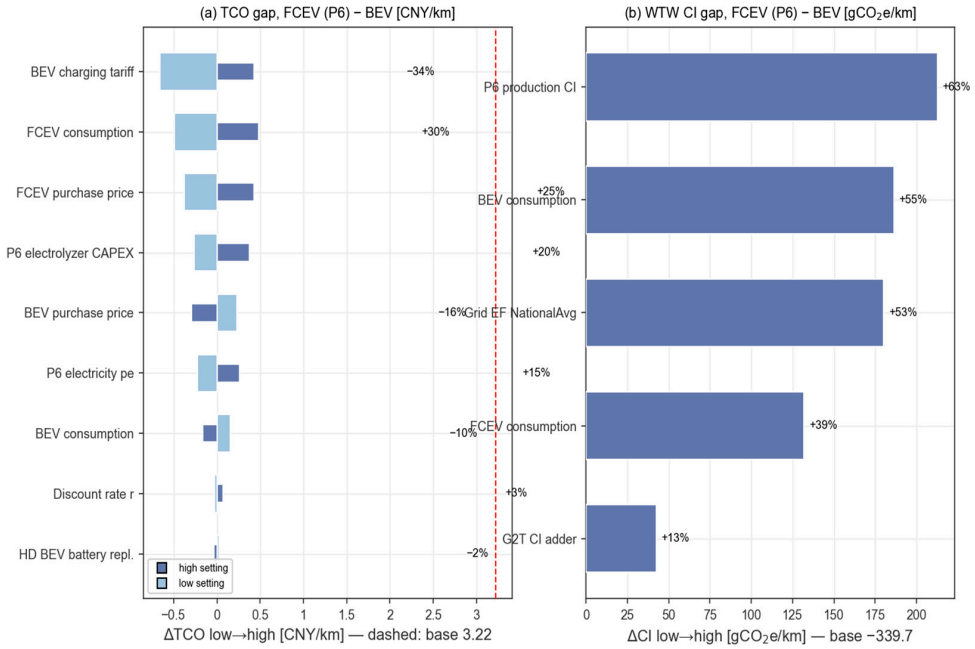


Figure 7. One-at-a-time sensitivity of the FCEV(P6)—BEV gap, HD long-haul, tornado form: (**a**) TCO gap per kilometre (base 3.22 CNY/km); (**b**) WTW CI gap per kilometre (base −339.7 gCO_2e/km). Bars: each driver's low–high response (dark blue: high setting; light blue: low setting); dashed lines: base values. BEV–diesel swings: Table 8; the utilization and capacity ratios apply only per tonne-kilometre (Section 2.4).

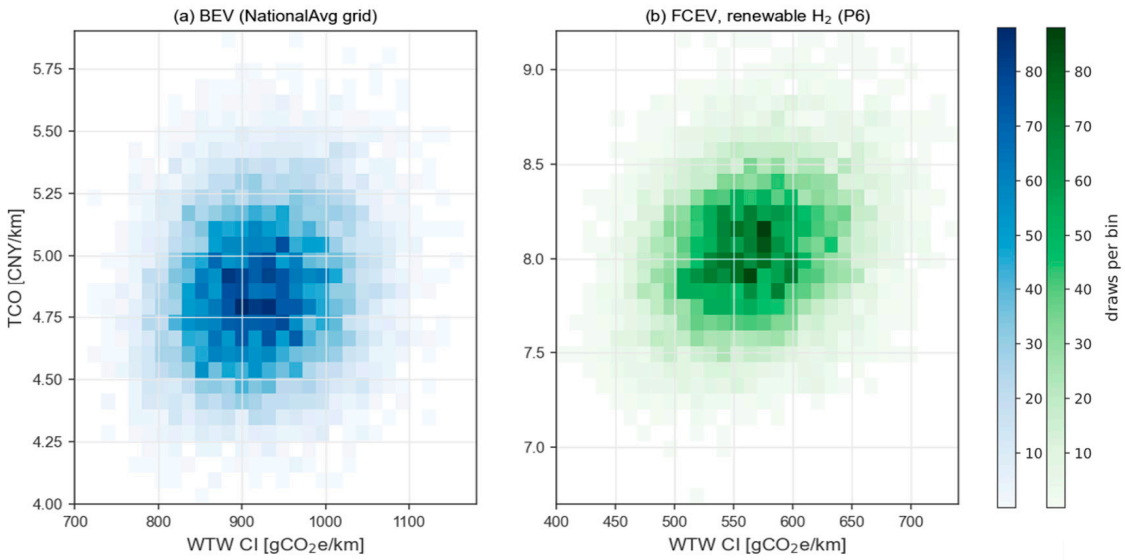


Figure 8. Joint Monte Carlo density of TCO and WTW CI for the HD long-haul duty (N = 10,000, common random numbers): (**a**) BEV, national-average grid (blue scale); (**b**) FCEV (P6) with p_e draws (green scale); shared colour scale (draws per bin). Parity probabilities are reported in Table 9 (panel (**b**)).

Table 9. Monte Carlo summary (10,000 draws, common random numbers). Panel (**a**): means and 90% intervals (P05–P95) for TCO and WTW CI. Panel (**b**): parity probabilities P[ACC target < ACC source] on the per-tonne-kilometre ACC basis of Equation (15) at selected carbon prices.

(a) TCO and WTW CI Distributions.

Output	Unit	Mean	P05	P95
TCO, Diesel, HD long-haul	CNY/km	5.376	5.141	5.616
TCO, BEV, HD long-haul	CNY/km	4.86	4.419	5.338
TCO, FCEV (P6), HD long-haul	CNY/km	8.065	7.46	8.69
TCO, Diesel, LD urban	CNY/km	5.004	4.724	5.291
TCO, BEV, LD urban	CNY/km	4.977	4.609	5.362
TCO, FCEV (P6), LD urban	CNY/km	8.671	7.777	9.655
WTW CI, Diesel, HD long-haul	gCO_2e/km	1190.003	1073.758	1313.086
WTW CI, BEV, HD long-haul (National average grid)	gCO_2e/km	921.694	807.361	1040.616
WTW CI, FCEV (P6), HD long-haul	gCO_2e/km	566.668	483.503	654.51
WTW CI, Diesel, LD urban	gCO_2e/km	441.996	384.213	503.569
WTW CI, BEV, LD urban (National average grid)	gCO_2e/km	266.98	229.963	306.554
WTW CI, FCEV (P6), LD urban	gCO_2e/km	200.01	167.083	235.351

(b) Parity Probabilities.

Pair	Duty	Region Scope	Carbon Price p_c [CNY/tCO_2]	Probability [-]
FCEV(P6) < BEV	HD long-haul	National average	0	0.0000
FCEV(P6) < BEV	HD long-haul	National average	100	0.0001
FCEV(P6) < BEV	HD long-haul	National average	300	0.0007
FCEV(P6) < BEV	HD long-haul	National average	1000	0.0070
FCEV(P6) < BEV	HD long-haul	mean of 6 regions	0	0.0003
FCEV(P6) < BEV	HD long-haul	mean of 6 regions	100	0.0007
FCEV(P6) < BEV	HD long-haul	mean of 6 regions	300	0.0017
FCEV(P6) < BEV	HD long-haul	mean of 6 regions	1000	0.0181
FCEV(P6) < BEV	LD urban	National average	0, 100, 300	0 (all)
FCEV(P6) < BEV	LD urban	mean of 6 regions	0, 100, 300	0 (all)
FCEV(P6) < BEV	HD long-haul	Northwest (max)	100	0.0027
FCEV(P6) < BEV	HD long-haul	Northwest (max)	300	0.0049
BEV < diesel	HD long-haul	National average	0	0.1569
BEV < diesel	HD long-haul	National average	100	0.1622
BEV < diesel	HD long-haul	National average	300	0.1784
BEV < diesel	HD long-haul	National average	1000	0.2337
BEV < diesel	HD long-haul	North	0	0.1569
BEV < diesel	HD long-haul	North	1000	0.0600
BEV < diesel	HD long-haul	South	1000	0.3519

3. Results and Discussion

3.1. Delivered Hydrogen Costs by Production Pathway and Region

Figure 2 and Table 5 present the delivered hydrogen cost matrix across the six production pathways and six deployment regions, with renewable electrolysis (P6) costed at the purchased-power base of Equation (3) (pe = 0.25 CNY/kWh) and its zero-purchase-price counterpart (S0) retained as a labelled scenario. Base-case delivered costs ranged from 33.0 CNY/kg (coal gasification, P1, and industrial by-product hydrogen, P4) to 54.3 CNY/kg (grid electrolysis in the East), and propagating the literature low-high parameter ranges widened the envelope to 23.7–76.9 CNY/kg. The four fossil and industrial pathways clustered in a narrow 33.0–37.0 CNY/kg band: coal gasification (P1) and industrial by-product hydrogen (P4) were jointly cheapest at 33.0 CNY/kg, followed by natural-gas SMR (P3) at 34.5 CNY/kg and coal gasification with CCS (P2) at 37.0 CNY/kg. Under purchased power the two electrolytic routes joined the top of the cost range rather than bracketing the fossil cluster: renewable electrolysis delivered 44.1 CNY/kg in the Northwest to 53.7 CNY/kg in Central China, and grid electrolysis 42.4–54.3 CNY/kg. Their regional ordering flipped within the band—purchased-power renewable electrolysis undercut grid electrolysis on the North, Northeast, East, and national-average supplies (47.5 vs. 51.2, 46.2 vs. 49.1, 52.8 vs. 54.3, and 48.5 vs. 51.2 CNY/kg), while grid electrolysis remained cheaper on the tariff-favoured Northwest grid (42.4 vs. 44.1 CNY/kg) and in Central China and the South—because the two routes' production layers follow different regional quantities: full-load hours for P6, industrial tariffs for P5. Under the S0 scenario the renewable route would instead deliver 31.1–40.7 CNY/kg and undercut every fossil pathway (Section 3.6 quantifies the gap between the two specifications); every P6-competitiveness statement in this paper is therefore conditional on which of the two electricity-purchase regimes holds.

Table 5 decomposes this ordering into production and delivery layers. The production-gate anchors for P1–P4 span only 11.0–15.0 CNY/kg, whereas the downstream chain adds a common 22.0 CNY/kg for fossil routes (2.0 purification to GB/T purity, 10.0 compression and transport at the 200 km base distance, and 10.0 refuelling). Post-production stages therefore account for roughly two-thirds of the delivered price of fossil-route hydrogen. A production-cost advantage alone cannot decide pathway competitiveness. Regional differentiation entered only through the electrolytic routes: the production layer of P6 combined the *FLH*-scaled capital charge with the purchased-power term $p_e \times SEC$ (24.1 CNY/kg in the Northwest at approximately 1950 h/year vs. 33.7 CNY/kg in Central China at approximately 1050 h/year, Table 3), and that of P5 followed the regional industrial tariff structure (22.4–34.3 CNY/kg, a 1.5-fold spread between the Northwest and East grids). The producer-owned variant of Section 2.3 shifts the P6 production layer by replacing the PPA price with the region's dominant-resource plant LCOE; its delivered prices and the ownership bracket are tabulated alongside the base case in.

