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Prospective Total Cost of Ownership of road freight vehicles in Switzerland

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Abstract

As part of the MSc in Mechanical Engineering at ETH Zurich, this semester project was conducted during the Spring Semester 2025 at the Paul Scherrer Institute (PSI). It was supervised by Prof. Dr. R. McKenna (ETH Zurich) with co-supervision by Dr. Romain Sacchi and Christian Bauer (PSI). The project contributes to the further development of *Carculator*, an open-source tool developed at PSI within the Swiss Competence Center for Energy Research (SCCER) "Efficient Technologies and Systems for Mobility," funded by Innosuisse. The focus is on the prospective Total Cost of Ownership (TCO) of road freight vehicles in Switzerland, with a comparison between conventional diesel, battery-electric, and fuel-cell trucks (ICEV-d, BEV, and FCEV, respectively).

The motivation arises from the crucial role of heavy-duty vehicles in Switzerland's freight-related greenhouse gas emissions and the uncertainty fleet operators face when planning investments under rapidly evolving regulatory and technological conditions. While numerous European TCO studies exist, few reflect the Swiss context, which is strongly shaped by higher prices, cantonal taxes, and the federal LSVA heavy vehicle fee. This project addresses this gap by developing a transparent and parameterized TCO model adapted to Swiss conditions.

A bottom-up approach is applied to capture acquisition, component replacement, energy, maintenance, insurance, infrastructure, taxation, and driver costs, while accounting for uncertainty in future technology and cost developments. The model is parameterized such that most of the developed parameters can be reused and extended to enhance the *Carculator* framework at the European level.

The results show that under base-case conditions in Zurich in 2025, battery-electric trucks already reach cost competitiveness with diesel, while fuel-cell trucks remain significantly more expensive. For regional delivery (GVWR 22 t, cargo 12 t, truck lifetime 15 years, 100% depot charging), the TCO amounts to 0.346 €/t·km (ICEV-d), 0.319 €/t·km (BEV), and 0.575 €/t·km (FCEV). For long-haul transport (GVWR 38 t, cargo 20 t, truck lifetime 15 years, 50% depot charging), the corresponding values are 0.126 €/t·km (ICEV-d), 0.098 €/t·km (BEV), and 0.147 €/t·km (FCEV). All monetary results are expressed in Euro_{2025}/t·km.

Scenario analysis indicates that by 2030, continued battery cost reductions and efficiency improvements consolidate the advantage of BEVs, making them the most cost-effective option across regional and long-haul applications. Fuel-cell trucks remain costlier in this timeframe due to fuel cell costs and hydrogen prices. By 2050, however, with further technological progress and large-scale deployment, FCEVs could reach cost parity with BEVs in long-haul transport. Importantly, truck lifetime, fuell cell replacements assumptions strongly influence competitiveness: shorter truck lifetimes favour BEVs, while longer service periods improve the position of FCEVs given their higher upfront and replacement costs.

Scenario analysis indicates that by 2030, battery-electric trucks consolidate their cost advantage, remaining the most cost-effective option across both regional and long-haul applications. Fuel-cell trucks, by contrast, remain significantly more expensive in this timeframe due to high fuel cell costs and hydrogen prices. By 2050, however, under constant Swiss electricity tariffs and with declining hydrogen costs, FCEVs could surpass BEVs in long-haul transport, while they remain uncompetitive in regional duty cycles. Importantly, competitiveness is highly sensitive to truck lifetime and, in particular, to fuel cell replacement assumptions: shorter lifetimes systematically favor BEVs, whereas longer service periods improve the position of FCEVs only if the number of fuel cell replacements is limited, since each additional replacement substantially increases their TCO.

In conclusion, the parameterized TCO model developed here provides a transparent and flexible tool for Swiss fleet operators and decision-makers. It highlights the early cost advantage of BEVs, the potential long-term role of FCEVs, and the decisive role of regulatory and market conditions in shaping Switzerland's freight decarbonization pathways.

Contents

1 Introduction

Road freight transport is a backbone of economic activity in Switzerland and across Europe, carrying around 62% of goods transport performance in Switzerland [1] and the majority of inland freight volumes across Europe [2]. However, it is also a major source of greenhouse gas emissions and air pollution. In Switzerland, freight transport alone represented about 2.5 Mt CO_2-eq in 2023, corresponding to nearly 6% of the country's total emissions [3]. As both the European Union and Switzerland pursue ambitious decarbonization strategies, reducing emissions from heavy-duty vehicles has become a central challenge. Battery-electric vehicles (BEV) are increasingly viewed as a promising alternative to conventional diesel vehicles (ICEV-d), while fuel-cell electric vehicles (FCEV) remain under consideration for specific niches. Yet the economic competitiveness of these technologies depends on a wide set of interlinked factors, including acquisition costs, fuel and electricity prices, vehicle utilization, infrastructure requirements, maintenance, taxation, and financing.

For logistics operators, investment decisions are primarily guided by economic performance. The Total Cost of Ownership (TCO) is therefore the most relevant metric for comparing drivetrain technologies. European studies indicate that BEVs can already reach or approach cost parity with diesel under favorable conditions, especially in regional transport. However, results are highly sensitive to assumptions such as energy prices, vehicle lifetimes, and taxation. In Switzerland, additional boundary conditions complicate the picture: cantonal vehicle taxes, general prices above the European average, and the federal LSVA heavy-vehicle fee. BEVs and FCEVs are exempt from LSVA until 2029, but this exemption is scheduled to expire, introducing a major source of uncertainty for long-term cost assessments.

This project addresses these challenges by extending the *Carculator* framework [4], an open-source modeling tool developed at PSI, with Swiss-specific parameters. Thus, results are reported for a Swiss-specific scope while some parameters can be use for a European baseline. The objective is twofold: (i) to quantify and compare the TCO of diesel, battery-electric, and fuel-cell trucks in regional and long-haul applications, and (ii) to assess the sensitivity of these results to critical drivers such as energy price trajectories, taxation schemes, and component replacement needs. The tool is designed to remain parameterized, transparent, and accessible, supporting both academic analysis and decision-making by fleet operators.

This report is organized around the central question of how diesel, battery-electric, and fuel-cell trucks compare in terms of cost competitiveness, today and in the future. Chapter 2 reviews the literature on cost competitiveness of freight vehicle technologies. Chapter 3 introduces the modeling framework and methodology, while Chapter 4 presents its parameterization. Chapter 5 applies the model to European and Swiss scenarios. Chapter 6 discusses the comparative TCO results, and Chapter 7 concludes with the main findings and outlines future research directions.

2 Cost competitiveness of freight vehicle technologies

The economic viability of alternative drivetrains in heavy-duty transport has been widely studied, as the transition from conventional diesel vehicles to low-carbon technologies requires not only technical feasibility but also cost competitiveness. For logistics operators, investment decisions are strongly determined by the TCO. Indeed, the total cost of ownership (TCO) is an estimate of all the direct and indirect costs involved in acquiring and operating a product or system over its lifetime [5]. This section reviews insights from existing studies, identifies the key cost drivers, and highlights specific aspects of the Swiss context.

2.1 Insights from European studies

Several recent analyses have compared the cost performance of diesel, BEV and FCEV in European road freight. The paper *Analyzing the competitiveness of low-carbon drive-technologies in road-freight: A total cost of ownership analysis in Europe* [6] demonstrated that BEV can already reach cost parity with diesel trucks in specific use cases, particularly in regional or urban transports where daily mileage and charging opportunities are compatible with battery limitations. The research on *Rapidly declining costs of truck batteries and fuel cells enable large-scale road freight electrification* [7] further emphasized the rapid decline in battery and fuel-cell system costs.

Despite these encouraging trends, the competitiveness of low-carbon drivetrains is highly sensitive to input assumptions. *Challenges and opportunities in truck electrification revealed by big operational data* [8] demonstrated that energy consumption savings are the most influential factor for both TCO and CO_2 outcomes, while battery replacement can significantly increase costs and emissions. Moreover, their analysis highlighted the critical role of usage intensity: high-mileage electric trucks can outperform diesel counterparts, whereas underutilization leads to higher TCO. These findings emphasize the need for flexible, parameterized models that capture variations in energy efficiency, battery lifetimes, and utilization patterns, rather than relying solely on average European conditions.

2.2 Key cost drivers in TCO

Several recurring drivers of total cost of ownership in freight transport were identified:

- **Acquisition costs:** Battery-electric and fuel-cell trucks face substantially higher upfront purchase prices compared to diesel vehicles, mainly due to battery and fuel-cell system costs. Although expected to decline through economies of scale and technological learning, acquisition remains the dominant contributor to TCO differentials today. Residual value assumptions at the end of life also play a role in determining effective purchase cost.
- **Component replacements:** The potential need to replace high-value components, such as batteries or fuel cells, during a truck's lifetime can add significant uncertainty and strongly affect TCO.
- **Energy and fuel costs:** Diesel prices in Europe and Switzerland are shaped by oil markets and taxation. Electricity costs depend on grid mix, tariffs, and the availability of private versus public charging. For fuel-cell trucks, hydrogen price trajectories remain highly uncertain, as they depend on production pathways and refuelling infrastructure.
- **Maintenance and insurance:** Battery-electric trucks are generally expected to require less maintenance thanks to fewer moving parts, but uncertainties remain regarding long-term durability and battery degradation. Insurance costs also add to the recurring operational expenses.
- **Infrastructure:** Unlike diesel, electric trucks often require dedicated charging infrastructure, which can be a significant additional cost for operators.

- **Taxes and fees:** Regulatory instruments strongly shape cost competitiveness. For instance, exemptions from road charges or reduced taxation can make zero-emission trucks (ZETs) more attractive, while the phase-out of such exemptions introduces long-term uncertainty.
- **Driver costs:** Independent of drivetrain technology, labor costs constitute one of the largest contributors to freight transport TCO, often exceeding the technological differentials between vehicles.
- **Financing and discount rates:** The cost of capital affects the annualized burden of capital-intensive vehicles. Lower financing costs accelerate the point of cost parity with conventional diesel trucks.

These factors are strongly interdependent and their relevance varies depending on national and regional conditions. For instance, the impact of taxes, energy costs, or infrastructure availability can outweigh technological differences between drivetrains. This highlights the importance of considering country-specific frameworks, such as taxation regimes or electricity price structures, which can substantially shift the TCO balance and will be discussed in the following section on the Swiss context.

2.3 The Swiss context and the research gap

Switzerland presents several unique boundary conditions that differentiate its freight sector from the broader European average. Cantonal differences in taxation and infrastructure planning create heterogeneous incentives for fleet operators. Prices for energy and services are generally higher in Switzerland than in neighboring countries, with electricity costs in particular standing above the European average. A particularly influential driver is the federal LSVA heavy vehicle fee: although ZETs are currently exempt, this advantage will phase out after 2029, an important consideration given the long investment horizon of heavy-duty trucks (see §5.3 for more details).

In summary, existing literature has provided strong evidence that low-carbon drivetrains, particularly BEVs, can become cost-competitive with diesel under certain conditions. However, results remain highly context-dependent. Most European studies do not capture the specific features of the Swiss freight system, including cantonal taxes, LSVA regulation, and electricity price structures. The only study that explicitly considered Switzerland is the multi-country TCO analysis by Noll et al. [6], which highlighted that Swiss trucks exhibit systematically higher TCO than their European counterparts and that the LSVA exemption strongly improves the competitiveness of zero-emission vehicles. Nonetheless, their framework did not include cantonal variations or the forthcoming phase-out of the LSVA exemption after 2029, leaving important Swiss-specific dynamics unaddressed.

To address this gap, the present project extends the *Carculator* european framework [4] while also providing Swiss-specific parameters, aiming to build a transparent and flexible tool for quantifying prospective TCO across vehicle types and scenarios. Beyond methodological improvements, the framework is explicitly designed to remain accessible for fleet operators and decision-makers, thereby supporting both academic analysis and practical decision-making in the Swiss freight sector.

3 Building a bottom-up TCO framework

3.1 Definition of TCO and modeling approach

The Total Cost of Ownership (TCO) of a heavy-duty vehicle is defined as the sum of all costs incurred during its operational lifetime, normalized per ton-kilometer of transported goods.