Figure 2 also positions the simulated costs against the 35–40 CNY/kg market anchor for 2024 dispenser prices adopted in Section 2.2 (the dashed line in the figure marks the band's 35 CNY/kg lower edge). Coal, by-product, and SMR hydrogen at 33.0–34.5 CNY/kg sit at or just below the lower edge of the anchor, consistent with these routes' continued role as the price-setting supplies, and coal plus CCS (37.0 CNY/kg) falls inside the band. Under purchased power, both electrolytic routes clear the upper edge of the anchor in every region (44.1 CNY/kg or above for P6, its regional minimum; 42.4 CNY/kg for P5 in the tariff-favoured Northwest, the single exception); only under the S0 specification would renewable hydrogen at the national-average resource mix (35.5 CNY/kg) fall inside the band. Within the production layer of both electrolytic routes, electricity purchases now dominate by construction: the specific consumption of 52 kWh/kg multiplies either the regional industrial tariff (P5) or the curtailed-power PPA price (P6), so the regional

spread of the P5 production layer in Figure 2 is inherited almost entirely from power-market geography, while P6 reflects the joint effect of full-load hours and the purchased-power term. This aligns with the literature, in which electricity purchases are reported to contribute roughly 70–80% of the levelized cost of electrolytic hydrogen [21].

The simulated band also sits comfortably inside the published spread of Chinese pathway costs, whose production-gate anchors range from 7.2 to 17.2 CNY/kg for coal gasification, 9.1 to 25.2 for SMR, 8 to 15.1 for by-product, 20 to 55 for grid electrolysis, and 5.3 to 104 CNY/kg for renewable routes [20,21,23]. Discrepancies among these source estimates were resolved ex ante by the boundary harmonization layer of Section 2.2 rather than by selective quotation [25]. Given the width of the underlying literature, these cost estimates inherit its uncertainty rather than narrowing it.

3.2. Total Cost of Ownership by Vehicle Class and Powertrain

Figure 3 and Table 6 summarize first-owner TCO at the 2024 baseline with fuel priced at the national-average renewable pathway under purchased power (48.5 CNY/kg; the S0 counterpart is 35.5 CNY/kg). For the 49 t long-haul tractor, the BEV was cheapest at 4.70 CNY/km, 11.5% below diesel (5.31 CNY/km), while the FCEV stood at 7.92 CNY/km, a 49.1% premium over diesel. The same ordering held in the regional HD duty (BEV 6.04 vs. diesel 6.19 CNY/km; FCEV 9.44 CNY/km). In the 4.5 t class, the BEV's cost advantage narrowed sharply in the urban duty (4.87 vs. 4.95 CNY/km, −1.6%) while the FCEV premium widened to 67.3% (8.29 CNY/km); in the regional LD duty, the BEV led diesel by 11.8% (2.85 vs. 3.22 CNY/km).

The stacked decomposition in Figure 3 shows why the orderings differ across powertrains. Fuel is the largest single component for diesel (48% of HD long-haul TCO) and, under purchased power, the dominant one for the FCEV (52%), whereas the BEV shifts weight toward capital: capital net of residual value and the midlife battery replacement contribute approximately 21% of its TCO, against roughly 7% for diesel. For the FCEV, the 15,000 h stack-replacement trigger falls within the vehicle life in the HD duties (at 6.6 years long-haul, Table 6); in the LD duties the trigger lies beyond the 10-year life, so no replacement is triggered or costed (Table 6). In the LD urban duty, driver wages dominate all powertrains (54% of diesel TCO), so powertrain differences compress while the FCEV's capital intensity (3.09 vs. 0.57 CNY/km for diesel) remains the decisive penalty.

Table 6 also reports the tonne-km normalization, and here the ranking partially reverses. Dividing by payload-adjusted transport work (BEV intensity 17.85 vs. 21.0 t-km/km for diesel, a payload ratio of 0.85) lifts the BEV long-haul TCO to 0.263 CNY/t-km, 4.1% above diesel's 0.253 CNY/t-km, despite its 11.5% per-km advantage; in the LD urban duty the corresponding figures are +9.3% per t-km against −1.6% per km (payload ratio 0.90). Only in the LD regional duty does the BEV lead on both bases (2.51 vs. 2.56 CNY/t-km). Because the FCEV payload ratio is close to unity (0.96), its per-t-km premium (+55.3% long-haul) differs only modestly from its per-km premium. Which metric should govern procurement therefore depends on whether fleets can backfill the foregone payload, a duty-specific operational question—and one whose answer now has a quantified robustness check: with the capacity ratios swept (Section 2.7), the long-haul per-tonne-kilometre reversal collapses to a single analytic break-even condition (Section 3.6), the BEV winning per tonne-kilometre if and only if its capacity ratio exceeds the per-kilometre TCO ratio of approximately 0.885.

Across the six hydrogen pathways, the FCEV column of Figure 3 is a band rather than a point: each 1 CNY/kg of delivered hydrogen moves HD TCO by 0.085 CNY/km (at 8.5 kg/100 km) and LD TCO by 0.030 CNY/km. Under the purchased-power base, the FCEV long-haul TCO spans approximately 6.6 CNY/km at its favourable end—by-product hydrogen (33.0 CNY/kg delivered)—to approximately 8.4 CNY/km with grid electrolysis

in the East grid (54.3 CNY/kg). The LD urban band runs from 7.8 to 8.5 CNY/km. Even at the favourable end of this band, the FCEV remained above diesel (5.31 CNY/km) and, in the HD class, above the BEV (4.70 CNY/km); only under the S0 specification would renewable hydrogen in the Northwest (31.1 CNY/kg, 6.44 CNY/km) approach the band's lower edge.

Two caveats condition Figure 3. To start, the rankings of the capital-intensive options are discount-rate sensitive: within the 5–12% band sampled in the uncertainty analysis, higher hurdle rates penalize the BEV and FCEV disproportionately, and the sign of the BEV–diesel margin in the LD class is not robust to this choice [11,12]; parity probabilities are quantified in Section 3.6. The second is an asymmetry of grid sensitivity: the BEV TCO is grid-insensitive in the base case because charging is priced at regulated tariffs [6], while its carbon intensity changes with the grid (Section 3.3). The 2030 outlook is treated as a separate scenario layer (Section 2.1) and is not drawn in Figure 3. The EU parity windows of 2025–2026 reported for early HDV segments [7] should be transplanted to China only cautiously, given the flagged uncertainty in current Chinese catalogue prices.

3.3. Well-to-Wheel Carbon Intensity Across Regional Grids and Pathways

Well-to-wheel carbon intensities by pathway and by charging region are reported in Figure 4 and Table 4. At the production layer, the pathway ordering is renewable electrolysis (3.5 $kgCO_2e/kg$) far below by-product (10.9), SMR (11.5), and coal plus CCS (11.8), with coal gasification at 22.8 $kgCO_2e/kg$; grid electrolysis spans 22.9–39.0 $kgCO_2e/kg$ as the product of the 52 kWh/kg specific consumption and the regional operating-margin grid factor [4]. A common gate-to-tank adder of 3.1 $kgCO_2e/kg$ applies to all pathways. At the vehicle level for the 49 t long-haul class, the renewable-H_2 FCEV emitted 561 gCO_2e/km, 53% below diesel (1190 gCO_2e/km). By-product hydrogen landed at parity with diesel (1190 gCO_2e/km)—a coincidence that holds exactly under the assumed economic allocation of the by-product, since both equal 14.0 $kgCO_2e/kg \times 8.5$ kg/100 km. SMR and coal-plus-CCS hydrogen ran 4.3–6.4% above diesel (1241 and 1266 gCO_2e/km). Coal-gasification hydrogen reached 2201 gCO_2e/km, 85% above diesel, and grid-electrolytic hydrogen ranged from 2208 to 3578 gCO_2e/km across grids.

The regional grid factors of Table 3 (0.44 $kgCO_2/kWh$ in the South grid to 0.75 in the North; national reference 0.5366 [4]) propagate almost linearly into the BEV chain. The HD BEV ranged from 739 gCO_2e/km on the South grid to 1259 gCO_2e/km on the North grid, around a 900.7 gCO_2e/km national average. The simulated HD BEV exceeded diesel by 5.8% in the North grid and remained only about 11% below diesel in the Northeast; in the South grid it was 38% below diesel. For the LD urban duty, the BEV (214–365 gCO_2e/km) stayed 18–52% below its diesel counterpart (442 gCO_2e/km) in every grid. Expressed per tonne-km, the HD BEV spans 41.4–70.5 $gCO_2e/t\text{-}km$ against 56.7 for diesel.

Figure 4 highlights the trap of grid electrolysis in coal-heavy grids. Grid-electrolytic hydrogen produced the dirtiest FCEV chains in the entire option set, from 2208 gCO_2e/km on the South grid to 3578 gCO_2e/km on the North grid, up to 3.0 times diesel and 6.4 times the renewable-H_2 FCEV. More strikingly, in this six-region aggregation the grid route exceeded even coal-gasification hydrogen (2201 gCO_2e/km) in every grid entry, including the lowest-carbon South grid. Reference [24] found grid-electrolytic hydrogen dirtier than coal hydrogen across eight northern Chinese provinces; the present results extend that conclusion to the full regional set at 2022-vintage operating-margin factors. Across the whole option set, the simulated intensities span a factor of 18, from 198 gCO_2e/km (LD renewable-H_2 FCEV) to 3578 gCO_2e/km, underscoring that fuel-chain choice, not vehicle class, dominates the carbon outcome.

Three scope caveats qualify these values; all values are operational fuel-chain WTW emissions, excluding vehicle manufacturing (Section 2.1). The coal and SMR figures were used at their WTT-WTW basis, since direct-only coal values understate chain emissions by a reported 20–30% [25]. The SMR band of 9–14 $kgCO_2e/kg$ carries a declared methane-leakage assumption, and the by-product value depends on the allocation convention [23,33]. The grid factors themselves are annual operating-margin averages rather than marginal factors, which may diverge under rapid charging growth [28–30]; grid decarbonization toward 2030 was confined to the scenario layer.

3.4. The Cost–Carbon Landscape and Pareto Fronts

Figure 5 assembles the two preceding result sets into a joint cost–carbon landscape and identifies the Pareto-non-dominated options per class on the figure's per-tonne-kilometre basis. On the per-kilometre basis, described in the text for completeness, the HD long-haul front pairs the BEV (cheapest) with the renewable-H_2 FCEV (cleanest at 561 gCO_2e/km but 49.1–52.5% costlier than diesel across the HD duties under purchased power). Diesel retains a front position only in the North grid, the one region where the BEV chain is dirtier per kilometre (1258.9 vs. 1190.0 gCO_2e/km); everywhere else the BEV is both cheaper and cleaner, and diesel is dominated. Every fossil-hydrogen FCEV variant lies off the front: SMR, coal-plus-CCS, and by-product chains combine a higher cost with equal or higher emissions than diesel, and are dominated by the BEV in five of the six regional grids and by diesel in the coal-based North grid. The grid-H_2 FCEV is dominated on both axes by diesel and the BEV in every region.

On the figure's per-tonne-kilometre basis, the picture reshuffles once payload penalties are internalized. In the North grid, the HD front collapses to diesel and the renewable-H_2 FCEV: the BEV (0.263 CNY/t-km at 70.5 $gCO_2e/t\text{-}km$) is dominated by diesel (0.253 CNY/t-km at 56.7 $gCO_2e/t\text{-}km$), because its payload penalty outweighs its per-km cost advantage in exactly the grids where its charging chain is dirtiest. In the four cleaner grids (East, Central, Northwest, South), the three-way front is retained; in Northeast, as in North, it collapses to diesel and the renewable-H_2 FCEV, the BEV there being dominated per tonne-kilometre as well (0.263 CNY/t-km at 59.2 $gCO_2e/t\text{-}km$, against diesel's 0.253 at 56.7). Carbon pricing behaves differently on the two bases. Any strictly positive carbon price erodes diesel's per-km position immediately: the BEV is already cheaper per kilometre in all four duty-class combinations, and its carbon penalty in the coal-heavy grids is far too small to offset the cost gap within the 0–1000 CNY/tCO_2 sweep. Per tonne-km, by contrast, diesel remains competitive at low carbon prices, and in the coal grids the carbon-internalized ranking never crosses at all, since the BEV is not cleaner after normalization. The critical prices quantifying these statements follow in Section 3.5 (Table 7); notably, in the LD regional duty no carbon price is needed, as the BEV already dominates diesel on both bases.

The LD panels of Figure 5 sharpen the class contrast. Per kilometre, diesel disappears from the front entirely: the LD BEV is both cheaper (4.87 vs. 4.95 CNY/km urban; 2.85 vs. 3.22 regional) and cleaner (214–365 vs. 442 gCO_2e/km) in every grid, so diesel is Pareto-dominated even before any carbon price is applied. The urban per-tonne-km front is three-way, restoring diesel on cost, the renewable-H_2 FCEV on carbon (198 gCO_2e/km, the global minimum of the option set), and the BEV as the interior compromise. The renewable-H_2 FCEV holds frontier membership, in both classes, only on the carbon axis.

Three patterns summarize the landscape. What first stands out is the BEV's efficiency, which concentrates on the cleaner end of the grid spectrum: its frontier position strengthens monotonically as the regional factor falls—the cost–carbon expression of grid-insensitive cost and grid-sensitive emissions. The green-H_2 FCEV presents a different pattern, occupying

the low-CI, high-cost frontier alone; its climate advantage over the national-average BEV is 0.34 $kgCO_2e/km$ (561 vs. 900.7 gCO_2e/km; 0.63 $kgCO_2e/km$ against diesel), so whether that advantage justifies a premium of 68.4% over the BEV (49.1% over diesel) in the long-haul duty is a carbon-price question, deferred to Section 3.5. Coal-H_2 and grid-H_2 FCEVs complete the picture: they never survive dominance in any region, class, or metric basis, implying that the FCEV's value proposition in logistics is conditional on fuel carbon intensity rather than on the vehicle platform itself. This duty-dependence of powertrain rankings is consistent with European TCO modelling [8], and the corridor-range restriction that constrains HD BEVs in practice [10] would, if imposed, strengthen the diesel position at the dirty-cost corner.

3.5. Critical Carbon Prices and Ranking Reversals

Figure 6 and Table 7 report the critical carbon price p* obtained from Equation (16) for the four pair families—Diesel → BEV, Diesel → FCEV_best (the least-cost FCEV option in each region), BEV→FCEV_P6, and the reverse FCEV_P6→BEV—evaluated on the per-tonne-kilometre ACC basis of Equation (15) for every class, duty scenario, and regional grid. Four resolutions occur, following the convention of Section 2.6: a positive finite p* where the ACC curves cross within the [0, 3000] CNY/tCO_2 reporting interval; p* = 0 (already dominant) where the cleaner option is already the cheaper one per tonne-kilometre; n/a where the target is not cleaner than the source per tonne-kilometre; and >3000 where a crossing exists but lies beyond the reporting bound. Across the 112 pair–class–duty–region combinations (Table 7, condensed here; the full matrix is in Appendix B, Table A2), 8 return a positive finite p* (681.7–2936.4 CNY/tCO_2), 7 are already dominant (p* = 0), 46 return n/a, and 51 cross beyond the reporting bound.

Over the two focal duty scenarios (HD long-haul and LD urban) and their seven region rows, the Diesel → BEV family yields a positive finite p* in 5 of 14 focal combinations (n = 5), median 1679.3 CNY/tCO_2 (interquartile range 835.9–2253.5)—a family untouched by the electricity-purchase regime, since neither diesel nor BEV costs involve hydrogen. The BEV → FCEV_P6 family now crosses within the reporting bound in a single focal combination—HD long-haul on the North grid, 2927.9 CNY/tCO_2, within 2.4% of the 3000 CNY/tCO_2 bound. The Diesel → FCEV_best family returns n/a throughout: under purchased power, the least-cost clean pathway is by-product hydrogen (P4, 33.0 CNY/kg delivered) in every region, and the P4 chain's carbon intensity equals diesel's well-to-wheel intensity, so no FCEV pathway that is both cheaper-than-diesel-adjacent and cleaner remains for carbon pricing to arbitrage at the pathway-minimum cost. Over the full matrix, the Diesel → BEV family keeps its six positive crossings (median 1966.4 CNY/tCO_2; range 681.7–2858.7) and the BEV → FCEV_P6 family retains two (2927.9 and 2936.4 CNY/tCO_2, both on the North grid). The reverse FCEV_P6→BEV family returns no finite p* in any region, a consistency check that renewable-hydrogen FCEVs remain the cleaner member of that pair everywhere.

The policy content of this section rests largely on the regional detail in Table 7 and the full matrix in Appendix B (Table A2). In the LD regional-delivery duty, the BEV is already the cheaper and cleaner option per tonne-kilometre against diesel in all seven regions (p* = 0). The LD urban duty behaves differently: the payload penalty reverses the cost order, and finite thresholds reappear only on the two cleanest grids—2253.5 CNY/tCO_2 in South and 2447.7 CNY/tCO_2 in Central, beyond 3000 CNY/tCO_2 elsewhere. In the HD class, Diesel→BEV crossings are finite only on the cleaner southern and central grids (681.7–835.9 CNY/tCO_2 in the long-haul duty, 2858.7 CNY/tCO_2 in the regional-delivery duty in the South, 1679.3 CNY/tCO_2 in the long-haul duty at the national average). In the North grid the BEV is dirtier than diesel on either basis (1258.9 vs. 1190.0 gCO_2e/km per kilometre; 70.5 vs. 56.7 $gCO_2e/t\text{-}km$ per tonne-kilometre). In the

Northeast it is about 11% cleaner per kilometre (1057.5 gCO_2e/km), but the 0.85 payload ratio pulls it back to 59.2 gCO_2e/t-km against diesel's 56.7. In both grids no carbon price, however high, delivers a switch to the BEV, for the different reasons tabulated in Appendix B. The BEV→FCEV_P6 family crosses within range only on the North grid (2927.9 CNY/tCO_2 long-haul; 2936.4 CNY/tCO_2 regional-delivery), precisely where the BEV's grid exposure is largest; under the S0 specification the family would instead cross on the three northern grids at 1644.3–2191.3 CNY/tCO_2, and purchased power above roughly 0.09–0.23 CNY/kWh (depending on the grid) pushes each crossing beyond the 3000 CNY/tCO_2 bound (Section 3.6)—the two North-grid crossings survive at pe = 0.25 by less than 2.5%.

Each reported p* is a break-even carbon price—the price at which the carbon-internalized rankings of Equation (15) flip—not a market price or a forecast; the question of whether these thresholds are met at current Chinese carbon prices therefore has a uniform answer: none of the eight finite crossings is. These thresholds sit far above current Chinese carbon-market reality. The national emissions trading scheme traded in the 60–105 CNY/tCO_2 band in 2024 [38]; even the lowest positive crossing in Table 7 (681.7 CNY/tCO_2) exceeds the top of that band roughly six-fold, and the maximum (2858.7 CNY/tCO_2 in the Diesel→BEV family; 2936.4 CNY/tCO_2 overall) exceeds it roughly 28-fold. At the 2024 trading band, carbon pricing alone therefore triggers none of the finite Diesel→BEV or BEV→FCEV(P6) transitions; only the seven already-dominant pairs ($p^* = 0$) are actionable at any nonnegative price, and the 2030 scenario layer shifts the near-term lever from carbon pricing toward vehicle-cost and infrastructure policy. The European Union Emissions Trading System marker of about 540 CNY/tCO_2 likewise remains below every positive finite crossing. The thresholds also exceed the 170–360 CNY/tCO_2 pathway-crossover prices reported for Chinese hydrogen production routes [23], because the present p* embeds the full vehicle-level cost gap—delivery adders, vehicle capital differences, and payload normalization—rather than production economics alone. Because both ACCs are linear in the carbon price, Figure 6 plots the ΔACC curves over the full [0, 3000] CNY/tCO_2 reporting interval. The four finite HD long-haul crossings of Table 7 (681.7, 835.9, 1679.3, and 2927.9 CNY/tCO_2) appear as starred markers in panels (a) and (c); the four remaining finite crossings (HD regional and LD urban: 2253.5, 2447.7, 2858.7, and 2936.4 CNY/tCO_2) are read from Table 7 and Appendix B. Under the 2030 outlook scenario, the Diesel→BEV threshold falls to zero in all seven HD long-haul regions and twelve finite Diesel→BEV crossings reappear in the HD regional and LD urban duties (961.1–2712.6 CNY/tCO_2, concentrated on the cleaner grids), still beyond any near-term carbon price; the FCEV-side transitions remain beyond the 3000 CNY/tCO_2 bound in every combination, because even the cheaper 2030 electrolyzer leaves purchased-power renewable hydrogen above by-product hydrogen, whose chain carbon equals diesel's. In the same scenario layer, the HD long-haul FCEV TCO at national-average renewable supply falls from 7.92 to 7.28 CNY/km against an unchanged diesel 5.31 CNY/km, narrowing the fuel-cell premium from 49.1% to 37.1%—the labelled 2030 scenario layer of Section 2.1. These scenario values carry the same literature anchoring as the 2024 baseline.

3.6. Sensitivity and Uncertainty Results

Figure 7 arranges the one-at-a-time tornado responses of Equation (17) for the HD class, over twenty drivers (seventeen vehicle-and-chain drivers plus the P6 electricity price and the two payload capacity ratios). For P5, electricity price is by construction the first-order driver of delivered cost (tariff × *SEC* = 22.4–34.3 CNY/kg regional spread), quantified in Section 3.1. Figure 7 reports vehicle-level TCO and CI gaps, not LCOH. For the FCEV(P6)–BEV cost gap per kilometre (base 3.22 CNY/km under the purchased-power base), the BEV

charging tariff (0.75–1.5 CNY/kWh) produces the largest swing, 1.09 CNY/km or 33.8% of the gap, followed by the FCEV consumption (0.97 CNY/km, 30.2%), the FCEV purchase price (0.81 CNY/km, 25.2%), the P6 electrolyzer capital cost (2800–4500 CNY/kW; 0.64 CNY/km, 19.9%), the BEV purchase price (0.53 CNY/km, 16.4%), and the P6 electricity price p_e (0.20–0.31 CNY/kWh; 0.49 CNY/km, 15.1%); the discount rate (5–12%) moves the gap by only 0.10 CNY/km (3.0%) [11]. The utilization factor and both capacity ratios have exactly zero per-kilometre swing—they act only through the tonne-kilometre normalization, as Section 2.4 establishes analytically—and their per-t-km swings are therefore read from the stored tornado data rather than the per-kilometre panels. For the BEV–diesel gap per kilometre (base 0.61 CNY/km in the BEV's favour, before payload normalization), the same tariff swing amounts to 178% of the gap; the diesel retail price (6.8–8.0 CNY/L [5]) and diesel consumption each swing 69–72% of it. The BEV's cost advantage is the more fragile of the two rankings, and payload normalization decides its sign per tonne-kilometre. On the carbon axis, the renewable-hydrogen production carbon intensity (2.3–4.8 $kgCO_2e/kg$) dominates the FCEV–BEV gap with a 212.5 gCO_2e/km swing (62.6%), followed by BEV consumption (186.4 gCO_2e/km, 54.9%), the regional grid factor (180.1 gCO_2e/km, 53.0%), FCEV consumption (132.0 gCO_2e/km, 38.9%), and the gate-to-tank adder (42.5 gCO_2e/km, 12.5%). For the BEV–diesel gap, the diesel well-to-wheel factor (3.1–3.7 $kgCO_2e/L$ [42]), BEV consumption, and the regional grid factor (0.483–0.590 $kgCO_2/kWh$ at the national average [4]) contribute swings of 210.0, 186.4, and 180.1 gCO_2e/km respectively, confirming grid carbon intensity as the leading BEV-side driver. Because Figure 7 renders the FCEV(P6)–BEV panels only, the BEV–diesel swings quoted above are tabulated in Table 8 (data: tornado_oat.csv and rev_tornado20.csv in the deposit).