The TCO of freight trucks depends on a wide variety of heterogeneous drivers, including purchase prices, operational energy consumption, maintenance costs, taxation schemes, and regulatory exemptions. A bottom-up framework is therefore adopted, in which each cost component is represented explicitly and aggregated into yearly and lifetime values. This approach contrasts with top-down averages, as it reflects case-specific inputs such as cantonal taxes

The model builds on the methodology of Noll et al. (2022) [6] and *International Council on Clean Transportation* (ICCT) works (2023), but is adapted to the Swiss context by explicitly integrating the LSVA heavy vehicle fee and cantonal tax schemes, both of which strongly affect the competitiveness of alternative powertrains. At the same time, the project aimed to enhance *Carculator*; therefore, most costs are based on European estimates, while only a subset is Swiss-specific. Thus, to ensure compatibility, all costs are expressed in Euro_{2025}, with exchange rates and/or inflation adjustments applied where necessary.

3.2 Model architecture

The framework was implemented as a **parameterized Excel tool**. The tool is structured into modular and interconnected sheets, ensuring transparency and flexibility:

- **ReadMe**: a user guide to improve clarity and usability.
- **UserInput**: central interface where a year (2025, 2030, 2035 or 2050) and a scenario are selected (Base, Low, High) and vehicle-specific parameters (e.g., canton of registration, GVWR, cargo mass) are defined.
- **ScenarioData**: trajectories of energy prices, component costs, and other scenario-dependent variables across the years and the 3 different scenarios.
- **FixedParameters**: constants independent of scenarios (e.g., diesel density, LHV values).
- **BatteryCosts**: learning curve–based projections for battery pack costs under three scenarios (Base, Low, High).
- **CantonalTax**: lookup tables capturing cantonal-level vehicle taxes (Graubünden, Ticino, Geneva, Vaud, Bern, Zurich and Fribourg).
- **LSVATax**: implementation of the Swiss heavy vehicle fee, with ZETs exemption until 2029 and taxation from 2030 onwards under discounted rates.
- **TCO_ICEV-d / TCO_BEV / TCO_FCEV**: technology-specific sheets aggregating all costs into annualized TCO.
- **Summary**: consolidated outputs comparing ICEV-d, BEV, and FCEV, including total cost of ownership (in €/t·km and €/km), cost component breakdown (€/t·km), and purchase price (€).

This modular architecture ensures that each component can be independently updated while maintaining consistency across the model.

3.3 User inputs

The *UserInput* sheet exposes the controls listed below in table 1. Values chosen by the user override the default scenario values for the specific simulation run, while respecting feasibility constraints (e.g., payload ≤ GVWR). Up to 28 inputs can be choose by the user.

Table 1: User-adjustable inputs (examples shown are illustrative defaults for long-haul duty)

Input	Example	Unit	Comment
usage	long haul	–	Choose either {long haul, regional}
canton	Zurich	–	Canton of registration (VD, GE, BE, ZH, FR, GR, TI)
scenario	Base	–	Scenario choice {Low, Base, High}
year	2025	–	Scenario year (2025, 2030, 2035 or 2050)
first_registration_year	2020	–	Enter year of first registration (YYYY)
GVWR	38	t	Gross vehicle weight rating
cargo_mass	20	t	Payload mass (typical LH: 20t, regional: 10t); must be ≤ GVWR
truck_lifetime	15	years	Truck economic lifetime (typ.:10-15 years)
discount_rate	9,50%	-	For annualizing costs (typ.:7-9,5%)
Battery electric truck (BEV)			
AC_depot_enabled	Yes	–	Flag: depot AC charging enabled
battery_storage_capacity_bev	700	kWh	Battery storage capacity (typical: 300–550 kWh regional, 600–900 kWh LH)
electricity_consumption	125	kWh/100km	Energy consumption (typical 105–130)
public_charging_share	50	%	Share of public charging (sums to 1 with depot)
depot_charging_share	50	%	Complement to public share
OBC_power_kW	22	kW	Onboard charger rating (typical 22–44 kW)
Battery / electrified parameters (BEV, FCEV, ICEV)			
battery_type	NMC-532	–	Battery chemistry selector (e.g., NMC, LFP, NCA)
electric_power	400	kW	Electric motor rated power (350–450 kW HDT)
battery_power	200	kW	Peak battery power (starter/auxiliary)
battery_lifetime_replacements	0	–	Expected replacements over lifetime (typ. 0–1)
Fuel cell truck (FCEV)			
fuel_cell_power	350	kW	Fuel-cell system nominal power
hydrogen_mass	80	kg	Hydrogen mass stored onboard (typ. 45-80kg)
battery_storage_capacity_fcev	50	kWh	Buffer battery capacity (typ. 30–100 kWh)
hydrogen_fuel_consumption	8	kg/100km	Typical range: 6–10 kg/100km
fuel_cell_lifetime_replacements	1	–	Expected replacements over lifetime (typ. 0–2)
Diesel truck (ICEV)			
truck_category	EURO VI-VII	–	Emission standard (EURO 0–V or VI-VII)
combustion_power	400	kW	Engine rated power
diesel_mass	150	kg	Fuel mass (1 L ≈ 0.832 kg)
diesel_fuel_consumption	21.6	L/100km	Typical range: 15–26 L/100km

3.4 Scenario data: time-varying parameters and trajectories

The *ScenarioData* sheet compiles all parameters that evolve over time, with uncertainties represented through 'Low' and 'High' scenarios. The 'Low' case reflects optimistic assumptions (i.e., low prices), while the 'High' case represents more pessimistic outcomes, relative to the 'Base' scenario as baseline. Cost trajectories are provided for 2025, 2030, 2035, and 2050. Parameters that are structurally time-invariant (e.g., physical constants) or for which no uncertainty ranges are defined (e.g., depot charging station costs) are stored in *FixedParameters*. The scenario year and thus the corresponding parameter set for a specific run is chosen by the user in *UserInput* (see §3.3). Table 2 summarizes the time-varying parameters.

3.5 Technology-specific cost items (illustrative: BEV)

Table 3 reports the itemised cost build-up used for BEVs in the workbook. Each line maps directly to a named calculation in the *TCO_BEV* sheet. The other two tables (for ICEV-d and FCEV) are represented in the Appendix A. Numeric values depend on the selected scenario year and user inputs (for this run, the values presented in table 1 were used); formulas are shown in compact analytical form for transparency.

Table 2: ScenarioData: time-varying parameters (definition and unit)

Parameter name	Definition	Unit
`glider_mass_regional`	Sum of truck body structure, drivetrain/suspension, chassis/frame, wheels/tires (regional)	kg
`glider_cost_per_kg_regional`	Cost per kg of base glider (regional)	€/kg
`glider_mass_LH`	Sum of truck body structure, drivetrain/suspension, chassis/frame, wheels/tires (long-haul)	kg
`glider_cost_per_kg_LH`	Cost per kg of base glider (long-haul)	€/kg
`lightweighting_regional`	Vehicle mass reduction achieved by design or materials (regional)	%
`lightweighting_LH`	Vehicle mass reduction achieved by design or materials (long-haul)	%
`lightweighting_regional_residual`	Residual potential mass reduction after initial lightweighting (regional)	%
`lightweighting_LH_residual`	Residual potential mass reduction after initial lightweighting (long-haul)	%
`glider_lightweighting_cost_per_kg`	Marginal cost of reducing 1 kg from chassis/glider (excl. powertrain)	€/kg
`electric_powertrain_cost_per_kW`	Cost per kW of the electric drive system (motor, inverter, transmission)	€/kW
`combustion_powertrain_cost_per_kW_regional`	Cost per kW of a diesel powertrain (regional)	€/kW
`combustion_powertrain_cost_per_kW_LH`	Cost per kW of a diesel powertrain (long-haul)	€/kW
`fuel_cell_cost_per_kW`	Production cost per kW of hydrogen fuel cell system	€/kW
`power_battery_cost_per_kW`	Cost for battery system peak power per kW output	€/kW
`power_battery_cost_per_kW_ICEV`	Cost for power-oriented battery (for start-up)	€/kW
`diesel_tank_cost_per_kg`	Storage tank cost per kg of diesel capacity	€/kg
`hydrogen_tank_cost_per_kg`	Storage tank cost per kg of H_2 capacity	€/kg
`hydrogen_price_per_kg`	Operational energy price of hydrogen	€/kg
`diesel_price_per_liter`	Operational energy price of diesel in Switzerland	€/L
`electricity_public_price_per_kWh`	Public charging electricity price in Switzerland	CHF/kWh
`ICM_high1`	Indirect cost multiplier (base glider and low-complexity systems)	–
`ICM_high2`	Indirect cost multiplier (high complexity systems like fuel cells)	–
`kilometers_per_year_LH`	Annual mileage (long-haul trucks)	km/year
`kilometers_per_year_regional`	Annual mileage (regional trucks)	km/year
`maintenance_cost_per_km_ICEV_LH`	Average maintenance cost per km, ICEV long-haul	€/km
`maintenance_cost_per_km_ICEV_regional`	Average maintenance cost per km, ICEV regional	€/km
`maintenance_cost_per_km_BEV_LH`	Average maintenance cost per km, BEV long-haul	€/km
`maintenance_cost_per_km_BEV_regional`	Average maintenance cost per km, BEV regional	€/km
`maintenance_cost_per_km_FCEV_LH`	Average maintenance cost per km, FCEV long-haul	€/km
`maintenance_cost_per_km_FCEV_regional`	Average maintenance cost per km, FCEV regional	€/km
`insurance_rate_per_year`	Annual insurance premium	fraction of CAPEX/year
`exhaust_treatment_cost`	Aftertreatment system cost (SCR/DPF, etc.)	€/kg kerb weight
`adblue_price_per_L`	AdBlue price	CHF/L
`onboard_charger_cost_per_kW`	Onboard charger cost per kW	€/kW
`driver_cost_per_year`	Annual driver salary (Switzerland)	€/year
`residual_value_ICEV`	Residual value at end of life (fraction of purchase cost, ICEV)	–
`residual_fraction_BEV_LH`	Residual value fraction for BEV long-haul	–
`residual_fraction_BEV_regional`	Residual value fraction for BEV regional	–
`residual_fraction_FCEV_LH`	Residual value fraction for FCEV long-haul	–
`residual_fraction_FCEV_regional`	Residual value fraction for FCEV regional	–

Table 3: BEV itemised cost build-up (illustrative run, Base 2025)

Parameter	Value	Unit	Formula	Comment
glider_cost (C_{glider})	43 571.20	€	$m_{\text{glider}} \cdot c_{\text{glider,kg}}$	Chassis/glider
lightweighting_cost ($C_{\text{lightweight}}$)	346.41	€	$m_{\text{glider}} \cdot \lambda \cdot c_{\text{light,kg}}$	λ: lightweighting factor
electric_powertrain_cost ($C_{\text{electric,pt}}$)	19 200.00	€	$P_e \cdot c_{e,\text{kW}}$	Motor + inverter
energy_battery_cost	61 110.00	€	$E_{\text{bat}} \cdot c_{\text{bat,kWh}}$	Battery pack (energy)
power_battery_cost	6 962.00	€	$P_{\text{bat}} \cdot c_{\text{bat,kW}}$	Battery pack (power)
battery_cost (C_{battery})	68 072.00	€	$E_{\text{bat}} \cdot c_{\text{bat,kWh}} + P_{\text{bat}} \cdot c_{\text{bat,kW}}$	Total battery cost
onboard_charger_cost (C_{OBC})	1 339.14	€	$P_{\text{OBC}} \cdot c_{\text{OBC,kW}}$	If AC depot enabled
energy_cost (C_{energy})	3.11E-02	€/t·km	$\frac{EC}{100} \cdot p_{\text{el,public}} \cdot \left(\frac{s_{\text{public}}}{100} + \frac{s_{\text{depot}}}{100}(1 - d_{\text{el,depotVSpublic}})\right) \cdot \gamma_{\text{CHF-EUR}} \cdot \frac{1}{m_{\text{cargo}}}$	Weighted public/depot electricity
component_replacement_cost (C_{repl})	0	€	$E_{\text{bat}} \cdot c_{\text{bat,kWh}} \cdot n_{\text{bat}}$	Battery replacements
component_replacement_price	0	€	$\mu_{\text{high1}} \cdot C_{\text{repl}}$	With markup
purchase_price (C_{purchase})	178 648.76	€	$\mu_{\text{high1}} \cdot (C_{\text{glider}} + C_{\text{lightweight}} + C_{\text{electric,pt}} + C_{\text{battery}} + C_{\text{OBC}})$	Excl. infra cost
amortisation_factor (AF)	1.28E-01	–	$\frac{i}{1-(1+i)^{-L}}$	i: discount rate, L: lifetime
amortised_purchase_price ($C_{\text{amort,purchase}}$)	1.17E-02	€/t·km	$\frac{C_{\text{purchase}} \cdot AF}{km_{\text{year}} \cdot m_{\text{cargo}}}$	Annualised CAPEX
maintenance_cost (C_{maint})	6.80E-03	€/t·km	$\frac{c_{\text{maint,BEV}}}{m_{\text{cargo}}}$	Routine maintenance
insurance_cost (C_{ins})	1.83E-03	€/t·km	$\frac{C_{\text{purchase}} \cdot c_{\text{ins,yr}}}{km_{\text{year}} \cdot m_{\text{cargo}}}$	Proportional to CAPEX
driver_cost (C_{driver})	3.32E-02	€/t·km	$\frac{c_{\text{driver,yr}}}{km_{\text{year}} \cdot m_{\text{cargo}}}$	Very high in CH
cantonal_tax_cost ($C_{\text{tax,cantonal}}$)	1.45E-03	€/t·km	model-specific	See Section 5.4
lsva_taxable_years (Y_{LSVA})	6.00	years	$\text{IF}(y_0 > 2029;\ L;\ \max(0;\ L - (2029 - y_0 + 1)))$	Years taxed after 2029
lsva_tax_cost ($C_{\text{tax,LSVA}}$)	1.07E-02	€/t·km	$\frac{Y_{\text{LSVA}} \cdot c_{\text{LSVA}}}{L} \cdot \frac{\text{GVWR}}{m_{\text{cargo}}}$	Federal fee
amortised_compo_repl_price ($C_{\text{amort,repl}}$)	0.00E+00	€/t·km	$\frac{C_{\text{repl}} \cdot (1+i)^{-L/2} \cdot AF}{km_{\text{year}} \cdot m_{\text{cargo}}}$	Mid-life timing
infrastructure_cost (C_{infra})	2.32E-03	€/t·km	see Eq. (**??**)	Depot CAPEX+O&M per kWh
residual_credit (C_{residual})	7.47E-04	€/t·km	$C_{\text{amort,purchase}} \cdot f_{\text{res}} \cdot (1+i)^{-L}$	End-of-life credit
total_cost_per_tkm	9.84E-02	€/t·km	sum of €/t·km items	Total cost of ownership

4 Parameterization of the TCO model

4.1 Calculation logic

Each technology-specific TCO sheet computes a transparent bill of materials (CAPEX) and a set of operating expenses (OPEX). All recurring costs are normalized to €/t·km by dividing by the annual mileage and the payload; one-off costs are annualized with an annuity factor and then normalized to €/t·km. Prices that were in CHF in the *ScenarioData* sheet are converted to € using `EUR_per_CHF` (see section 5.3).

4.1.0.1 Common structure (all powertrains).

- **Amortisation factor**: The annuity factor (AF) converts upfront investments into equivalent annual payments with r, the discount rate (%) and L, the truck lifetime (in years):

$$AF = \frac{r}{(1-(1+r)^{-L})}$$

- **Purchase price (€):** The purchase price corresponds to the total initial investment needed to acquire the vehicle, including all major subsystems and indirect cost multipliers (ICMs). ICMs account for overhead, R&D, marketing, distribution, warranty, and profit margins. In this model, two levels of complexity are distinguished: $\texttt{ICM}_{\text{high1}}$ (chassis, cabin, battery packs, electric drive) and $\texttt{ICM}_{\text{high2}}$ (fuel cells, hydrogen storage), expressed without unit.

  For each technology, the purchase price is calculated as follows:

$$C^{\text{ICEV-d}}_{\text{purchase}} = \texttt{ICM}_{\text{high1}} \cdot \left(C_{\text{glider}} + C_{\text{lightweight}} + C_{\text{combustion\_pt}} + C_{\text{exhaust}} + C_{\text{starter\_battery}} + C_{\text{diesel\_tank}}\right)$$

$$C^{\text{BEV}}_{\text{purchase}} = \texttt{ICM}_{\text{high1}} \cdot \left(C_{\text{glider}} + C_{\text{lightweight}} + C_{\text{electric\_pt}} + C_{\text{battery}} + C_{\text{OBC}}\right)$$

$$C^{\text{FCEV}}_{\text{purchase}} = \texttt{ICM}_{\text{high1}} \cdot \left(C_{\text{glider}} + C_{\text{lightweight}} + C_{\text{electric\_pt}} + C_{\text{battery}}\right) + \texttt{ICM}_{\text{high2}} \cdot \left(C_{\text{fuel\_cell}} + C_{\text{H2\_tank}}\right)$$

  where C is a cost in €: C_{glider}: glider cost, $C_{\text{lightweight}}$: lightweighting cost, $C_{\text{electric\_pt}}$: electric powertrain cost, C_{battery}: battery cost, C_{OBC}: onboard charger cost (BEV only), $C_{\text{combustion\_pt}}$: combustion powertrain cost (ICEV only), C_{exhaust}: exhaust treatment system cost (ICEV only), $C_{\text{starter\_battery}}$: starter battery (ICEV only), $C_{\text{diesel\_tank}}$: diesel tank (ICEV only), $C_{\text{fuel\_cell}}$: fuel cell system (FCEV only), $C_{\text{H2\_tank}}$: hydrogen storage tank (FCEV only).

- **Amortised purchase price** (€/t·km): The upfront purchase price is annualized using the annuity factor AF and normalized by mileage and payload:

$$C_{\text{amort,purchase}} = \frac{C_{\text{purchase}} \cdot AF}{km_{\text{year}} \cdot m_{\text{cargo}}}.$$

  with km_{year} = annual mileage [km/year] and m_{cargo} = cargo mass [t].

- **Residual value credit** (€/t·km): At the end of its lifetime, the truck retains a residual value which can be recovered (e.g., through resale of the vehicle or salvage of major components). This credit is deducted from the TCO, as it offsets part of the initial investment:

$$C_{\text{residual}} = C_{\text{amort,purchase}} \cdot f_{\text{residual}} \cdot (1+r)^{-L}$$

where f_{residual} is the fraction of the purchase price recovered at resale (residual fraction), r the discount rate and L the truck's lifetime.

- **Energy cost** (€/t·km): consumption per 100 km times the relevant fuel/electricity price, divided by `cargo_mass`.
- **Maintenance cost** (€/t·km): technology-specific `maintenance_cost_per_km` (for ICEVs AdBlue is added) divided by `cargo_mass`.
- **Insurance cost** (€/t·km): proportional to `purchase_price` via an annual `insurance_rate_per_year`, normalized by mileage and payload (= purchase_price * insurance_rate_per_year / cargo_mass / kilometers_per_year).
- **Cantonal vehicle tax** (€/t·km): lookup-based (GVWR, canton), harmonized across technologies, converted with `EUR_per_CHF`, normalized by mileage and payload (more details in §5.4).
- **LSVA heavy-vehicle fee** (€/t·km): weight- and year-dependent. ICEVs pay the pre-2028 tariff until 2028 and the post-2028 tariff thereafter; ZETs are exempt until 2029, then charged with the post-2028 rate (more details in §5.3).
- **Driver cost** (€/t·km): `driver_cost_per_year` normalized by mileage and payload.

4.1.0.2 ICEV-d bill of materials (CAPEX, in €). The purchase price of an internal combustion engine vehicle (ICEV-d) is calculated based on the following costs:

$$\begin{aligned}
C_{\text{glider}} &= m_{\text{glider}} \cdot c_{\text{glider,kg}} \\
C_{\text{lightweight}} &= m_{\text{glider}} \cdot \lambda_{\text{light}} \cdot c_{\text{light,kg}} \\
C_{\text{combustion_pt}} &= P_{\text{comb}} \cdot c_{\text{comb,kW}} \\
C_{\text{exhaust}} &= P_{\text{comb}} \cdot c_{\text{exhaust}} \cdot m_{\text{kerb}} \\
C_{\text{starter_battery}} &= P_{\text{bat}} \cdot c_{\text{starter,kW}} \\
C_{\text{diesel_tank}} &= m_{\text{diesel}} \cdot c_{\text{tank,kg}}
\end{aligned}$$

where: m_{glider} = glider mass [kg], $c_{\text{glider,kg}}$ = glider cost per kg [€/kg], λ_{light} = lightweighting factor [-], $c_{\text{light,kg}}$ = lightweighting cost per kg [€/kg], P_{comb} = combustion engine power [kW], $c_{\text{comb,kW}}$ = combustion powertrain cost per kW [€/kW], c_{exhaust} = exhaust treatment cost [€/kg kerb weight], m_{kerb} = kerb weight [kg], P_{bat} = starter battery power [kW], $c_{\text{starter,kW}}$ = starter battery cost per kW [€/kW], m_{diesel} = diesel mass [kg], $c_{\text{tank,kg}}$ = diesel tank cost per kg [€/kg].

ICEV OPEX specifics.

For diesel trucks, the main operating expenditures (OPEX) are expressed as the following:

Note that C_{energy} represents the fuel-related energy cost in €/t·km, C_{AdBlue} captures the additional cost of AdBlue dosing in €/km, and $C_{\text{maintenance}}$ denotes the total maintenance cost per ton-kilometer including AdBlue in €/t·km.

$$
\begin{aligned}
C_{\text{energy}} &= \frac{FC_{\text{diesel}}}{100} \cdot p_{\text{diesel}} \cdot \frac{1}{m_{\text{cargo}}} \\
C_{\text{AdBlue}} &= \frac{FC_{\text{diesel}}}{100} \cdot \rho_{\text{diesel}} \cdot \alpha_{\text{AdBlue}} \cdot p_{\text{AdBlue}} \cdot \gamma_{\text{CHF-EUR}} \\
C_{\text{maintenance}} &= \frac{c_{\text{maint,ICEV}} + C_{\text{AdBlue}}}{m_{\text{cargo}}}
\end{aligned}
$$

where FC_{diesel} = diesel fuel consumption [L/100 km], p_{diesel} = diesel price [€/L], ρ_{diesel} = diesel density [kg/L], α_{AdBlue} = AdBlue dosing ratio [L AdBlue/L diesel], p_{AdBlue} = AdBlue price [CHF/L], m_{cargo} = cargo mass [t], $\gamma_{\text{CHF-EUR}}$ = currency conversion factor [€/CHF], $c_{\text{maint,ICEV}}$ = maintenance cost per km [€/km].

4.1.0.3 BEV bill of materials (CAPEX, in €). The purchase price of a battery-electric truck (BEV) is calculated based on the following costs:

$$
\begin{aligned}
C_{\text{glider}} &= m_{\text{glider}} \cdot c_{\text{glider,kg}} \\
C_{\text{lightweight}} &= m_{\text{glider}} \cdot \lambda_{\text{light}} \cdot c_{\text{light,kg}} \\
C_{\text{electric\_pt}} &= P_{\text{elec}} \cdot c_{\text{elec,kW}} \\
C_{\text{battery}} &= E_{\text{bat}} \cdot c_{\text{bat,kWh}} + P_{\text{bat}} \cdot c_{\text{bat,kW}} \\
C_{\text{OBC}} &= P_{\text{OBC}} \cdot c_{\text{OBC,kW}}
\end{aligned}
$$

where P_{elec} = electric drive power [kW], $c_{\text{elec,kW}}$ = unit cost of electric powertrain [€/kW], E_{bat} = battery storage capacity (for BEV) [kWh], $c_{\text{bat,kWh}}$ = unit cost of battery storage (depending on the chemistry) [€/kWh], P_{bat} = battery power [kW], $c_{\text{bat,kW}}$ = unit cost of battery power [€/kW], P_{OBC} = onboard charger power [kW], $c_{\text{OBC,kW}}$ = unit cost of onboard charger [€/kW].

BEV OPEX specifics.