The purchased-power base and the S0 specification bracket every P6-competitiveness statement in this paper, and the bracket is linear in p_e. Each 0.01 CNY/kWh adds 0.52 CNY/kg to the delivered cost of P6 (SEC = 52 kWh/kg), so the S0-to-base move (p_e: 0 to 0.25 CNY/kWh) is equivalent to a 13.0 CNY/kg swing—1.11 CNY/km on the HD long-haul TCO—larger than any single driver bar the charging tariff in Figure 7. Three landmarks calibrate the bracket from above (S0) to below (base). The Northwest cost advantage is an S0 result: P6 Northwest stops being the least-cost delivered option once p_e exceeds approximately 0.036 CNY/kWh, where it reaches the 33.0 CNY/kg of coal-gasification and by-product hydrogen (Table 5), and it leaves the 35–40 CNY/kg dispenser band above approximately 0.17 CNY/kWh; at 0.20, 0.25, and 0.31 CNY/kWh it delivers 41.5, 44.1, and 47.3 CNY/kg. Vehicle-level economics follow: moving from S0 to the base widens the FCEV(P6)–BEV gap from 2.11 to 3.22 CNY/km and the FCEV premium over diesel from 28.3% to 49.1%. The ranking-reversal thresholds shift last: the finite BEV → FCEV(P6) crossings that S0 yields on the three northern grids (1644.3–2191.3 CNY/tCO_2) move beyond the 3000 CNY/tCO_2 reporting bound once p_e exceeds approximately 0.09 (Northwest), 0.12 (Northeast), or 0.23 CNY/kWh (North); at the 0.25 CNY/kWh base only the two North-grid crossings (2927.9 and 2936.4 CNY/tCO_2) survive, each by less than 2.5%. Renewable electrolysis on purchased power at these market prices is therefore not cost-competitive against by-product hydrogen in any case examined here, and the S0 specification of Section 3.1—together with the finite curtailment-resource constraint—delineates exactly the conditions under which it would be.

Base gaps: TCO −0.611 CNY/km (BEV cheaper) and CI 289.3 gCO_2e/km (BEV cleaner), HD long-haul, national-average grid.

The capacity ratios, newly swept, resolve the payload question. On the OAT side, sweeping κBEV over its literature-anchored range [0.67, 0.95] (0.67 = the 2020 heavy-BEV cargo-capacity multiplier of [11]; 0.95 = an optimistic battery-packaging improvement) moves the HD long-haul per-tonne-kilometre BEV–diesel gap across its sign: the analytic

break-even condition of Section 3.2 states that the BEV wins per tonne-kilometre if and only if κBEV exceeds the per-kilometre TCO ratio, approximately 0.885 at the national average—so at the literature's 2020 heavy-truck value of 0.67 the BEV's per-tonne-kilometre disadvantage widens to about 32%, while at 0.95 the BEV dominates diesel per tonne-kilometre at any carbon price ($p^* = 0$). The critical price responds sharply near the boundary: on the national-average grid, p^*(Diesel → BEV) falls from beyond 3000 CNY/tCO_2 at κBEV = 0.80 to 1679 CNY/tCO_2 at the 0.85 base, 182 CNY/tCO_2 at 0.88, and zero above 0.885; in the Northeast the crossing reappears only above the CI-ratio threshold of approximately 0.889 (between 0.885 and 0.889 the BEV is cheaper but still dirtier per tonne-kilometre, so no crossing exists), and on the North grid the BEV remains dirtier for every $\kappa \leq 0.95$ (CI ratio 1.058), so no carbon price helps there. In the LD urban duty, the reversal is robust: the break-even ratio is 0.984, above the swept range, so the payload penalty keeps diesel cheaper per tonne-kilometre for all $\kappa \leq 0.95$. In the Monte Carlo, with both capacity ratios drawn as triangular variates, the probability that the BEV undercuts FCEV(P6) per tonne-kilometre is at least 0.99 nationally and at least 0.95 in every region at any carbon price up to 1000 CNY/tCO_2, and the probability that it undercuts diesel per tonne-kilometre is 0.157 at zero carbon price (rising to 0.234 at 1000 CNY/tCO_2 nationally, 0.352 in South, and falling to 0.060 in North, where carbon pricing penalizes the dirtier-than-diesel BEV chain).

Equation (18) was evaluated over 10,000 Latin Hypercube draws with common random numbers across powertrains, so paired differences reflect parameter uncertainty rather than sampling noise. Figure 8 and Table 9 show the resulting clouds and summary statistics. In the HD long-haul class, mean TCO is 5.38 CNY/km for diesel (90% interval 5.14–5.62), 4.86 CNY/km for BEV (4.42–5.34), and 8.07 CNY/km for FCEV(P6) with the p_e draws (7.46–8.69). The FCEV's fifth percentile lies above the BEV's ninety-fifth, so the cost ordering is preserved under uncertainty. The well-to-wheel 90% intervals of the BEV (921.7 gCO_2e/km; 807.4–1040.6) and diesel (1190.0; 1073.8–1313.1) in fact do not overlap, though they separate by only a narrow margin (BEV P95 1040.6 vs. diesel P05 1073.8). In the LD urban class the diesel and BEV TCO distributions are nearly congruent (5.00 vs. 4.98 CNY/km), which is where the parity contest is genuinely unresolved.

The parity probabilities in Table 9 quantify that contest. The probability that FCEV(P6) undercuts BEV in the HD long-haul class is 0.0000 at zero carbon price on the national-average grid under the purchased-power base (region-mean 0.0003; at most 0.0017 in Northwest). It rises only to 0.0007 at 300 CNY/tCO_2 nationally (0.0049 at most, in the Northwest) and reaches 0.007 nationally at 1000 CNY/tCO_2 (0.046 in the North, the dirtiest BEV grid). In the LD urban class, no crossings are observed at any price up to 1000 CNY/tCO_2. These frequencies are counts out of 10,000 draws, so their resolution floor is 10^{-4}. Values below 10^{-3} rest on fewer than ten crossings (relative standard error of order 100%), and zero-count cells mean no crossings observed in 10,000 draws (approximate 95% upper bound 3×10^{-4}); the qualitative verdict therefore turns on the ≤0.1% order of magnitude, while the fourth decimal place carries no interpretive weight. Under the S0 specification, these probabilities would be roughly an order of magnitude larger (the deterministic gap shrinking from 3.22 to 2.11 CNY/km), but they remain below 2% at 1000 CNY/tCO_2. By contrast, the probability that BEV undercuts diesel rises with the carbon price wherever the BEV is cleaner—nationally from 0.162 at 100 CNY/tCO_2 to 0.234 at 1000 CNY/tCO_2, and to 0.352 in the South. In the North, it falls instead (from 0.157 at zero to 0.060 at 1000 CNY/tCO_2), because there the BEV is the dirtier option and carbon pricing penalizes it first. Convergence is adequate for these readings of the mean gap (not of the tail counts): the running mean of the HD FCEV(P6)–BEV per-t-km gap changed by 0.06% between 1000 and 10,000 draws (0.1180 to 0.1180 CNY/t-km).

3.7. Policy Implications: Regional Siting and Green-Hydrogen Certification

The certification arithmetic of Table 4 is decisive. The base-case delivered renewable-hydrogen carbon intensity is 6.6 $kgCO_2e/kg$ (production 3.5 $kgCO_2e/kg$ plus the 3.1 $kgCO_2e/kg$ gate-to-tank adder), spanning roughly 5.2–8.2 $kgCO_2e/kg$ across the sensitivity ranges of the production carbon intensity and the adder. Every value in that span exceeds the strict renewable-fuel thresholds of 3.38–4.4 $kgCO_2e/kg$ associated with the European delegated regulation [35,36]. The delivery adder, not production, decides eligibility: with the base adder of 3.1 $kgCO_2e/kg$, certification at 4.4 $kgCO_2e/kg$ would require a production carbon intensity at or below 1.3 $kgCO_2e/kg$, and at 3.38 $kgCO_2e/kg$ at or below 0.28 $kgCO_2e/kg$. Neither threshold is reachable within the 2.3–4.8 $kgCO_2e/kg$ literature band used here. The practical implication is to certify at the production gate and dispense close to the point of production; grid-electrolytic hydrogen is not a remedy. Qualification requires the grid factor itself to fall to the certification threshold divided by the electrolysis demand: at the 4.4 $kgCO_2e/kg$ threshold and the 52 kWh/kg specific consumption used here, the implied grid factor is about 85 gCO_2/kWh ($4.4/52 \times 1000$), and at 3.38 $kgCO_2e/kg$ about 65 gCO_2/kWh. The former falls within the roughly 83–99 gCO_2/kWh eligibility window quoted in [26,36], whose upper edge reflects the higher specific consumptions assumed there; the stricter 3.38 threshold would require a grid factor below that window. The regional operating-margin grid factors (0.44–0.75 $kgCO_2/kWh$, national average 0.5366 [4]) lie four to nine times above the qualification window.

The same tables support a two-regime siting rule. Under purchased power—the revised base—renewable electrolysis remains cheapest where capacity factors are highest (44.1 CNY/kg delivered in the Northwest against 46.2–53.7 CNY/kg elsewhere, Table 5), but it no longer undercuts the fossil cluster anywhere, and the least-cost clean supply is by-product hydrogen (P4, 33.0 CNY/kg) in every region; the producer-owned lower bound of Section 2.3 moves the renewable price down by 5.0–8.7 CNY/kg (35.4 CNY/kg in the Northwest on the PV anchor) without changing the ordering, because balance-of-system costs excluded there would push it back up. Under the S0 specification (zero purchase cost, bounded by the finite curtailment resource) the original ordering returns: 31.1 CNY/kg in the Northwest, undercutting every fossil route. Renewable production therefore belongs, in either regime, in the renewable-rich Northwest—the highest-full-load-hour setting modelled here (1950 h/year; Table 3)—with dispensing kept near the gate to preserve the certification outcome; whether the electricity is bought at the PPA price or self-generated on the component-cost floor, the FLH gradient favours the same siting. Hydro-rich southwestern provinces offer comparable resources in the literature but lie outside the seven modelled grid settings; extending the siting rule to them would require their own resource data. In the coal-dominated North grid, fleet electrification should wait for grid cleanup, because there the BEV's well-to-wheel intensity (1258.9 gCO_2e/km, HD long-haul) still exceeds the diesel's (1190.0). In the Northeast the BEV is about 11% cleaner per kilometre (1057.5 gCO_2e/km) and can be prioritized now for per-kilometre gains, but its advantage disappears per tonne-kilometre once the 0.85 payload ratio is applied (59.2 vs. 56.7 $gCO_2e/t\text{-}km$; robust down to $\kappa = 0.889$ per Section 3.6), so its full benefits there likewise await grid cleanup. In both grids, grid-electrolytic hydrogen is worst of all (tank-side 35.9–42.1 $kgCO_2e/kg$) [24]. Coal-hydrogen FCEVs, finally, are Pareto-dominated options and poor targets for support; by-product-hydrogen FCEVs tie diesel on carbon and lose on cost, so support should follow certified renewable supply, not the vehicle platform.