For battery-electric trucks, the main operating expenditures (OPEX) include:

$$
\begin{aligned}
C_{\text{energy}} &= \frac{EC}{100} \cdot p_{\text{el,public}} \cdot \Big(\frac{s_{\text{public}}}{100} + \frac{s_{\text{depot}}}{100} \cdot (1 - d_{\text{el,depotVSpublic}})\Big) \cdot \gamma_{\text{CHF-EUR}} \cdot \frac{1}{m_{\text{cargo}}} \\
C_{\text{infra}} &= \begin{cases} 0, & \text{if } s_{\text{depot}} \le 0, \\ \dfrac{\Big[(C_{\text{equip}} + C_{\text{install}}) \cdot AF_{\text{LCOC}} + \phi_{\text{O\&M}} \cdot C_{\text{equip}}\Big]}{E_{\text{station}}} \cdot \dfrac{EC}{100} \cdot \dfrac{s_{\text{depot}}}{m_{\text{cargo}}}, & \text{otherwise,} \end{cases} \\
AF_{\text{LCOC}} &= \frac{r}{1 - (1+r)^{-L_{\text{LCOC}}}}, \qquad E_{\text{station}} = \text{annual\_energy\_station\_MWh} \times 1000. \\
C_{\text{repl}} &= \frac{\texttt{ICM}_{\text{high1}} \cdot \big(E_{\text{bat}} \cdot c_{\text{bat,kWh}} \cdot N_{\text{repl}}\big) \cdot (1+r)^{-L/2} \cdot AF}{km_{\text{year}} \cdot m_{\text{cargo}}}
\end{aligned}
$$

where EC = electricity consumption [kWh/100 km], $s_{\text{public}}\&s_{\text{depot}}$ = public and depot charging shares (value between 50 and 100)[–], $p_{\text{el,public}}$ = public electricity tariffs [CHF/kWh], $d_{\text{el,depotVSpublic}}$ = depot discount VS public (=50%), LC_{depot} = levelized depot charging cost [€/kWh], $C_{\text{bat,repl}}$ = cost of battery replacement [€], C_{equip} = equipment cost [€], C_{install} = installation cost [€], $AF_{\text{infra}} = \frac{r}{1-(1+r)^{-L_{\text{infra}}}}$ = annuity factor for depot infrastructure [–], L_{infra} = infrastructure lifetime [years], $\pi_{\text{O\&M}}$ = annual O&M fraction of equipment cost [–], E_{station} = annual station energy throughput [MWh/year], N_{repl} = number of expected battery replacements over the truck lifetime [–].

Here, C_{energy} is the electricity cost per ton-kilometer (€/t·km) , C_{infra} the amortized depot infrastructure cost per ton-kilometer (€/t·km) , and C_{repl} the cost contribution of mid-life battery replacement per ton-kilometer (€/t·km) .

4.1.0.4 FCEV bill of materials (CAPEX, in €). The purchase price of a fuel-cell electric truck (FCEV) combines the glider, lightweighting and electric subsystems (as in BEVs) with additional costs for the fuel cell system and hydrogen storage tanks:

$$C_{\text{purchase}}^{\text{FCEV}} = \texttt{ICM}_{\text{high1}} \cdot \left(C_{\text{glider}} + C_{\text{lightweight}} + C_{\text{electric\_pt}} + C_{\text{battery}}\right) + \texttt{ICM}_{\text{high2}} \cdot \left(C_{\text{fuel\_cell}} + C_{\text{H2\_tank}}\right)$$

Where the new terms are:
$C_{\text{battery}} = E_{\text{bat}} \cdot c_{\text{bat,kWh}} + P_{\text{bat}} \cdot c_{\text{bat,kW}}$
E_{bat} = battery storage capacity (for FCEV) [kWh],
$C_{\text{fuel\_cell}} = P_{\text{FC}} \cdot c_{\text{FC,kW}}$, with P_{FC} the fuel cell system power [kW] and $c_{\text{FC,kW}}$ its cost per unit power [€/kW],
$C_{\text{H2\_tank}} = m_{\text{H2}} \cdot c_{\text{tank,kg}}$, with m_{H2} the hydrogen storage capacity [kg] and $c_{\text{tank,kg}}$ the storage cost per kg of hydrogen [€/kg],
$\texttt{ICM}_{\text{high2}}$ is the indirect cost multiplier for complex subsystems such as fuel cells and hydrogen tanks.

FCEV OPEX specifics. Operating costs for fuel-cell trucks include hydrogen consumption and mid-life component replacements (battery + fuel cell):

$$C_{\text{energy}} = \frac{FC_{\text{H2}}}{100} \cdot p_{\text{H2}} \cdot \frac{1}{m_{\text{cargo}}}$$

$$C_{\text{repl}} = \frac{\left(\texttt{ICM}_{\text{high1}} \cdot C_{\text{bat,repl}} + \texttt{ICM}_{\text{high2}} \cdot C_{\text{FC,repl}}\right) \cdot (1+r)^{-L/2} \cdot AF}{km_{\text{year}} \cdot m_{\text{cargo}}}$$

where the new variables are: FC_{H2} = hydrogen fuel consumption [kg/100 km], p_{H2} = hydrogen price [€/kg], $C_{\text{bat,repl}}$ = battery replacement cost [€], $C_{\text{FC,repl}}$ = fuel cell system replacement cost [€].

Thus, C_{energy} expresses the hydrogen cost per ton-kilometer (€/t·km), while C_{repl} accounts for mid-life replacements of the battery and fuel cell, discounted and annualized before being normalized per ton-kilometer (€/t·km).

4.1.0.5 Total cost of ownership. The total cost of ownership (TCO) aggregates all cost components into a single indicator, normalized by mileage and payload (€/t·km):

$$C_{\text{TCO}} = C_{\text{energy}} + C_{\text{amort,purchase}} + C_{\text{maint}} + C_{\text{ins}} + C_{\text{tax,cantonal}} + C_{\text{tax,LSVA}} + C_{\text{infra}} + C_{\text{driver}} + C_{\text{amort,repl}} - C_{\text{residual}}$$

where C_{energy} = energy cost [€/t·km], $C_{\text{amort,purchase}}$ = amortised purchase cost [€/t·km], C_{maint} = maintenance cost [€/t·km], C_{ins} = insurance cost [€/t·km], $C_{\text{tax,cantonal}}$ = cantonal vehicle tax [€/t·km], $C_{\text{tax,LSVA}}$ = LSVA heavy vehicle fee [€/t·km], C_{infra} = infrastructure cost [€/t·km], C_{driver} = driver cost [€/t·km], $C_{\text{amort,repl}}$ = amortised component replacement cost [€/t·km], C_{residual} = residual value credit [€/t·km].

4.1.0.6 Summary sheet. The *Summary* sheet consolidates, for a given scenario (e.g., *Base 2025*), (i) the detailed cost components in €/t·km, (ii) the resulting TCO in €/t·km (and €/km as a convenience metric), and (iii) the upfront `purchase_price` in € for ICEV-d, BEV, and FCEV. This supports direct, component-level traceability of cost drivers across technologies.

4.2 Component costs

Currency conversion approach Some of the cost data used in the ICCT works were reported in 2022 U.S. dollars. To ensure consistency with the European framework of the analysis, these values were first adjusted for inflation to 2025 U.S. dollars using the U.S. GDP deflator. Subsequently, the costs were converted into euros applying the average exchange rate projected for 2025. The conversion followed the equation:

$$\text{Value}_{\text{EUR},2025} = \text{Value}_{\text{USD},2022} \times \frac{\text{CPI}_{\text{US},2025}}{\text{CPI}_{\text{US},2022}} \times \text{FX}_{\text{USD/EUR},2025} \tag{4.1}$$

where $\text{CPI}_{\text{US,year}}$ denotes the consumer price index (or GDP deflator) for the United States in a given year, and $\text{FX}_{\text{USD/EUR},2025}$ is the 2025 average exchange rate between the U.S. dollar and the euro. This procedure ensures that all cost figures are expressed in real 2025 euros, which allows a coherent comparison between technologies and scenarios.

In practice, combining the 2022 average exchange rate of 1 USD = 0.95 EUR [9] with the cumulative Euro area inflation of 9.32% between 2022 and 2025 [10], a simplified conversion factor of

$$1\ USD_{2022} \approx 1.04\ EUR_{2025}$$

was applied if needed.

Glider mass and cost per kg. Based on Ricardo's teardown study [11], the glider mass was defined as the sum of the Truck Body Structure, Drivetrain & Suspension, Chassis/Frame, and Wheels & Tires. This yields a glider mass of 9'570 lb (4'340.9 kg) for a battery-electric tractor (600 kWh battery, 350 kW drive), and 10'440 lb (4'735.5 kg) for a fuel cell tractor (390 kW fuel cell, 60 kg H_2 storage, 12 kWh battery, 350 kW drive). Low and High scenarios are defined as 10% and +30% relative to the Base value.

To estimate the cost per kilogram, we relied on the ICCT cost breakdown [12], which reports a Base glider cost of 36'000 USD_{2022} for regional (short-haul) tractors and 42'000 USD_{2022} for long-haul tractors (Tables A6–A7). After conversion using 1 $\text{USD}_{2022} \approx 1.04$ EUR_{2025} (see eq. 4.1), the costs are 37'440 EUR_{2025} (regional) and 43'680 EUR_{2025} (long-haul). Dividing these by the respective Ricardo glider masses gives:

$$\frac{37440}{4341} \approx 8.6 \text{ EUR2025/kg (regional)}, \quad \frac{43680}{4736} \approx 9.2 \text{ EUR2025/kg (long-haul)}.$$

These values were adopted as the baseline glider cost per kg in the *ScenarioData* sheet, with regional trucks corresponding to day cab tractors and long-haul trucks corresponding to sleeper tractors. Low and High scenarios were constructed by applying a ±0.5 €/kg uncertainty margin around these baseline values.

Residual lightweighting potential. The cost-effective weight reduction potentials for heavy-duty vehicles were taken from Ricardo-AEA's study on lightweighting [13], which reports values relative to a 2015 baseline articulated truck. For regional tractors, the study indicates 8.6% in 2025, 9.9% in 2030, 10.0% in 2035 (interpolated following the eq. 4.2), and 10.2% in 2050. For long-haul tractors, the corresponding values are 7.6% in 2025, 8.0% in 2030, 9.05% (interpolated) in 2035, and 10.6% in 2050. The Low scenario is defined as 30% below the Base value, while the High scenario is defined as 30% above the Base value.

Since our glider masses are based on Ricardo's teardown of Class 8 vehicles from 2021 [11], i.e. vehicles produced around 2022, part of the 2015–2022 lightweighting potential is already embedded in the baseline. To avoid double counting, we rebase the Ricardo-AEA percentages by subtracting the interpolated 2022 reference level (6.38% for regional and 5.50% for long-haul, linearly interpolated between 2020 and 2025) from the published 2025–2050 potentials.

Formally, the residual potential applied in the TCO model is calculated as:

$$LW_{\text{residual}}(t) \;=\; LW_{\text{RicardoAEA}}(t) \;-\; LW_{\text{RicardoAEA}}(2022),$$

with $LW_{\text{RicardoAEA}}(2022) = LW(2020) + \frac{(LW(2025) - LW(2020))}{2025-2020} \times (2022 - 2020)$.

The resulting residual potentials applied in our Scenario Data are, for example, 2.22% in 2025 and 3.82% in 2050 for regional trucks, and 2.1% in 2025 and 5.1% in 2050 for long-haul trucks. The Low scenario is floored at 0%.

Lightweighting cost per kilogram. The marginal cost of glider lightweighting was derived from Ricardo-AEA's study on HDV lightweighting [13]. Figure ES1 of this report provides cost-effective mass reduction potentials and associated costs for articulated trucks (40 t GVW, kerb weight 14,550 kg, including engine, transmission, chassis, suspension, cab and body). The estimated marginal costs are 1.3 €/kg for short-term measures (up to 2020), 6.3 €/kg for medium-term measures (up to 2030), and 39.9 €/kg for long-term measures (up to 2050).

For intermediate years, we apply linear interpolation between the reported horizons. The general formula is:

$$C(t) \;=\; C(t_1) + \frac{t - t_1}{t_2 - t_1}\big(C(t_2) - C(t_1)\big), \tag{4.2}$$

where t_1 and t_2 are the bounding years and $C(t_1), C(t_2)$ their respective costs. For example, the 2025 value is interpolated between 2020 and 2030, yielding

$$C(2025) = 1.3 + \frac{2025 - 2020}{2030 - 2020}(6.3 - 1.3) = 3.8\,\text{€/kg}.$$

Similarly, 2035 is interpolated between 2030 and 2050, resulting in 14.7 €/kg. In our ScenarioData, the Base scenario follows these interpolated values, while Low and High scenarios are defined as ±30% multiplicative deviations.

Electric powertrain cost per kW. The cost of the electric drive system (motor, inverter, and transmission) was derived from the ICCT study on the total cost of ownership of long-haul Class 8 trucks in the United States [14]. The report provides direct manufacturing cost estimates of 60 USD/kW in 2022, 23 USD/kW in 2030, and 18 USD/kW in 2040. We converted these values to EUR_{2025} using a rate of 1 USD_{2022} = 1.04 EUR_{2025} (eq. 4.1), yielding 62.4, 23.9, and 18.7 EUR/kW, respectively. Intermediate years were obtained by linear interpolation: for 2025, 48.0 EUR/kW; for 2035, 21.3 EUR/kW; and for 2050, 13.5 EUR/kW. These values were then used in the ScenarioData sheet to parameterize the evolution of electric powertrain costs under the Base scenario.

Combustion powertrain cost per kilowatt. The cost of diesel engines was taken from Noll et al. [6], who report values in €2019/kW for different vehicle segments. For long-haul trucks (HDT), the engine cost distribution is given as 39.50 (min), 40.77 (most likely), and 41.90 (max) €/kW. For medium-duty trucks (MDT), representing regional use, the reported values are 67.72 (min), 79.00

(most likely), and 90.29 (max) €/kW. To integrate these values in our TCO model, we adjusted them to EUR_{2025} using a cumulative inflation factor of +23.74% between 2019 and 2025, as reported by [10]. This yields the following values in EUR_{2025}/kW: Long-haul: 48.88 (low), 50.45 (base), 51.85 (high); Regional: 83.80 (low), 97.75 (base), 111.72 (high). These values were assumed constant across all scenario years (2025–2050), since no significant long-term learning effect is expected for mature diesel powertrains.

Fuel cell cost per kW. We use ICCT (2023) [14] cost points for fuel cell systems of Class 8 long-haul trucks: 826 USD/kW in 2022, 301 USD/kW in 2030, and 242 USD/kW in 2040. Intermediate years are obtained by linear interpolation (eq. 4.2), and 2050 is linearly extrapolated from the 2030–2040 trend. Values are then converted to EUR using 1 USD_{2022} = 1.04 EUR_{2025}. This yields: 2025: 654.3 EUR/kW, 2030: 313.0 EUR/kW, 2035: 282.4 EUR/kW, 2040: 251.7 EUR/kW, and 2050: 190.3 EUR/kW. Low and High scenarios are defined as 30% and +30% relative to the Base value.

Power battery cost assumptions. The parameter `power_battery_cost_per_kW` (cost for battery system peak power per kW output, expressed in €/kW) is derived from the values provided in the ICCT White Paper *The European Heavy-Duty Vehicles Market Decarbonization Pathway* [15]. Since the source reports costs in €/kWh, we converted them into €/kW assuming different C-rates: a 10C rate for the Base scenario, a 12C rate for the Low scenario, and an 8C rate for the High scenario. Values for 2025 and 2035 were obtained through linear interpolation (eq. 4.2) between the available datapoints (2022, 2030, and 2040), while values for 2050 were extrapolated based on the same trajectory.

Diesel fuel tank cost per kilogram. The cost of the diesel fuel tank is taken from Noll et al. [6], which reports a distributed (PERT) range in EUR_{2019} per kWh for the diesel segment: 0.15 (min), 0.21 (most likely), and 0.26 (max) $€_{2019}$/kWh. To align with our model, we convert these to a mass basis using the diesel lower heating value (LHV = 11.86 kWh/kg):

Cost [€/kg] = Cost [€/kWh] × 11.86.

This yields 1.78, 2.49, and 3.08 $€_{2019}$/kg, respectively. We then express all values in $€_{2025}$ using a cumulative price increase of 23.74% from 2019 to 2025 [10], i.e., multiplying by 1.2374. The resulting $€_{2025}$/kg values used in the ScenarioData sheet are: Low = 2.20 €/kg, Base = 3.08 €/kg, and High = 3.81 €/kg. These values are kept constant over time, as almost no material learning effect is expected for conventional diesel tank systems.

Hydrogen tank cost per kilogram. The cost of hydrogen storage tanks was taken from the ICCT study on the total cost of ownership of alternative powertrain technologies for Class 8 long-haul trucks [14]. The direct manufacturing costs reported are 1'261 USD/kilogram in 2022, 844 USD/kilogram in 2030, and 675 USD/kilogram in 2040. To obtain values for the intermediate years, we apply linear interpolation (eq. 4.2). For instance, the interpolated 2025 value between 2022 and 2030 yields $C(2025)$=1'126 €/kg, and 2035 interpolated between 2030 and 2040 gives $C(2035)$=790 €/kg. The 2050 value is extrapolated by extending the 2030–2040 trend, resulting in 530 €/kg. All costs are expressed in €2025 using a conversion factor of 1 USD_{2022} = 1.04 EUR_{2025} (4.1). Scenario bounds are defined as Low = Base × 0.7 and High = Base × 1.3.

Hydrogen price. We adopt average European green hydrogen price points from the ICCT Working Paper 2023–28 [16], reported in $€_{2023}$/kg, by doing the mean of the price for 5-LH (500 km), 5-LH (800 km), 5-LH (1,000 km) and 4-RD and we obtain: 10.38 (2023), 7.85 (2030), and 5.91 (2040). To express values in $€_{2025}$, we apply an annual inflation rate of 2.86% for two years (2023 → 2025), i.e. ×0.0286 [10]. This yields 10.98 $€_{2025}$kg (2023), 8.30 $€_{2025}$/kg (2030), and 6.26 $€_{2025}$/kg (2040).

Intermediate years are obtained by linear interpolation (eq. 4.2). giving 10.21 €$_{2025}$/kg for 2025 (between 2023 and 2030) and 7.28 €$_{2025}$/kg for 2035 (between 2030 and 2040). For 2050, we linearly extrapolate the 2030–2040 trend (about −0.204 €/kg/year) to obtain 4.22 €$_{2025}$/kg. These values define the Base scenario in the ScenarioData sheet; Low/High scenarios are implemented as deviations of −10% and +10%, respectively.

Diesel price per liter. The operational energy price for diesel in Switzerland was derived from recent market data. According to *GlobalPetrolPrices.com*, the price of diesel fuel in Switzerland was 1.76 CHF/L as of 1 September 2025 [17]. This value was converted into euros using the official exchange rate of 1.76 CHF = 1.90 EUR [18], yielding a base diesel price of 1.90 EUR/L. To reflect uncertainty, we define a low scenario of 1.60 EUR/L and a high scenario of 2.20 EUR/L (± 0.3 €/L). As future diesel prices are highly volatile and cannot be predicted with confidence, these values are assumed constant across all scenario years (2025–2050).

Electricity price per kWh. Public charging costs for electricity in Switzerland were derived from ewz (Elektrizitätswerk der Stadt Zürich) data for both private customers and business users [19], [20]. For DC public charging, we defined three scenarios: a low price of 0.50 CHF/kWh (based on ewz and ENIWA tariffs), a base price of 0.62 CHF/kWh (the mean of ewz 0.50, ENIWA 0.50, evpass 0.79, GOFAST 0.59, MOVE 0.62, and Plug'n Roll 0.74), and a high price of 0.79 CHF/kWh (evpass AC). These values are assumed to remain constant across all scenario years (2025–2050).

Manufacturer markup factors. Indirect cost multipliers (ICMs) are applied to account for additional expenses such as research and development, overhead, marketing and distribution, warranty expenditures, as well as for-profit margins. Following the ICCT Working Paper 2023-10 on the purchase costs of zero-emission trucks in the United States [12], we distinguish between two complexity levels.

For *High 1* (chassis, cabin, battery packs, electric drive), the base scenario markup factor is set to 1.27. The 2025 value corresponds to the midpoint between 2020 and 2030, while the high scenario is defined as +30% from the base, and the low scenario is fixed at 1.10.

For *High 2* (fuel cells and hydrogen storage), the base scenario markup factor is set to 1.368. As for High 1, the high scenario is defined as +30% from the base, and the low scenario remains at 1.10.

The 2030 values of the model corresponds to 2030 values of the ICCT and then the values are kept constant beyond 2030 (for 2030, 2035 and 2050).

Annual mileage. The annual mileage of long-haul trucks in Switzerland was derived from the Swiss e-Cargo study [21]. For the base scenario, we assume 97'500 km/year, in line with observed operational data. The low and high scenarios are based on daily driving distances of 300 km/day and 450 km/day ([21]) over 260 assumed operating days, corresponding to 78'000 km/year and 117'000 km/year, respectively.

For regional trucks, the annual mileage is taken as 28'600 km/year, which corresponds to a representative daily distance of 110 km/day ([21]) over 260 assumed operating days. The low and high scenarios are defined as ±30% around the base value, yielding 20'020 km/year and 37'180 km/year. This range is consistent with additional evidence from the company *Infras*, where the average value of 36'597 km/year lies within the uncertainty bounds.

Maintenance costs. Maintenance cost assumptions are based on Table 5 of the ICCT European TCO study [16], which reports values in €/100 km for different truck classes and powertrain types in 2023. For diesel long-haul trucks, the baseline value is 18.50 $€_{2023}$/100 km, corresponding to 0.185 $€_{2023}$/km. After adjustment to €2025 using a cumulative EU inflation factor of 1.0286 for 2023–2025, this yields 19.03 $€_{2025}$/100 km or 0.190 $€_{2025}$/km. Regional diesel trucks (4-RD) are reported at 15.77 $€_{2023}$/100 km, updated to 16.22 $€_{2025}$/100 km (≈ 0.162 $€_{2025}$/km).

Battery-electric trucks show lower maintenance requirements: 13.24 $€_{2023}$/100 km for long-haul (13.62 $€_{2025}$/100 km, ≈ 0.136 $€_{2025}$/km) and 10.51 $€_{2023}$/100 km for regional duty (10.81 $€_{2025}$/100 km, ≈ 0.108 $€_{2025}$/km).

Fuel-cell trucks are assumed to follow the same cost structure as diesel in the 2023 study, i.e. 18.50 $€_{2023}$/100 km for long-haul and 15.77 $€_{2023}$/100 km for regional. Accordingly, values in €2025 become 19.03 $€_{2025}$/100 km (≈ 0.190 $€_{2025}$/km) for long-haul and 16.22 $€_{2025}$/100 km (≈ 0.162 $€_{2025}$/km) for regional operations. These values are consistent with the "Hydrogen fuel cell 2023" rows of the ICCT dataset. For hydrogen fuell cell 2030 and beyond the study report 13.78 €/100km for long haul and 11.05 €/100km for regional.

All values reported above are entered into the `ScenarioData` sheet of the Excel model as base assumptions. Low/High scenario ranges are implemented as ±30% deviations from the base values to capture parameter uncertainty.

Insurance rate. The annual insurance premium for heavy-duty trucks is modeled as a fixed fraction of the capital expenditure (CAPEX). Following Noll et al. (2022) [6], we assume a base value of 2% of the truck CAPEX per year. To capture uncertainty, scenario variation is represented as ±30% around the base, corresponding to a range of 1.4%–2.6% of CAPEX/year. These values are suppose to remain constant accross the years.

Exhaust treatment cost. The cost of the exhaust aftertreatment system (including SCR, DPF, and DEF tank) was taken from Noll et al. (2022) [6], who reported a value of 0.71 €/kg kerb weight in 2019 euros. This value was adjusted to 2025 using the EU inflation calculator [10], resulting in a base cost of 0.88 €/kg. To capture uncertainty, a low scenario of 0.616 €/kg (-30%) and a high scenario of 1.144 €/kg (+30%) were defined. These values are assumed constant across all scenario years (2025–2050).

AdBlue price. The parameter `adblue_price_per_L` represents the retail price of AdBlue in Switzerland in CHF/L. For the Base 2025 scenario, a reference value of 0.85 CHF/L was taken from Swiss filling stations (Varo Eclépens; Simond Vufflens-la-Ville; Friderici Tolochenaz; Simond Cheseaux-sur-Lausanne) [22], [23]. Scenario variation is modeled as Base ±30%, leading to a range of 0.595–1.105 CHF/L. This reflects the uncertainty of future price developments while anchoring the baseline on observed 2025 pump values. Due to uncertainties about future prices, the values remain constant in the model accross the years.