On instruments, the arithmetic narrows the credible menu. Extending emissions trading to transport fuels would internalize carbon at the 60–105 CNY/tCO_2 now observed [38], an order of magnitude below every finite p* in Table 7. A fuel-carbon-value-style rebate in the range of 0.02–1.19 CNY/kg [15] is worth at most about 0.10 CNY/km at the HD

consumption of 0.085 kg/km, under 3.5% of the 3.22 CNY/km FCEV(P6)–BEV gap under the purchased-power base (5% of the 2.11 CNY/km S0 gap). Rebate schemes of this design therefore cannot close the green-hydrogen cost gap on their own. Demonstration-city-cluster subsidies that reward verified fuel carbon intensity rather than vehicle capital cost alone, and that condition support on gate-certified supply sited in renewable-rich regions, follow directly from the joint cost–carbon structure reported here [3].

3.8. Comparison with Literature and Limitations of the Assessment

Benchmarked against Tables 5 and 7, the harmonized results sit within the published bands, with the electricity-purchase regime deciding which band edge applies. Under the purchased-power base, the Northwest renewable delivered cost of 44.1 CNY/kg corresponds to about 6.2 USD/kg—above the 3.6–4.8 USD/kg liftoff band for heavy-duty applications [10]—and the full renewable regional band of 5.3–6.5 EUR/kg (44.1–53.7 CNY/kg at 8.3 CNY/EUR, six deployment regions) clears the top of the 4–6 EUR/kg heavy-duty parity range [12]; under the S0 specification the same quantities (31.1 CNY/kg, 4.4 USD/kg, 3.75–4.90 EUR/kg) fall inside both bands. The overall delivered band of 33.0–54.3 CNY/kg in the base case (23.7–76.9 CNY/kg over the full literature ranges) is consistent with the Chinese pathway surveys that anchor it [20,21,23] when read under the boundary declaration of Section 2.3; most directly, the Asian Development Bank Institute's 2024 assessment of hydrogen-truck total cost of ownership in China [13] examines cost parity for fuel-cell trucks under Chinese price and policy settings, and the present pathway- and region-resolved matrix supplies the delivered-cost resolution that such national-level assessments abstract away. The TCO decomposition—fuel and capital dominance in the HD class, driver-cost weight in China—follows the structure of European heavy-duty studies [7,8]. The vehicle-level p* values exceed the 170–360 CNY/tCO2 production-side crossovers of [23] for the reasons given in Section 3.5; the comparison is a boundary check, not a contradiction.

The comparisons also carry an international reading, made explicit by a same-framework European scenario layer built entirely on the ICCT parameter set for the EU 5-LH 800 km class, model year 2023 [7] (Table 10): truck prices, energy prices, driver cost, maintenance, insurance, and the 9.5%/5-year financing of that study, mapped onto the present duty definition and coupling metrics. Even at the 2024 EU ETS average of about 540 CNY/tCO_2—several times the Chinese market band—carbon pricing alone would not close the vehicle-level cost gaps quantified here, since every positive finite p* of the Chinese matrix exceeds 681.7 CNY/tCO_2. In the European run, the Diesel→BEV break-even sits at roughly 420–770 EUR/tCO_2 (about 3.5–6.4 thousand CNY/tCO_2, depending on the grid factor bracket of 200–400 gCO_2/kWh assumed for the charging mix), above even the EU ETS2 price levels contemplated for road transport, and the BEV→FCEV(P6) transition lies effectively out of range at about 10,000 EUR/tCO_2—so the European ordering is strictly more carbon-price-demanding than the Chinese one, the mirror image of China's smaller vehicle-price premiums. Conversely, the certification arithmetic is stricter in Europe than in China today: the delivered renewable-hydrogen intensity of 6.6 kgCO_2e/kg exceeds the 3.38–4.4 kgCO_2e/kg RFNBO thresholds [35,36], making the gate-certification siting rule of Section 3.7 a prerequisite for standards-aligned supply in either market. While the parameterization is China-specific, the coupled framework and its ranking logic—pathway-resolved delivered cost crossed with region-resolved grid carbon intensity at the vehicle level, closed by break-even carbon prices and parity probabilities—are directly transferable, and the European layer demonstrates the transfer on a fully independent parameter set.

Several limitations should be acknowledged. First, the analysis is a literature-anchored parametric simulation, not a measurement study: all outputs derive from harmonized literature parameters, and the absolute values are indicative rather than definitive. Sec-

ond, the baseline is static at 2024 conditions; the 2030 layer is a labelled scenario construct that makes no forecast claim. Third, the operating-margin grid factors are annual averages rather than marginal factors, so the fleet-level consequences of added charging load are not captured [29,30]. Fourth, infrastructure enters only through energy prices, and range-constrained scheduling or corridor availability—which can cut off BEV duty feasibility [10]—is not modelled. Fifth, the LD FCEV consumption is scaled from heavy-duty data and carries low confidence. Sixth, the carbon price is flat, certification is assumed strict (additionality and time-matching are not modelled for China), the national-average reference rows carry widened ±10% Monte Carlo bands, and the per-t-km results inherit the utilization assumption (u = 0.7) together with the capacity-ratio distributions, whose literature anchor is strongest at its ends (0.67 heavy-BEV 2020 and 1.00 packaging parity [11]) and weakest at the 0.85 base, which sits above the 2020 heavy-truck band and within the medium-duty band of the same source. Seventh, the provincial tariff and renewable-FLH inputs of Table 3 are authors' compilations without per-province source documents; the P6 layer now prices purchased renewable electricity at the PPA band [26]—with the zero-purchase S0 scenario retained and bounded by the curtailment resource—while the producer-owned variant rests on component-cost anchors (module and turbine prices, no balance-of-system, no fixed O&M), so it is a declared lower bound rather than a full plant-side costing. Eighth, technology learning and cost-decline trajectories are not modelled: all cost parameters are frozen at their stated vintages, so beyond the labelled 2030 scenario layer no projected reductions in electrolyzer or vehicle costs are captured. Ninth, the European scenario layer inherits ICCT's parameter set wholesale—including its financing structure and its exclusion of road tolls—and brackets rather than resolves the EU charging-mix carbon intensity, so its break-evens are indicative of ordering, not forecasts. Tenth, the hydrogen delivery chain is costed as three literature-anchored per-kilogram adders (Section 2.3): compression and transport are lumped in a single term, the base case fixes the delivery distance at 200 km (the distance curve of Section 2.3 serves only as a sensitivity device), and the refuelling adder carries no station-capacity or utilization dependence; mode-differentiated delivery modelling (tube-trailer, liquid, pipeline corridors) remains future work (Section 4.3).

Table 10. European scenario layer (HD long-haul duty, ICCT 5-LH 800 km class, model year 2023 [7]; 9.5% discount, 5-year holding, ICCT residual schedule; road tolls excluded; driver cost mapped at the manuscript's duty speed; EU charging-mix carbon intensity bracketed at 200–400 gCO_2/kWh).

Quantity	Diesel	BEV	FCEV (Green H_2)
Retail price [EUR]	176,000	457,000	675,000
Energy price	1.22 EUR/L	0.20 EUR/kWh	10.30 EUR/kg
Consumption (per 100 km)	30.7 L	141 kWh	8.41 kg
TCO [EUR/km]	1.19	1.49	2.47
TCO premium vs. diesel	—	+25.5%	+107.7%
WTW CI [gCO_2e/km]	1044	326–653 (grid bracket)	555

4. Conclusions

4.1. Main Findings

This study couples six literature-anchored hydrogen pathways with seven regional grid settings, two vehicle classes, and three powertrains in a parametric simulation of total cost of ownership and well-to-wheel carbon intensity. Cost and carbon are reported side by side throughout, because the two do not always agree. All carbon results reported below are operational fuel-chain well-to-wheel (WTW) emissions—the well-to-tank fuel chain plus tank-to-wheel conversion—and exclude vehicle manufacturing, battery production, and other cradle-to-grave items (Section 2.1); they should therefore be read as fuel-cycle comparisons rather than cradle-to-grave life-cycle assessments.

1. Delivered hydrogen costs span 33.0–54.3 CNY/kg in the purchased-power base case (31.1–54.3 under the zero-purchase S0 scenario), and the driver is pathway-specific: the tariff–consumption product for grid electrolysis (P5), full-load hours and the purchased-power term for renewable electrolysis (P6), and production anchors plus the shared delivery chain for fossil and by-product routes P1–P4 (Section 3.1). By contrast, the FCEV–BEV cost gap is driven from the vehicle side, and the BEV charging-tariff sweep alone moves the HD gap by 33.8% (Section 3.6).
2. In total cost of ownership, the HD long-haul BEV undercuts diesel by 11.5% (4.70 vs. 5.31 CNY/km), while the green-hydrogen FCEV at national-average supply carries a 49.1% premium under purchased power (28.3% under S0). The BEV advantage reverses once costs are normalized per tonne-kilometre—a reversal governed by a single break-even condition on the capacity ratio (approximately 0.885)—and the LD urban FCEV premium reaches 67.3% (Section 3.2).
3. In well-to-wheel carbon intensity, renewable-hydrogen FCEVs (561 gCO_2e/km, HD) beat the national-average BEV (900.7 gCO_2e/km) and diesel (1190.0 gCO_2e/km). Grid-electrolytic hydrogen, by contrast, reaches 3578 gCO_2e/km on the coal-heavy North grid, so the regionally resolved grid factor rather than the national average decides whether hydrogen logistics decarbonizes at all (Section 3.3).
4. The Pareto structure is regional. BEVs are non-dominated on cleaner grids once payload penalties are counted, green-hydrogen FCEVs hold a low-carbon, high-cost frontier position, and coal- and grid-hydrogen FCEVs are dominated on both axes in nearly all regions (Section 3.4).
5. Critical carbon prices sit an order of magnitude or more above current Chinese market prices: of the 112 evaluated pairings, 8 cross within the 0–3000 CNY/tCO_2 reporting interval (681.7–2936.4 CNY/tCO_2), 7 are already dominant ($p^* = 0$), 46 return no crossing, and 51 cross beyond the bound, against a market band of 60–105 CNY/tCO_2 (Section 3.5)—the maximum crossing exceeds the band's top roughly 28-fold. Simulated green-hydrogen cost-parity probabilities at 100 CNY/tCO_2 stay at or below 0.3% even in the most favourable region (Northwest), and the S0-to-base move in the P6 electricity price alone pushes every S0 finite BEV → FCEV crossing except the two North-grid ones beyond the bound (Section 3.6). A same-framework European layer on the ICCT parameter set shows the EU ordering to be strictly more carbon-price-demanding still, with Diesel → BEV break-evens near 3.5–6.4 thousand CNY/tCO_2 (Section 3.8).
6. Certification eligibility is decided at delivery rather than production: the delivered renewable-hydrogen carbon intensity of 6.6 $kgCO_2e$/kg exceeds the 3.38–4.4 $kgCO_2e$/kg thresholds, so supply should be gate-certified, sited in the renewable-rich Northwest under purchased-power or dedicated-supply contracts, and dispensed near production. On the coal-heavy grids, BEV electrification should be prioritized only where it is genuinely cleaner, which today means per kilometre in the Northeast and not until grid cleanup in the North (Section 3.7).