Onboard charger cost per kW. The onboard charger cost was derived from ICCT Working Paper 2023-10 on purchase costs of zero-emission trucks in the United States [12]. The study reports 2020 baseline costs of 49, 79, and 165 $/kW (all expressed in 2022 USD). These values were first converted to euros using the 2022 average USD–EUR exchange rate of 0.9513 €/USD [18], yielding baseline costs of approximately 46.6, 75.2, and 156.9 €/kW. ICCT projects cost reductions relative to the 2020 baseline of 19% by 2025 and 28% by 2030. Applying these factors gives 2025 costs of 37.8, 60.9, and 127.1 €/kW, and 2030 costs of 33.6, 54.1, and 113.0 €/kW. As ICCT does not provide further projections, these 2030 values are assumed constant through 2050. For uncertainty, the low and high scenarios correspond to the lowest and highest baseline estimates, while the mid-range estimate is used for the base scenario.

Driver cost. Driver salaries represent a major share of truck operating costs, particularly in Switzerland where wage levels are substantially higher than the European average. Based on Noll et al. (2022) [6], we adopt Swiss annual salaries for medium- and heavy-duty truck drivers of 47’597 € (entry), 64’803 € (mean), and 81’368 € (senior). In the model, the mean salary is used as the base scenario, with low and high scenarios corresponding to entry and senior levels. These values are assumed constant in real terms (expressed in €2022 without further inflation adjustment).

Residual value. Residual (salvage) values are included in the TCO model as fractions of the initial purchase cost. All values are based on Appendix D of the ICCT (2023) European TCO study [16], which reports estimated salvage values after five years of operation for different truck classes and technologies.

For ICEV-diesel (long-haul and regional), reported residual fractions are 26, 27 and 28%, which are nearly identical across duty cycles; therefore a single parameter row is used in the model. Those 3 points correspond respectivelty to the Low, Base and High scenario. For BEV long-haul (5-LH), residual fractions are 16–22–14% (2023), 29–32–34% (2030), and 30–33–35% (2040). Missing years are filled by linear interpolation (e.g. 2025 ≈ 19.7–24.9–19.7%, 2035 ≈ 29.5–32.5–34.5%), and 2050 is extrapolated from the 2030–2040 trend (≈ 31–34–36%). Those 3 points correspond respectivelty to the Low, Base and High scenario. Moreover, for BEV regional (4-RD), the fractions are 24% (2023), 35% (2030), and 37% (2040), with intermediate years interpolated (e.g. 2025 ≈ 27.1%, 2035 ≈ 36%) and 2050 extrapolated to ≈ 39%. Low and High scenarios are defined as ±30% relative to the Base value (for BEV regional).

For FCEV long-haul, reported values are 22% (2023), 32, 33 and 33% (2030), and 33–35% (2040); intermediate years are linearly interpolated and 2050 extrapolated (e.g. ≈ 34, 37 and 37%). For FCEV regional (4-RD), the fractions are 24% (2023), 32% (2030), and 36% (2040); interpolation yields 2025 ≈ 26.7% and 2035 ≈ 34%, while extrapolation to 2050 gives ≈ 38%. Scenario bounds are again defined as Low = Base × 0.7 (-30%) and High = Base × 1.3 (+30%).

Fixed parameters. Several parameters were set as fixed inputs that do not vary accross the years nor accross the scenarios to ensure consistency in the cost modeling framework (for exemple: the AdBlue dosing ratio, the diesel density). For vehicles equipped with SCR (Selective Catalytic Reduction) systems, AdBlue dosing ratios were assumed to vary by vehicle size according to TotalEnergies guidance [24]: 6% of diesel consumption for heavy-duty trucks (over 35 t), 5% for medium-duty trucks, and 3% for light-duty trucks (below 18 t). Infrastructure cost assumptions for battery-electric vehicles were taken directly from Noll et al. [6], who analyzed low-carbon technologies in European road freight. For regional trucks, depot charging equipment (22 kW) was assumed to cost 10’000 €, with installation costs of 3’813 €, and an annual station energy throughput of 66 MWh. For long-haul applications, megawatt-scale charging (150 kW) was assumed at 150’000 € for equipment, 100’000 € for installation, and 450 MWh/year of delivered energy. Operation and maintenance costs were taken as 1% of equipment cost per year, with a charging station lifetime of 15 years.

Battery costs. Battery cost trajectories were parameterized for the main commercially relevant chemistries: NMC-111, NMC-532, NMC-622, NMC-811, NMC-955, LFP, and NCA. Emerging technologies not yet widely applied in trucks, such as LTO, Li–O_2, Li–S, and SiB, were excluded from the model due to the lack of reliable cost data.

For NMC and LFP chemistries, cost assumptions for 2025 and 2030 are based on bottom-up production modeling by Orangi et al. [25] (from their spreadsheet available as supplementary material), with NMC-622 costs taken as the mean of the “NMC622-Gr” and “NMC622-GrSi” pathways. The original values were reported in 2020 USD per kWh. To ensure consistency with the rest of the model, these costs were first converted into EUR using the average 2020 exchange rate (0.8799 EUR/USD) [26], and subsequently adjusted to constant Euro_{2025} values using the cumulative inflation rate for the Euro area between 2020 and 2025 (+22.82%) [27].

This procedure resulted in the following parameterized battery costs (in Euro_{2025}/kWh): NMC-111: 106.99, NMC-532: 99.42, NMC-622: 95.43, NMC-811: 87.97, NMC-955: 83.43, LFP: 74.14. These values were then integrated into the *BatteryCosts* sheet to represent the Base 2025 case.

For the *High* scenario in 2025 and 2030, battery cost assumptions from Hasselwander et al. [28] (expressed in €2023) were converted into €2025 values using the inflation factor 1.0286 from [29]. Moreover, since no cost data for NMC-955 was provided by Hasselwander et al., the *High* scenario for this chemistry was defined as 5% above the corresponding base value.

As for NCA, the values reported by Hasselwander et al. [28] were lower than those in Orangi et al. [25]. To ensure consistency, the two sources were aligned: the *Base* scenario value for NCA was set to 92.57 €/kWh (corresponding to Hasselwander et al. [28]), while the *High* 2025 scenario adopts the 96.07 €/kWh from [25]. The *High* scenario for 2030 was defined as +20% from *Base* Scenario 2030.

The *Low* scenarios for 2025 and 2030 were defined as 5% below the corresponding base values, since these were considered already robust estimates and unlikely to decrease significantly further.

Post-2030 trajectories adopt a learning curve framework using the following formula:

$$b = \frac{\ln(\text{PR})}{\ln(2)}, \qquad \text{cost}_y = \text{cost}_{y_0}\,(1+g)^{\,b\,(y-y_0)}. \tag{4.3}$$

where:

- cost_y is the cost at year y,
- cost_{y_0} is the reference cost at base year y_0,
- PR is the progress ratio ($0.89 \le \text{PR} \le 0.93$),
- $b = \log_2(\text{PR})$ is the learning curve exponent,
- g is the growth rate (doublings of cumulative production per year),

Given evidence that battery cost declines slow down as material cost floors are approached, the historical 20% learning rate (Ziegler & Trancik [30]) was reduced to a conservative range. We choose to apply a progress ratios (PR) of 0.90 in the base case (10% learning rate), 0.89 for the low case (11%), and 0.93 for the high case (7%). These correspond to exponents $b = \log_2(PR)$ of -0.17 (Low), -0.15 (Base), and -0.13 (High). Cumulative production growth rates were set to $g = 0.15$ doublings/year for the base case (one doubling every 6.7 years), $g = 0.17$ for the low case (~5.9 years), and $g = 0.13$ for the high case (~7.7 years).

Overall, this methodology ensures consistency across scenarios while capturing both near-term cell chemistry differences and long-term cost deceleration trends as Li-ion battery costs approach raw material limits.

4.3 Treatment of uncertainty

Uncertainty is incorporated in two complementary ways. First, the `UserInput` sheet contains parameters that the operator is expected to select directly (e.g. usage type, canton, payload). While most of these are scenario choices, some also represent structural uncertainties with major impact on TCO. Examples include `truck_lifetime`, which depends on the average replacement cycle in the operator's fleet, as well as `battery_lifetime_replacements` and `fuel_cell_lifetime_replacements`, which determine the number of costly subsystem replacements over the vehicle's life. However, the vehicle lifetime is set per default to be 15 years, following assumptions in the ICCT White Paper on European heavy-duty vehicle decarbonization [16]. An other example is the discount rate that is set at 9.5% by default (as in ICCT work [16]), but alternative values down to 7% (as in Noll et al. [6]) can be tested.

Second, the `ScenarioData` sheet defines explicit ranges (*Low*, *Base*, *High*) for parameters subject to high variability and/or future developments, such as energy prices (diesel, hydrogen, electricity) or fuel cell costs. Similarly, the `BatteryCosts` sheet specifies cost ranges with uncertainty bounds for Li-ion batteries, differentiated by chemistry (see § 4.2). Selecting a scenario propagates consistently across all cost components and into the final TCO outputs, thereby enabling sensitivity analysis and the identification of robust cost-competitiveness thresholds.

This layered structure ensures that day-to-day use of the tool remains simple for operators, while still allowing systematic exploration of structural uncertainties with high impact on results in research applications.

4.4 Assumptions and system boundaries

We report TCO per ton-kilometre net of VAT, exclude tolls outside Switzerland and heat pump costs. Payload penalties are captured implicitly via the payload normalisation (€/t·km), given GVWR and vehicle mass assumptions in *ScenarioData*. Monetary values are expressed in EUR; CHF figures are converted using a fixed parameter ($\gamma_{\text{CHF-EUR}}$ = 1.07 CHF/EUR) which corresponds to the exchange rate applied to convert Swiss francs into euros on the 30 August, 2025.

4.5 Model refinements and extensions

During the development of the Excel tool, several structural and functional improvements were introduced to increase transparency, flexibility, and robustness. First, the `UserInput` sheet was reorganized into a structured table with unique parameter identifiers and descriptive metadata (value, unit, comment). This allowed replacing cell-specific references (e.g. `UserInput!B21`) with parameter-based lookup formulas. As a result, the order of rows in the *UserInput* sheet can now be changed freely without affecting the consistency of the calculations.

Thus, the systematic use of the `XLOOKUP` function could be implemented to connect model parameters across different sheets. This approach improves readability of formulas and facilitates further extensions of the model, since additional parameters can be integrated without altering the existing structure.

Then, documentation within the Excel file was enhanced by adding clear descriptions, units, and sources for all major input parameters. This ensures that each assumption can be traced back to its origin and allows for greater transparency and reproducibility.

However, these changes alone were not sufficient. To further improve clarity, all cell-based references for which XLOOKUP functions were used or of the type UserInput!Bxx, were replaced by explicit parameter names, which are now used consistently across formulas. For example, instead of writing a cell reference, a formula can now directly use a defined name such as `cargo_mass` because the name parameter is defined like this: `cargo_mass = XLOOKUP("cargo_mass", UserInputTable`

[Parameter], UserInputTable[Value]). This logic has been applied systematically to all user inputs. We believe that this approach could eventually be extended to all parameters in the model, thereby ensuring full transparency and consistency throughout. Indeed, for the moment names are only defined for the most used paramaters and not all.

In addition, categories (BEV, FCEV, ICEV) were introduced in the input table, making it possible to filter or sort inputs by vehicle technology. A dedicated helper column (DVSource) was also created to handle drop-down lists properly, ensuring that predefined value lists (e.g. for usage, canton, truck category, scenario, year) remain linked to the correct parameters even after sorting. For all other parameters, the input cells remain free for numerical entry. Nevertheless, in order to make this work we had to proceed with this DVSource method and create a hidden sheet containing the definition of the lists, so that sorting is not affected. The only drawback is that a drop-down arrow is displayed for every parameter cell, even if no list is actually associated with it.

Furthermore, a composite key was rapidly introduced by concatenating scenario and year, which provides a unique lookup reference for parameters that vary by both scenario definition and time. However, at the beginning of the project, the ScenarioData sheet only included two time points (2025 and 2030). This limited design became problematic when the scope was extended to 2035 and 2050, as every formula had to be manually adjusted to capture the enlarged data range. Moreover, the original implementation relied on INDEX/MATCH combinations that referenced fixed column ranges (e.g. =INDEX(ScenarioData!$D$31:$I$31;MATCH(scenario_year;ScenarioData!$D$5:$I$5;0))). Such formulas were not easily scalable and required frequent updates. So, after having replace them with XLOOKUP (e.g. =XLOOKUP(scenario_year; ScenarioData!5:5; ScenarioData!31:31)), all fixed column ranges (e.g. ScenarioData!D6:I6) were replaced by entire row ranges (e.g. ScenarioData!6:6), which makes the formulas automatically scalable when new years are added.