4.2. Limitations

These conclusions are bounded by the limitations set out in Section 3.8 and claim no new evidence beyond them. The outputs are simulation results rather than measurements. It must be emphasized that all carbon intensities in this study are operational fuel-chain WTW emissions excluding vehicle manufacturing; comparisons with cradle-to-grave life-cycle studies require first adding embodied terms such as battery manufacturing (150–200 $kgCO_2e$/kWh [9]). The baseline is static at 2024 conditions, the 2030 layer is a scenario construct, and the operating-margin grid factors are averages rather than

marginals. Infrastructure enters only through energy prices. The provincial tariff and full-load-hour inputs of Table 3 are the authors' compilations. The P6 layer prices renewable electricity at the purchased-power band, with the zero-purchase S0 scenario retained as a bounded counterfactual and the producer-owned variant a component-cost lower bound (Sections 2.3 and 3.6). The absolute values remain indicative rather than definitive.

4.3. Future Work

Future work should proceed along six lines: spatial co-optimization of charging and refuelling infrastructure with duty scheduling; full network-level modelling of the hydrogen delivery chain—mode-differentiated transport (tube-trailer, liquid, pipeline corridors), boil-off and seasonal storage, and station-utilization endogeneity—replacing the adder-based treatment of Section 2.3; learning-curve projections to 2035–2040 with endogenous station networks; marginal, hourly matched grid emission factors; integration of transport fuels into emissions-trading pilots, with subsidies conditioned on verified carbon intensity; and replacement of the literature anchors with measured fleet data as the demonstration city clusters mature.

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Conflicts of Interest: The author declares no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

Abbreviation	Expansion
ACC	carbon-internalized average cost
BEV	battery electric vehicle
CEA	China carbon emissions (allowance) market
CI	carbon intensity
CO_2e	carbon dioxide equivalent
CRF	capital recovery factor
EF	emission factor
FCCV	fuel carbon value
FCEV	fuel cell electric vehicle
FLH	full-load hours
GCW	gross combination weight
G2T	gate-to-tank
HD	heavy duty
HHV	higher heating value
HRS	hydrogen refuelling station
LD	light duty
LCOH	levelized cost of hydrogen
LHV	lower heating value
MC	Monte Carlo
OAT	one-at-a-time (sensitivity analysis)
O&M	operation and maintenance
RFNBO	renewable fuel of non-biological origin
SEC	specific electricity consumption
TCO	total cost of ownership
WTT	well-to-tank
WTW	well-to-wheel

Appendix A. Harmonized Parameter Inventory

Table A1 consolidates the central values, ranges, sources, and vintages of every parameter used in the simulation into a single inventory, harmonized across Tables 1–4 and the running text. All monetary values are CNY2024 unless noted, and all grid factors are the 2022 operating-margin values published in 2024 [4].

Table A1. Consolidated harmonized parameter inventory (base [low-high]).

Group	Parameter	Unit	Base [Low-High]	Source	Vintage/Note
Energy basis	H_2 LHV	kWh/kg; MJ/kg	33.33; 120.0 (fixed)	declared	LHV basis; the 140.4 MJ/kg HHV of [20] rejected (L1)
Energy basis	Diesel LHV	MJ/kg; MJ/L; kWh/L	42.6; 35.4; 9.84 (fixed)	declared	at rho 0.832 kg/L
Energy basis	FX	CNY/EUR; CNY/USD	8.3; 7.0 (literature)/7.1 (2024 markers)	declared	year-tagged (L7)
Vehicle	HD purchase price (diesel/BEV/FCEV)	10^4 CNY	40/95/125 [35–48/75–120/95–160]	[40]	catalogue-consistent, CNY2024; medium confidence
Vehicle	LD purchase price (diesel/BEV/FCEV)	10^4 CNY	12/23/65 [10–14/18–28/50–85]	[40]	catalogue-consistent, CNY2024
Vehicle	HD consumption (diesel/BEV/FCEV)	L, kWh, kg-H_2 per km	0.35/1.45/0.085 [0.32–0.38/1.3–1.6/0.075–0.095]	[40]; authors' harmonization	China 49 t fleet, EU values not transplanted (L8)
Vehicle	LD consumption (diesel/BEV/FCEV)	L, kWh, kg-H_2 per km	0.13/0.42/0.030 [0.11–0.15/0.36–0.48/0.025–0.035]	[40]	LD FCEV-scaled, low confidence (L15)
Vehicle	Maintenance (HD diesel/BEV/FCEV)	CNY/km	1.30/0.95/1.25 (fixed)	authors' re-estimation [7,8,18]	LD: 0.55/0.38/0.50 CNY/km
Vehicle	Driver cost (HD/LD)	CNY/year	150,000/80,000 [130,000–170,000/70,000–90,000]	authors' re-estimation [7,18,39]	incl. social charges (L20)
Vehicle	Insurance rate (HD/LD)	%/year of price	4.0/3.5 (fixed)	authors' re-estimation [7,18,39]	(L20)
Vehicle	Other fixed (HD/LD)	CNY/year	8000/4000 (fixed)	authors' assumption	inspection/parking/admin
Vehicle	Residual share	fraction of price	0.2 [0.15–0.25]	authors' re-estimation [7,8]	end of life
Vehicle	HD BEV battery replacement	CNY at year 6	180,000 [140,000–230,000]	authors' assumption [7]	LD: none (warranty)
Vehicle	FC system share/stack trigger/stack cost	fraction; h; fraction	0.35 [0.3–0.4]; 15,000; 0.3 (fixed)	authors' assumption [7,8]	HD triggers at yr 6.6–7.5; LD beyond life
Vehicle	Lifetime (HD/LD)	year	8/10 (fixed)	authors' assumption	discount r = 7% [5–12%] [11,12]
Vehicle	Payload basis (HD/LD); capacity ratio BEV; FCEV	t; fraction	30/1.8; BEV 0.85 HD [0.67–0.95]/0.90 LD [0.80–1.00]; FCEV 0.96 HD [0.92–1.00]/0.97 LD [0.93–1.00]	[11]; heavy-BEV 2020 multiplier 0.67 and FCV 0.96 per [11]; packaging-parity upper bounds; [41] payload-normalization concept	(L18); swept in OAT and MC
Duty	LD urban/LD regional/HD regional/HD long-haul	km/year at km/h	30,000 @30; 60,000 @50; 100,000 @50; 160,000 @70	scenario definition	utilization u = 0.7 [0.6–0.8] [11]
H_2 production	P1 coal gasification	CNY/kg	11 [7.2–17.2]	[20]	production gate
H_2 production	P2 coal + CCS (80%)	CNY/kg	15 [11.2–19.4]	[21,22]	production gate
H_2 production	P3 SMR	CNY/kg	12.5 [9.1–25.2]	[21,23]	production gate
H_2 production	P4 by-product	CNY/kg	11 [8.0–15.1]	[21,22]	production gate
H_2 production	P5 industrial tariff (regional; National average)	CNY/kWh	0.43–0.66; 0.60 (National average)	provincial catalogue/trading	2024 (Table 3)
H_2 production	P6 electrolyzer CAPEX	CNY/kW	3500 [2800–4500]	authors' assumption [26]	2024 alkaline system
H_2 production	P6 fixed O&M; life; r	%/year; yr; %	2.5; 20; 7 (fixed)	authors' assumption	

Table A1. *Cont.*

Group	Parameter	Unit	Base [Low-High]	Source	Vintage/Note
H_2 production	P6 producer-owned plant (component anchors)	USD/kW	PV module 240; wind turbine 400; life 20 yr; O&M not reported	[25] (IEA/IEEFA basis)	declared lower bound; no BoS
H_2 production	P6 electricity purchase price (PPA)	CNY/kWh	0.25 [0.20–0.31]	[26]; dominance 53.7–68.7% [21]	base case; S0 = 0
H_2 production	SEC alkaline electrolyzer (LHV)	kWh/kg	52 [50–55]	authors' harmonization [23,24]	implied efficiency 64.1%
H_2 production	Renewable FLH (regional base; range)	h/year	1050–1950; 900–2400	CABEE/IRENA wind+PV blend	Table 3; National average 1400 [1260–1540]
H_2 delivery	Purification adder (P1-P4)	CNY/kg	2.0 [1.5–2.5]	[21]	PSA to GB/T 37244
H_2 delivery	Compression + transport (200 km)	CNY/kg	10 [7–12,16,17]	[22]	distance curve 7 + 0.015 × (d − 100), d in [100, 800] km
H_2 delivery	Refuelling station adder	CNY/kg	10 [8–12,17]	[25]	
H_2 delivery	H_2 market anchor (comparison band only)	CNY/kg	35–40 (not swept)	[14]	2024 dispenser anchor band (L11)
Carbon	Grid EF (regional; National average)	$kgCO_2$/kWh	0.44–0.75; 0.5366	[4]	MEE operating margin, 2022 (pub. 2024)
Carbon	Pathway production CI (P1/P2/P3/P4/P6)	$kgCO_2e$/kg	22.8/11.8/11.5/10.9/3.5 [20–25/10.6–13.1/9–14/8–13/2.3–4.8]	[24–26,34]	WTT-WTW basis (L4); P4 economic allocation; P3 CH_4-leakage band (L5)
Carbon	Gate-to-tank CI adder	$kgCO_2e$/kg	3.1 [2.9–3.4]	[25]	transmission, compression, refuelling
Carbon	Diesel WTW EF (derived)	$kgCO_2e$/L	3.4 [3.1–3.7]	derived [10,17,42]	combustion 2.66–2.68 + declared upstream uplift 0.44–1.0 $kgCO_2e$/L (Section 2.5) (L19)
Carbon	Electricity T&D/charging loss	fraction	0.065 [0.05–0.08]; 0.08 [0.05–0.15]	[27,29]	BEV chain
Energy price	Diesel retail 0# VAT incl.	CNY/L	7.3 [6.8–8.0]	[5]	NDRC notices 2023–2024
Energy price	BEV charging tariff (incl. service)	CNY/kWh	1.05 [0.75–1.50]	[6]	depot/mixed
Policy	China carbon market (2024)	CNY/tCO_2	60–105	[38]	EU ETS 2024 marker approx. 540 CNY/tCO_2; FCCV 0.02-1.19 CNY/kg [15]
Scenario	2030 outlook	-	HD BEV 750,000; HD FCEV 950,000; LD FCEV 450,000 CNY; electrolyzer 2800 CNY/kW; grid EF × 0.80	scenario layer	clearly labelled, not a forecast
Monte Carlo	Draws; seed; distributions	-	10,000 LHS; 20240924; triangular/uniform/truncated-normal	Section 2.7	common random numbers; National average +/−10% bands

Appendix B. Full Critical-Carbon-Price Matrix

Table A2 reports the complete 112-combination p* matrix underlying the condensed results of Table 7 in the main text.