5 Application to European and Swiss scenarios

5.1 Swiss-specific parameters

While most cost inputs in the model are aligned with the European Carculator framework [4], a subset of parameters had to be adjusted to reflect the Swiss context. These differences are non-negligible, as Switzerland exhibits significantly higher costs in several categories compared to the European baseline.

- **Annual mileage:** In Europe, long-haul trucks typically record average annual mileages of around 158'000 km, and regional trucks around 78'000 km [16]. In contrast, Swiss-specific data from the Swiss e-Cargo study provide average daily mileages, which, when annualized, correspond to approximately 97'500 km for long-haul and 28'600 km for regional operation [21]. These lower usage levels strongly affect the normalization of fixed costs over distance.
- **Taxation:** Switzerland applies both the federal LSVA charge (see §5.3) and cantonal vehicle taxes (see §5.4), which represent substantial recurring costs [31]. In contrast, European taxation is generally based on road tolls, fuel excise duties, or vignettes under the EU Directive 1999/62/EC, with lower impacts on TCO calculations.
- **Electricity costs:** Public charging tariffs in Switzerland are considerably higher than the average European levels. For heavy-duty trucks, this directly increases the operational costs of BEVs.
- **Fuel prices:** Diesel and AdBlue prices in Switzerland are above the European average, leading to higher operational expenditures for ICEV-d compared to large EU markets such as Germany or France.
- **Driver wages:** Labor costs in Switzerland are among the highest in Europe, representing a major share of total operating costs [6] .

All other cost parameters specified in the *ScenarioData* and *FixedParameters* sheets are based on European sources wherever possible. In cases where reliable European data were not available, US datasets were used as proxies. Therefore, all of the other cost parameters can be used directly in the Carculator framework.

5.2 European baseline: taxation

This tool has been developed in euros, aligned with the original European focus of the Carculator model. Although it includes Swiss-specific charges such as LSVA and cantonal taxes, in a purely European context these components would typically be excluded, as they are not EU-wide obligations. In Europe, road transport taxation is highly heterogeneous across Member States, combining distance-based tolls, time-based vignettes, and ownership taxes. At the EU level, only minimum requirements apply under Directive 1999/62/EC (Eurovignette Directive).

The magnitude of these costs differs substantially between Switzerland and its European neighbors. In Switzerland, the LSVA alone represents approximately 0.03–0.07 €/t·km for Euro VI trucks, before adding cantonal taxes. By contrast, in the EU, road charges are generally lower. For instance, the Comité National Routier (CNR) reports that motorway tolls for Euro VI trucks average around 0.20 €/km across major Member States, corresponding to roughly 0.005–0.02 €/t·km depending on payload assumptions (respectively for 40t and 10t) [31]. Country examples illustrate the variation:

- **Germany**: Maut tolls apply on more than 52'000 km of roads, with a rate of 0.183 €/km for Euro VI 40-tonne trucks [31].
- **France**: about 12'000 km of tolled motorways, with costs of 0,239 €/km [31].

- **Austria and Slovenia**: among the highest rates, up to respectively 0.42 and 0.43 €/km on motorways [31].

A striking difference emerges when comparing the relative weight of road taxation in Switzerland and in the European Union. In Switzerland, the federal heavy vehicle fee (LSVA) alone accounts for almost half of the total cost of ownership of a 40 t diesel truck with a 20 t payload (based on 0.056 €/t·km over a total of 0.13 €/t·km, see section 6). By contrast, according to the ICCT Working Paper 2023-28 [16], distance-based road charges in the EU long-haul baseline for 2023 represent only about 13% of the total cost (0.156 €/km out of 1.21 €/km for a Euro VI diesel truck of the same weight). This highlights how the Swiss LSVA constitutes a much stronger fiscal driver in the TCO framework compared to the taxation schemes applied in major EU markets.

Thus, although the model is expressed in euros for consistency, its inclusion of Swiss-specific fiscal instruments makes results less directly comparable to a European baseline.

5.3 Swiss scope: LSVA taxation of heavy-duty vehicles

In Switzerland, all heavy-duty vehicles (HDV) above 3.5 tonnes are subject to the *Leistungsabhängige Schwerverkehrsabgabe* (LSVA), or *Redevance Poids Lourds Proportionnelle aux Prestations* (RPLP) in French. The LSVA is a distance- and weight-based fee (in CHF/t·km) applied to both domestic and foreign trucks [32]. It constitutes a significant cost component in the TCO of freight vehicles and plays a central role in determining the competitiveness of alternative powertrains.

In the current model, the LSVA cost is computed in the respective *TCO* sheet of each techology as a function of parameters detailed in the *LSVATax* sheet: (i) the tariff by vehicle emission category, (ii) the payload, and (iii) the distance driven annually. The resulting cost in CHF/t·km is then converted to €/t·km at a fixed exchange rate of 1.07 (CHF/EUR, as of 30.08.2025) in the *FixedParameters* sheet.

LSVA base tariffs by vehicle category. The LSVA scheme differentiates between three categories. Category I applies to older trucks (Euro 0–V). Category II applies to Euro VI and VII trucks from 2029 onwards. Category III applies to Euro VI and VII trucks until 2028, and to BEV and FCEV starting in 2029. Until 2028, BEV and FCEV remain fully exempt from LSVA. This change was officially announced by the Swiss Federal Council on the **28 May 2025**, marking the gradual integration of zero-emission trucks into the LSVA scheme [32]. Table 4 summarizes the values implemented in the model.

Table 4: LSVA/RPLP base tariffs by vehicle category [32].

Parameter	Value	Unit	Comment
`lsva_first_category`	0.0326	CHF/t·km	Euro 0–V
`lsva_second_category`	0.0282	CHF/t·km	Euro VI and VII (from 2029)
`lsva_third_category`	0.0239	CHF/t·km	Euro VI/VII until 2028, BEV/FCEV from 2029

Transitional rebates for BEV and FCEV (2029–2035). While BEVs and FCEVs are exempt from LSVA until 2028, a gradual integration into the LSVA scheme is foreseen starting in 2029. A declining rebate is applied to their LSVA cost, beginning at 70% in 2029 and phasing out completely by 2035, after which zero-emission trucks pay the full Category III tariff. This implementation captures the transitional nature of fiscal incentives and their erosion over time. Table 5 details the rebate schedule.

Table 5: Transitional LSVA rebate for BEV and FCEV (2029–2035) [33].

Year	Rebate fraction
2029	0.7
2030	0.6
2031	0.5
2032	0.4
2033	0.3
2034	0.2
2035	0.1

Implications. The introduction of LSVA charges for BEV and FCEV after 2029 reduces their cost advantage compared to diesel. However, as shown in stakeholder consultations within the Swiss e-Cargo project, LSVA exemption has so far been a key driver for adoption of e-trucks. The gradual phasing-in of LSVA therefore represents both a fiscal necessity and a potential risk for fleet electrification.

5.4 Swiss scope: Cantonal vehicle taxation of heavy-duty vehicles

In addition to the federal LSVA/RPLP fee, Swiss cantons levy their own vehicle taxes on heavy-duty trucks. These cantonal charges represent a recurring annual cost. In the TCO model, the gross cantonal tax is calculated in a dedicated worksheet *CantonalTax* and subsequently integrated into the technology-specific TCO sheets (ICEV, BEV, FCEV).

The structure of cantonal taxation varies significantly:

- **Vaud:** fixed base rate up to 4 t (450CHF) and a surcharge per additional tonne (+78CHF per extra tonne). BEV/FCEV benefit from a 90% reduction, while Euro 6 (and Euro 7) ICEVs receive a 35% reduction. [34]
- **Bern:** base rate for the first tonne (240CHF), with a decay factor (0.86 per extra tonne) applied for each additional tonne. BEVs pay half the base rate (120CHF) and benefit from an additional 60% reduction for the first four years of registration. However, there is no mention for fuel cell electric trucks, so we supposed that they have the same discount than BEV. [35]
- **Geneva:** progressive tariff table defined for half-tonne increments of gross vehicle weight (GVWR). There is a 50% rebate from 2025 onward for BEV and FCEV tucks.[36]
- **Zurich:** two-part structure combining a weight-based component (CHF per tonne of GVWR) and an emission surcharge depending on Euro category (e.g. CHF 900 for Euro 0–V, CHF 300 for Euro VI/VII). [37]
- **Fribourg:** stepwise tariff depending on GVWR, with values specified for representative weight classes. There is no rebate mentionned for BEV and FCEV. [38]
- **Graubünden:** tax fully based on gross vehicle weight according to a detailed tariff table.[39] For electric trucks an approximate 80% reduction applies; no precision is given for hydrogen, so the same rebate is assumed for FCEVs.
- **Ticino:** taxation is based on a fixed component (105CHF) plus a proportional part calculated as 10CHF per registered kW of engine power (it corresponds to the parameter entered by the user: for BEV/FCEV: `electric_power` and for ICEV-d: `combustion_power`. No automatic rebate applies to BEVs or FCEVs, but exemptions may be requested under Article 6 of the cantonal law.[40]

Table 6 provides an overview of the different schemes implemented in the model.

Table 6: Overview of cantonal tax structures for heavy-duty trucks (CHF/year).

Canton	Tax basis	Special reductions
Vaud	Base fee (≤4 t) + surcharge/ton	ZET −90%, Euro VI/VII ICEV −35%
Bern	Base for first tonne + decay factor	ZET −50% the base rate, extra −60% for 4 years
Geneva	Progressive tariff by 0.5 t steps	ZET: 50% rebate from 2025 onwards
Zurich	Weight-based + emission surcharge	Lower surcharge for Euro VI/VII, no surcharge for ZET
Fribourg	Stepwise by GVWR brackets	None
Graubünden	Tariff table by GVWR	ZET: approx. −80%
Ticino	105CHF + 10CHF per registered kW	Possible rebate on request

Implementation of cantonal taxation in the model. In the Excel tool, the gross annual cantonal tax is computed as a base amount retrieved from the *CantonalTax* sheet, optionally adjusted by canton- and technology-specific reductions, then normalized to EUR/t·km.

ICEV-d (diesel). The base lookup $C_{\text{base}}^{\text{ICEV}}$ [CHF/year] with C the cost in CHF follows the conditional structure below (exactly as coded in Excel):

$$C_{\text{base}}^{\text{ICEV}} = \begin{cases} C_{F78} + S_{\text{Euro}} & \text{if canton = Zurich, with } S_{\text{Euro}} = \begin{cases} C_{E62} & \text{Euro 0–V,} \\ C_{E63} & \text{Euro VI/VII,} \end{cases} \\ C_{H160} & \text{if canton = Graubünden,} \\ C_{B154} & \text{if canton = Ticino,} \\ C_{F78} & \text{otherwise.} \end{cases}$$

Notes. (i) In Graubünden, the table is indexed by GVWR (rounded down to the nearest 100 kg; if GVWR > 40 t, the 40 t row is used). (ii) In Ticino, the ICEV-d tariff corresponds to the cantonal rule captured in cell `B154`.

The multiplicative reduction factor $R_{\text{canton}}^{\text{ICEV}}$ for ICEV-d is:

$$R_{\text{canton}}^{\text{ICEV}} = \begin{cases} 1 - r_{\text{Euro6}} & \text{if canton = Vaud and Euro VI/VII with } r_{\text{Euro6}} = 0.35\text{ ,} \\ 1 & \text{if canton} \in \{\text{Geneva, Fribourg, Bern, Zurich}\} \text{ or otherwise.} \end{cases}$$

Finally, the per-tonne-km cost (EUR/t·km) is:

$$c_{\text{cantonal}}^{\text{ICEV}} = \frac{C_{\text{base}}^{\text{ICEV}} \cdot R_{\text{canton}}^{\text{ICEV}} \cdot \gamma_{\text{CHF-EUR}}}{m_{cargo} \cdot D_{\text{annual}}^{\text{ICEV}}}.$$

We have m_{cargo} = cargo mass [t] and $\gamma_{\text{CHF-EUR}}$ = currency conversion factor [€/CHF]. In Excel, the annual mileage $D_{\text{annual}}^{\text{ICEV}}$ is read from `ScenarioData` (row 28 for long-haul, row 29 for regional, selected by `usage`), C_{XY} indicates that the cost is taken from cell (column X, row Y) in the *CantonalTax* sheet.