Table A2. Full critical-carbon-price matrix p* (CNY/tCO_2) by class, duty scenario, region, and pair (112 combinations), evaluated on the per-tonne-kilometre basis of Equation (15). p* status: "already dominant (p* = 0)" = the target is already cheaper and cleaner per tonne-kilometre, so no carbon price is needed; "finite" = a positive crossing within the reporting bound; "n/a" = the target option is not cleaner than the source per tonne-kilometre; ">3000" = the crossing lies beyond the 3000 CNY/tCO_2 reporting bound (labelled, not censored). Note on units: p* is evaluated on per-tonne-kilometre carbon intensities, CI_tkm = CI_km/(payload basis × powertrain capacity ratio × u = 0.7)—e.g., HD diesel 1190/21 = 56.7 gCO_2e/t-km—and the per-t-km CI columns are deposited as ci_clean_t_per_tkm and ci_dirty_t_per_tkm in t7_pstar_matrix.csv; recomputing p* from the printed per-kilometre CI columns without this normalization reproduces the wrong basis (the unit trap of Section 2.6). For typesetting, this table renders in landscape.

Class	Duty Scenario	Region	Pair (Source → Target)	Target Option	Source Option	TCO Target [CNY/km]	TCO Source [CNY/km]	WTW CI Target [gCO_2e/km]	WTW CI Source [gCO_2e/km]	TCO Target [CNY/t-km]	TCO Source [CNY/t-km]	p* [CNY/tCO_2]	p* Status
LD	LD urban	North	Diesel → BEV	BEV	Diesel	4.8699	4.9506	364.6	442.0	4.2945	3.9291	>3000	>3000
LD	LD urban	North	Diesel → FCEV (best)	FCEV (best)	Diesel	7.8195	4.9506	420.0	442.0	6.3979	3.9291	>3000	>3000
LD	LD urban	North	BEV → FCEV (P6)	FCEV (P6)	BEV	8.2541	4.8699	198.0	364.6	6.7535	4.2945	>3000	>3000
LD	LD urban	North	FCEV (P6) → BEV	BEV	FCEV (P6)	4.8699	8.2541	364.6	198.0	4.2945	6.7535	—	n/a
LD	LD urban	Northeast	Diesel → BEV	BEV	Diesel	4.8699	4.9506	306.3	442.0	4.2945	3.9291	>3000	>3000
LD	LD urban	Northeast	Diesel → FCEV (best)	FCEV (best)	Diesel	7.8195	4.9506	420.0	442.0	6.3979	3.9291	>3000	>3000
LD	LD urban	Northeast	BEV → FCEV (P6)	FCEV (P6)	BEV	8.2146	4.8699	198.0	306.3	6.7212	4.2945	>3000	>3000
LD	LD urban	Northeast	FCEV (P6) → BEV	BEV	FCEV (P6)	4.8699	8.2146	306.3	198.0	4.2945	6.7212	—	n/a
LD	LD urban	East	Diesel → BEV	BEV	Diesel	4.8699	4.9506	282.0	442.0	4.2945	3.9291	>3000	>3000
LD	LD urban	East	Diesel → FCEV (best)	FCEV (best)	Diesel	7.8195	4.9506	420.0	442.0	6.3979	3.9291	>3000	>3000
LD	LD urban	East	BEV → FCEV (P6)	FCEV (P6)	BEV	8.4122	4.8699	198.0	282.0	6.8828	4.2945	>3000	>3000
LD	LD urban	East	FCEV (P6) → BEV	BEV	FCEV (P6)	4.8699	8.4122	282.0	198.0	4.2945	6.8828	—	n/a
LD	LD urban	Central	Diesel → BEV	BEV	Diesel	4.8699	4.9506	228.5	442.0	4.2945	3.9291	2447.7	finite
LD	LD urban	Central	Diesel → FCEV (best)	FCEV (best)	Diesel	7.8195	4.9506	420.0	442.0	6.3979	3.9291	>3000	>3000
LD	LD urban	Central	BEV → FCEV (P6)	FCEV (P6)	BEV	8.4404	4.8699	198.0	228.5	6.9059	4.2945	>3000	>3000
LD	LD urban	Central	FCEV (P6) → BEV	BEV	FCEV (P6)	4.8699	8.4404	228.5	198.0	4.2945	6.9059	—	n/a
LD	LD urban	Northwest	Diesel → BEV	BEV	Diesel	4.8699	4.9506	277.1	442.0	4.2945	3.9291	>3000	>3000
LD	LD urban	Northwest	Diesel → FCEV (best)	FCEV (best)	Diesel	7.8195	4.9506	420.0	442.0	6.3979	3.9291	>3000	>3000
LD	LD urban	Northwest	BEV → FCEV (P6)	FCEV (P6)	BEV	8.1538	4.8699	198.0	277.1	6.6714	4.2945	>3000	>3000
LD	LD urban	Northwest	FCEV (P6) → BEV	BEV	FCEV (P6)	4.8699	8.1538	277.1	198.0	4.2945	6.6714	—	n/a
LD	LD urban	South	Diesel → BEV	BEV	Diesel	4.8699	4.9506	213.9	442.0	4.2945	3.9291	2253.5	finite
LD	LD urban	South	Diesel → FCEV (best)	FCEV (best)	Diesel	7.8195	4.9506	420.0	442.0	6.3979	3.9291	>3000	>3000
LD	LD urban	South	BEV → FCEV (P6)	FCEV (P6)	BEV	8.3864	4.8699	198.0	213.9	6.8617	4.2945	>3000	>3000
LD	LD urban	South	FCEV (P6) → BEV	BEV	FCEV (P6)	4.8699	8.3864	213.9	198.0	4.2945	6.8617	—	n/a

Table A2. *Cont.*

Class	Duty Scenario	Region	Pair (Source → Target)	Target Option	Source Option	TCO Target [CNY/km]	TCO Source [CNY/km]	WTW CI Target [gCO_2e/km]	WTW CI Source [gCO_2e/km]	TCO Target [CNY/t-km]	TCO Source [CNY/t-km]	p* [CNY/tCO_2]	p* Status
LD	LD urban	National average	Diesel → BEV	BEV	Diesel	4.8699	4.9506	260.9	442.0	4.2945	3.9291	>3000	>3000
LD	LD urban	National average	Diesel → FCEV (best)	FCEV (best)	Diesel	7.8195	4.9506	420.0	442.0	6.3979	3.9291	>3000	>3000
LD	LD urban	National average	BEV → FCEV (P6)	FCEV (P6)	BEV	8.2852	4.8699	198.0	260.9	6.7789	4.2945	>3000	>3000
LD	LD urban	National average	FCEV (P6) → BEV	BEV	FCEV (P6)	4.8699	8.2852	260.9	198.0	4.2945	6.7789	—	n/a
LD	LD regional	North	Diesel → BEV	BEV	Diesel	2.8455	3.2248	364.6	442.0	2.5092	2.5594	0	already dominant (p* = 0)
LD	LD regional	North	Diesel → FCEV (best)	FCEV (best)	Diesel	4.6548	3.2248	420.0	442.0	3.8085	2.5594	>3000	>3000
LD	LD regional	North	BEV → FCEV (P6)	FCEV (P6)	BEV	5.0894	2.8455	198.0	364.6	4.1641	2.5092	>3000	>3000
LD	LD regional	North	FCEV (P6) → BEV	BEV	FCEV (P6)	2.8455	5.0894	364.6	198.0	2.5092	4.1641	—	n/a
LD	LD regional	Northeast	Diesel → BEV	BEV	Diesel	2.8455	3.2248	306.3	442.0	2.5092	2.5594	0	already dominant (p* = 0)
LD	LD regional	Northeast	Diesel → FCEV (best)	FCEV (best)	Diesel	4.6548	3.2248	420.0	442.0	3.8085	2.5594	>3000	>3000
LD	LD regional	Northeast	BEV → FCEV (P6)	FCEV (P6)	BEV	5.0499	2.8455	198.0	306.3	4.1318	2.5092	>3000	>3000
LD	LD regional	Northeast	FCEV (P6) → BEV	BEV	FCEV (P6)	2.8455	5.0499	306.3	198.0	2.5092	4.1318	—	n/a
LD	LD regional	East	Diesel → BEV	BEV	Diesel	2.8455	3.2248	282.0	442.0	2.5092	2.5594	0	already dominant (p* = 0)
LD	LD regional	East	Diesel → FCEV (best)	FCEV (best)	Diesel	4.6548	3.2248	420.0	442.0	3.8085	2.5594	>3000	>3000
LD	LD regional	East	BEV → FCEV (P6)	FCEV (P6)	BEV	5.2474	2.8455	198.0	282.0	4.2934	2.5092	>3000	>3000
LD	LD regional	East	FCEV (P6) → BEV	BEV	FCEV (P6)	2.8455	5.2474	282.0	198.0	2.5092	4.2934	—	n/a
LD	LD regional	Central	Diesel → BEV	BEV	Diesel	2.8455	3.2248	228.5	442.0	2.5092	2.5594	0	already dominant (p* = 0)

Table A2. *Cont.*

Class	Duty Scenario	Region	Pair (Source → Target)	Target Option	Source Option	TCO Target [CNY/km]	TCO Source [CNY/km]	WTW CI Target [gCO_2e/km]	WTW CI Source [gCO_2e/km]	TCO Target [CNY/t-km]	TCO Source [CNY/t-km]	p* [CNY/tCO_2]	p* Status
LD	LD regional	Central	Diesel → FCEV (best)	FCEV (best)	Diesel	4.6548	3.2248	420.0	442.0	3.8085	2.5594	>3000	>3000
LD	LD regional	Central	BEV → FCEV (P6)	FCEV (P6)	BEV	5.2756	2.8455	198.0	228.5	4.3165	2.5092	>3000	>3000
LD	LD regional	Central	FCEV (P6) → BEV	BEV	FCEV (P6)	2.8455	5.2756	228.5	198.0	2.5092	4.3165	—	n/a
LD	LD regional	Northwest	Diesel → BEV	BEV	Diesel	2.8455	3.2248	277.1	442.0	2.5092	2.5594	0	already dominant (p* = 0)
LD	LD regional	Northwest	Diesel → FCEV (best)	FCEV (best)	Diesel	4.6548	3.2248	420.0	442.0	3.8085	2.5594	>3000	>3000
LD	LD regional	Northwest	BEV → FCEV (P6)	FCEV (P6)	BEV	4.9891	2.8455	198.0	277.1	4.0820	2.5092	>3000	>3000
LD	LD regional	Northwest	FCEV (P6) → BEV	BEV	FCEV (P6)	2.8455	4.9891	277.1	198.0	2.5092	4.0820	—	n/a
LD	LD regional	South	Diesel → BEV	BEV	Diesel	2.8455	3.2248	213.9	442.0	2.5092	2.5594	0	already dominant (p* = 0)
LD	LD regional	South	Diesel → FCEV (best)	FCEV (best)	Diesel	4.6548	3.2248	420.0	442.0	3.8085	2.5594	>3000	>3000
LD	LD regional	South	BEV → FCEV (P6)	FCEV (P6)	BEV	5.2216	2.8455	198.0	213.9	4.2723	2.5092	>3000	>3000
LD	LD regional	South	FCEV (P6) → BEV	BEV	FCEV (P6)	2.8455	5.2216	213.9	198.0	2.5092	4.2723	—	n/a
LD	LD regional	National average	Diesel → BEV	BEV	Diesel	2.8455	3.2248	260.9	442.0	2.5092	2.5594	0	already dominant (p* = 0)
LD	LD regional	National average	Diesel → FCEV (best)	FCEV (best)	Diesel	4.6548	3.2248	420.0	442.0	3.8085	2.5594	>3000	>3000
LD	LD regional	National average	BEV → FCEV (P6)	FCEV (P6)	BEV	5.1204	2.8455	198.0	260.9	4.1895	2.5092	>3000	>3000
LD	LD regional	National average	FCEV (P6) → BEV	BEV	FCEV (P6)	2.8455	5.1204	260.9	198.0	2.5092	4.1895	—	n/a
HD	HD regional	North	Diesel → BEV	BEV	Diesel	6.0391	6.1869	1258.9	1190.0	0.3383	0.2946	—	n/a
HD	HD regional	North	Diesel → FCEV (best)	FCEV (best)	Diesel	8.1170	6.1869	1190.0	1190.0	0.4026	0.2946	—	n/a

Table A2. *Cont.*

Class	Duty Scenario	Region	Pair (Source → Target)	Target Option	Source Option	TCO Target [CNY/km]	TCO Source [CNY/km]	WTW CI Target [gCO_2e/km]	WTW CI Source [gCO_2e/km]	TCO Target [CNY/t-km]	TCO Source [CNY/t-km]	p* [CNY/tCO_2]	p* Status
HD	HD regional	North	BEV → FCEV (P6)	FCEV (P6)	BEV	9.3483	6.0391	561.0	1258.9	0.4637	0.3383	2936.4	finite
HD	HD regional	North	FCEV (P6) → BEV	BEV	FCEV (P6)	6.0391	9.3483	1258.9	561.0	0.3383	0.4637	—	n/a
HD	HD regional	Northeast	Diesel → BEV	BEV	Diesel	6.0391	6.1869	1057.5	1190.0	0.3383	0.2946	—	n/a
HD	HD regional	Northeast	Diesel → FCEV (best)	FCEV (best)	Diesel	8.1170	6.1869	1190.0	1190.0	0.4026	0.2946	—	n/a
HD	HD regional	Northeast	BEV → FCEV (P6)	FCEV (P6)	BEV	9.2364	6.0391	561.0	1057.5	0.4582	0.3383	>3000	>3000
HD	HD regional	Northeast	FCEV (P6) → BEV	BEV	FCEV (P6)	6.0391	9.2364	1057.5	561.0	0.3383	0.4582	—	n/a
HD	HD regional	East	Diesel → BEV	BEV	Diesel	6.0391	6.1869	973.5	1190.0	0.3383	0.2946	>3000	>3000
HD	HD regional	East	Diesel → FCEV (best)	FCEV (best)	Diesel	8.1170	6.1869	1190.0	1190.0	0.4026	0.2946	—	n/a
HD	HD regional	East	BEV → FCEV (P6)	FCEV (P6)	BEV	9.7961	6.0391	561.0	973.5	0.4859	0.3383	>3000	>3000
HD	HD regional	East	FCEV (P6) → BEV	BEV	FCEV (P6)	6.0391	9.7961	973.5	561.0	0.3383	0.4859	—	n/a
HD	HD regional	Central	Diesel → BEV	BEV	Diesel	6.0391	6.1869	788.9	1190.0	0.3383	0.2946	>3000	>3000
HD	HD regional	Central	Diesel → FCEV (best)	FCEV (best)	Diesel	8.1170	6.1869	1190.0	1190.0	0.4026	0.2946	—	n/a
HD	HD regional	Central	BEV → FCEV (P6)	FCEV (P6)	BEV	9.8761	6.0391	561.0	788.9	0.4899	0.3383	>3000	>3000
HD	HD regional	Central	FCEV (P6) → BEV	BEV	FCEV (P6)	6.0391	9.8761	788.9	561.0	0.3383	0.4899	—	n/a
HD	HD regional	Northwest	Diesel → BEV	BEV	Diesel	6.0391	6.1869	956.8	1190.0	0.3383	0.2946	>3000	>3000
HD	HD regional	Northwest	Diesel → FCEV (best)	FCEV (best)	Diesel	8.1170	6.1869	1190.0	1190.0	0.4026	0.2946	—	n/a
HD	HD regional	Northwest	BEV → FCEV (P6)	FCEV (P6)	BEV	9.0642	6.0391	561.0	956.8	0.4496	0.3383	>3000	>3000
HD	HD regional	Northwest	FCEV (P6) → BEV	BEV	FCEV (P6)	6.0391	9.0642	956.8	561.0	0.3383	0.4496	—	n/a

Table A2. *Cont.*

Class	Duty Scenario	Region	Pair (Source → Target)	Target Option	Source Option	TCO Target [CNY/km]	TCO Source [CNY/km]	WTW CI Target [gCO_2e/km]	WTW CI Source [gCO_2e/km]	TCO Target [CNY/t-km]	TCO Source [CNY/t-km]	p* [CNY/tCO_2]	p* Status
HD	HD regional	South	Diesel → BEV	BEV	Diesel	6.0391	6.1869	738.5	1190.0	0.3383	0.2946	2858.7	finite
HD	HD regional	South	Diesel → FCEV (best)	FCEV (best)	Diesel	8.1170	6.1869	1190.0	1190.0	0.4026	0.2946	—	n/a
HD	HD regional	South	BEV → FCEV (P6)	FCEV (P6)	BEV	9.7231	6.0391	561.0	738.5	0.4823	0.3383	>3000	>3000
HD	HD regional	South	FCEV (P6) → BEV	BEV	FCEV (P6)	6.0391	9.7231	738.5	561.0	0.3383	0.4823	—	n/a
HD	HD regional	National average	Diesel → BEV	BEV	Diesel	6.0391	6.1869	900.7	1190.0	0.3383	0.2946	>3000	>3000
HD	HD regional	National average	Diesel → FCEV (best)	FCEV (best)	Diesel	8.1170	6.1869	1190.0	1190.0	0.4026	0.2946	—	n/a
HD	HD regional	National average	BEV → FCEV (P6)	FCEV (P6)	BEV	9.4363	6.0391	561.0	900.7	0.4681	0.3383	>3000	>3000
HD	HD regional	National average	FCEV (P6) → BEV	BEV	FCEV (P6)	6.0391	9.4363	900.7	561.0	0.3383	0.4681	—	n/a
HD	HD long-haul	North	Diesel → BEV	BEV	Diesel	4.7016	5.3124	1258.9	1190.0	0.2634	0.2530	—	n/a
HD	HD long-haul	North	Diesel → FCEV (best)	FCEV (best)	Diesel	6.5992	5.3124	1190.0	1190.0	0.3273	0.2530	—	n/a
HD	HD long-haul	North	BEV → FCEV (P6)	FCEV (P6)	BEV	7.8305	4.7016	561.0	1258.9	0.3884	0.2634	2927.9	finite
HD	HD long-haul	North	FCEV (P6) → BEV	BEV	FCEV (P6)	4.7016	7.8305	1258.9	561.0	0.2634	0.3884	—	n/a
HD	HD long-haul	Northeast	Diesel → BEV	BEV	Diesel	4.7016	5.3124	1057.5	1190.0	0.2634	0.2530	—	n/a
HD	HD long-haul	Northeast	Diesel → FCEV (best)	FCEV (best)	Diesel	6.5992	5.3124	1190.0	1190.0	0.3273	0.2530	—	n/a
HD	HD long-haul	Northeast	BEV → FCEV (P6)	FCEV (P6)	BEV	7.7186	4.7016	561.0	1057.5	0.3829	0.2634	>3000	>3000
HD	HD long-haul	Northeast	FCEV (P6) → BEV	BEV	FCEV (P6)	4.7016	7.7186	1057.5	561.0	0.2634	0.3829	—	n/a
HD	HD long-haul	East	Diesel → BEV	BEV	Diesel	4.7016	5.3124	973.5	1190.0	0.2634	0.2530	>3000	>3000
HD	HD long-haul	East	Diesel → FCEV (best)	FCEV (best)	Diesel	6.5992	5.3124	1190.0	1190.0	0.3273	0.2530	—	n/a

Table A2. *Cont.*

Class	Duty Scenario	Region	Pair (Source → Target)	Target Option	Source Option	TCO Target [CNY/km]	TCO Source [CNY/km]	WTW CI Target [gCO_2e/km]	WTW CI Source [gCO_2e/km]	TCO Target [CNY/t-km]	TCO Source [CNY/t-km]	p* [CNY/tCO_2]	p* Status
HD	HD long-haul	East	BEV → FCEV (P6)	FCEV (P6)	BEV	8.2783	4.7016	561.0	973.5	0.4106	0.2634	>3000	>3000
HD	HD long-haul	East	FCEV (P6) → BEV	BEV	FCEV (P6)	4.7016	8.2783	973.5	561.0	0.2634	0.4106	—	n/a
HD	HD long-haul	Central	Diesel → BEV	BEV	Diesel	4.7016	5.3124	788.9	1190.0	0.2634	0.2530	835.9	finite
HD	HD long-haul	Central	Diesel → FCEV (best)	FCEV (best)	Diesel	6.5992	5.3124	1190.0	1190.0	0.3273	0.2530	—	n/a
HD	HD long-haul	Central	BEV → FCEV (P6)	FCEV (P6)	BEV	8.3582	4.7016	561.0	788.9	0.4146	0.2634	>3000	>3000
HD	HD long-haul	Central	FCEV (P6) → BEV	BEV	FCEV (P6)	4.7016	8.3582	788.9	561.0	0.2634	0.4146	—	n/a
HD	HD long-haul	Northwest	Diesel → BEV	BEV	Diesel	4.7016	5.3124	956.8	1190.0	0.2634	0.2530	>3000	>3000
HD	HD long-haul	Northwest	Diesel → FCEV (best)	FCEV (best)	Diesel	6.5992	5.3124	1190.0	1190.0	0.3273	0.2530	—	n/a
HD	HD long-haul	Northwest	BEV → FCEV (P6)	FCEV (P6)	BEV	7.5464	4.7016	561.0	956.8	0.3743	0.2634	>3000	>3000
HD	HD long-haul	Northwest	FCEV (P6) → BEV	BEV	FCEV (P6)	4.7016	7.5464	956.8	561.0	0.2634	0.3743	—	n/a
HD	HD long-haul	South	Diesel → BEV	BEV	Diesel	4.7016	5.3124	738.5	1190.0	0.2634	0.2530	681.7	finite
HD	HD long-haul	South	Diesel → FCEV (best)	FCEV (best)	Diesel	6.5992	5.3124	1190.0	1190.0	0.3273	0.2530	—	n/a
HD	HD long-haul	South	BEV → FCEV (P6)	FCEV (P6)	BEV	8.2053	4.7016	561.0	738.5	0.4070	0.2634	>3000	>3000
HD	HD long-haul	South	FCEV (P6) → BEV	BEV	FCEV (P6)	4.7016	8.2053	738.5	561.0	0.2634	0.4070	—	n/a
HD	HD long-haul	National average	Diesel → BEV	BEV	Diesel	4.7016	5.3124	900.7	1190.0	0.2634	0.2530	1679.3	finite
HD	HD long-haul	National average	Diesel → FCEV (best)	FCEV (best)	Diesel	6.5992	5.3124	1190.0	1190.0	0.3273	0.2530	—	n/a
HD	HD long-haul	National average	BEV → FCEV (P6)	FCEV (P6)	BEV	7.9185	4.7016	561.0	900.7	0.3928	0.2634	>3000	>3000
HD	HD long-haul	National average	FCEV (P6) → BEV	BEV	FCEV (P6)	4.7016	7.9185	900.7	561.0	0.2634	0.3928	—	n/a

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