BEV and FCEV. For zero-emission trucks, the base lookup $[CHF/year]$ is:

$$C_{\text{base}}^{\text{ZEV}} = \begin{cases} C_{H159} & \text{if canton = Graubünden,} \\ C_{B153} & \text{if canton = Ticino,} \\ C_{F78} & \text{otherwise.} \end{cases}$$

The reduction factor is:

$$R_{\text{canton}}^{\text{ZEV}} = \begin{cases} 1 - r_{\text{BEV}} & \text{if canton = Vaud with } r_{\text{BEV}} = 0.9, \\ 1 - \dfrac{0.5 \cdot \max\big(0,\ Y_{\text{reg}} + L - 1 - \max(Y_{\text{reg}}, 2025) + 1\big)}{L} & \text{if canton = Geneva,} \\ \dfrac{C_{\text{BEV}}}{C_{\text{ICEV}}} \left(1 - r_{\text{extra}} \cdot \dfrac{\min(L, Y_{\max})}{L}\right) & \text{if canton = Bern,} \\ 1 & \text{if canton} \in \{\text{Zurich, Fribourg}\} \text{ or otherwise.} \end{cases}$$

The normalized cost (EUR/t·km) is:

$$c_{\text{cantonal}}^{\text{ZEV}} = \frac{C_{\text{base}}^{\text{ZEV}} \cdot R_{\text{canton}}^{\text{ZEV}} \cdot \gamma_{\text{CHF-EUR}}}{m_{\text{cargo}} \cdot D_{\text{annual}}^{\text{ZEV}}}.$$

In Excel, $D_{\text{annual}}^{\text{ZEV}}$ is read from `ScenarioData` (rows 30–31, selected by `usage`, as in the current BEV/FCEV formulas) and L corresponds to `truck_lifetime`.

Parameters (consistency with Excel).

- Vaud: $r_{\text{BEV}} = 0.90$ (BEV/FCEV), $r_{\text{Euro6}} = 0.35$ (ICEV Euro VI/VII).
- Geneva (BEV/FCEV): time-limited 50% rebate from 2025, implemented as a lifetime share (exactly as in the sheet).
- Bern (BEV/FCEV): with $Y_{\max} = 4$ years.
- Zurich (ICEV-d): Euro surcharge is additive in the base $C_{\text{base}}^{\text{ICEV}}$ (cells `E62/E63`), not a multiplicative factor.
- Graubünden: `H160` (ICEV-d), `H159` (BEV/FCEV); GVWR rounding to 100 kg and cap at 40 t.
- Ticino: `B154` (ICEV-d), `B153` (BEV/FCEV).

Implications. Preferential treatment for BEVs (e.g. in Vaud and Bern) can strengthen their competitiveness, particularly in the early years of adoption when purchase costs remain high. In Bern, for instance, BEVs benefit from both a structurally lower base fee and a temporary additional rebate, which makes their fiscal burden substantially lighter during the first four years of operation. However, the long-term stability of such reductions remains uncertain, which may limit their effectiveness in de-risking investments.

In the current version of the model, seven cantons are implemented (Vaud, Geneva, Bern, Zurich, Fribourg, Graubünden, and Ticino). These examples highlight the diversity of cantonal approaches, which complicates uniform modelling. This selection reflects both data availability and the heterogeneity of cantonal rules: each canton applies its own legal framework and tariff structure, and extending coverage to all 26 would have required significant additional effort.

Nevertheless, when compared to other cost items, cantonal taxes remain relatively minor contributors to total cost of ownership. By contrast, the federal heavy vehicle fee (LSVA/RPLP) is a far more significant driver of cost differentials across powertrains, especially in long-haul operations. For this reason, cantonal taxation has been integrated with a focus on representativeness rather than completeness.

6 Results: comparative TCO analysis

6.1 Long-haul trucks: cost breakdown by technology

6.1.1 Long haul - 2025

This section presents the comparative total cost of ownership (TCO) results obtained from the Excel model, using the illustrative input settings summarized in Table 1. The analysis covers three drivetrain technologies: conventional diesel (ICEV-d), battery-electric (BEV), and fuel-cell electric (FCEV), for the baseline year 2025, the Zurich canton, a truck with a GVWR of 38t and a cargo mass of 20t.

Table 7 reports the detailed cost breakdown per cost component. All recurring items are expressed in €/t·km, while upfront costs are translated into annuitized values through the amortisation factor. Residual credits are deducted at the end-of-life and reported here as negative contributions.

Table 7: Comparative TCO breakdown by cost component (Base 2025, Zurich canton).

Cost component	Unit	ICEV-d	BEV	FCEV
Purchase price	€	121 858,68	190 085,19	569 904,09
Amortised purchase price	ct./t·km	0,80	1,25	3,73
Amortised component repl. price	ct./t·km	0	0	1,12
Energy cost	ct./t·km	2,06	3,11	4,01
Maintenance cost	ct./t·km	1,02	0,68	0,95
Insurance cost	ct./t·km	0,12	0,19	0,58
Infrastructure cost	ct./t·km	0	0,23	0
Cantonal tax cost	ct./t·km	0,16	0,14	0,14
LSVA tax cost	ct./t·km	5,21	1,07	1,07
Driver cost	ct./t·km	3,32	3,32	3,32
Residual credit	ct./t·km	0,06	0,08	0,21
Total cost of ownership	ct./t·km	**12,64**	**9,92**	**14,71**
Total cost of ownership	€/km	**2,527**	**1,984**	**2,943**

Note: 'ct.' denotes euro cents (1 ct. = €0.01).

Figures 1–2 illustrate the cost structure and overall TCO comparison. Figure 1 displays the breakdown per cost component in €/t·km across the three technologies, while Figure 2 compares the total cost of ownership per ton-kilometer.

The results highlight significant differences in cost structure:

- **ICEV-d**: The largest single contributor is the LSVA heavy vehicle fee, followed by driver cost and then energy cost. Despite a relatively low purchase price, the overall TCO reaches 12.64 ct./t·km.
- **BEV**: Higher upfront purchase cost is partly offset by lower maintenance expenses. Infrastructure costs are visible but modest. Energy costs are relatively higher for BEVs than for ICEVs due to the assumption of 50% public charging in long-haul operation. Unlike regional duty cycles, long-haul transport cannot rely solely on depot charging, and public charging prices in Switzerland remain significantly higher. However, the exemption from LSVA charges until 2029 provides a substantial advantage compared to ICEV-d. Overall, **BEVs achieve the lowest TCO** at 9.92 ct./t·km.
- **FCEV**: Dominated by very high purchase and fuel cell costs, combined with expensive hydrogen consumption. Even with LSVA exemption, the TCO rises to 14.71 ct./t·km, making FCEVs the least cost-competitive option in this scenario.

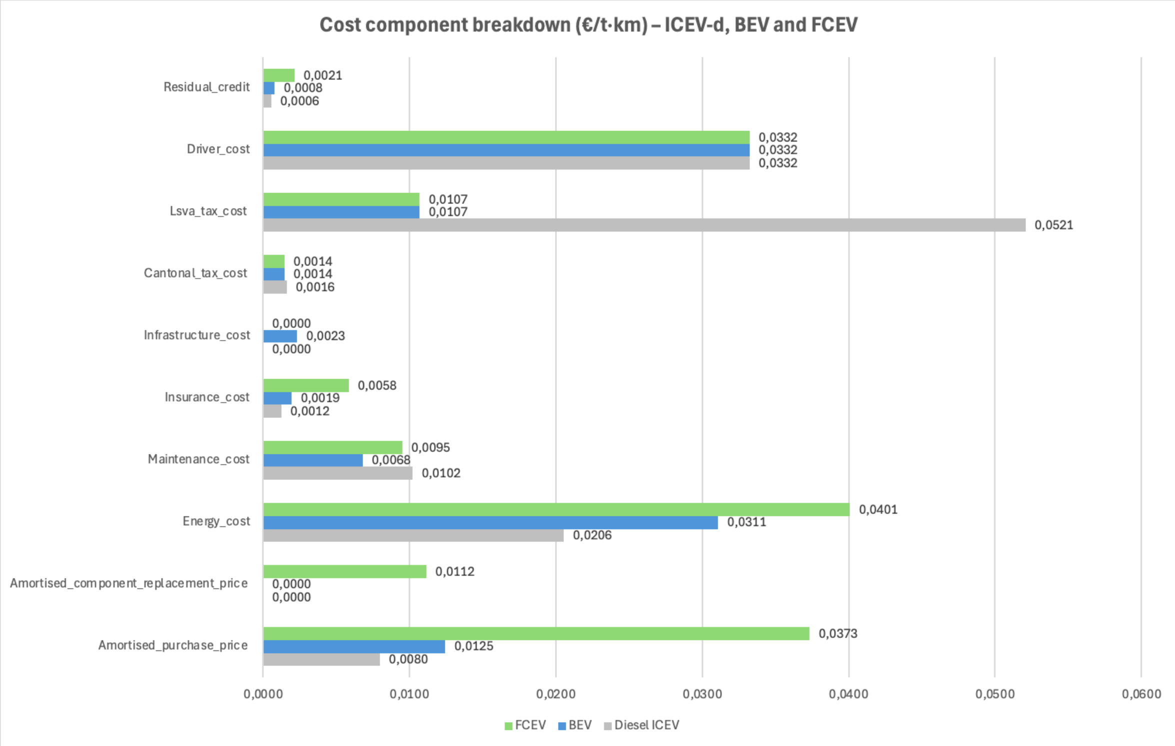

Figure 1: Comparison of cost components in €/t·km for ICEV-d, BEV, and FCEV (Long haul - Base 2025).

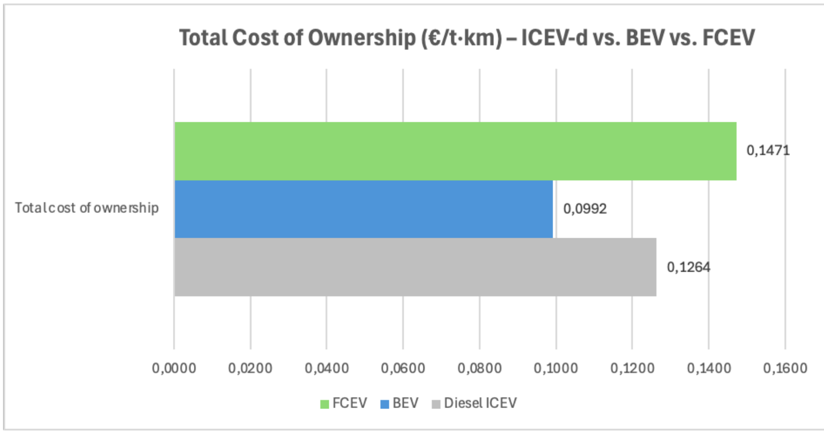

Figure 2: Total cost of ownership in €/t·km (Long haul - Base 2025).

6.1.2 Long haul - 2030

For the long-haul configuration (GVWR 38 t, cargo mass 20 t) with an equal split between depot and public charging, the Base 2030 scenario produces the results shown in Figures 9–7. Purchase prices amount to €112'696 for ICEV-d, €128'747 for BEVs, and €324'401 for FCEVs. As illustrated in Figure 8, the amortised purchase cost is lowest for ICEV-d at 0.0074 €/t·km, closely followed by BEVs at 0.0084 €/t·km, while FCEVs remain substantially higher at 0.0213 €/t·km. Component replacement costs are inexistent for diesel and BEVs but reach 0.0050 €/t·km for FCEVs (with a selected fuel cell replacement of 1 across the truck's lifetime).

Energy costs represent a key driver in long-haul operations, with values of 0.0206, 0.0311, and 0.0318 €/t·km for ICEV-d, BEV, and FCEV respectively. Maintenance costs favour BEVs (0.0068 €/t·km) compared to 0.0102 for ICEV-d and 0.0095 for FCEVs. Insurance remains a small contributor, at 0.0012, 0.0013, and 0.0033 €/t·km respectively. BEVs also incur infrastructure costs of 0.0023 €/t·km, reflecting partial reliance on depot charging. Cantonal taxes remain around 0.0016–0.0014 €/t·km, while LSVA is the dominant tax burden for ICEV-d (0.0521 €/t·km) compared to 0.0107 €/t·km for BEV and FCEV. Driver costs are uniform across technologies at 0.0332 €/t·km. Residual credits partially offset these costs, ranging from 0.0005 for diesel to 0.0007 and 0.0018 for BEVs and FCEVs.

Overall, the total cost of ownership amounts to 12.57, 9.46, and 11.45 ct./t·km for ICEV-d, BEV, and FCEV respectively, corresponding to 2.514, 1.893, and 2.289 €/km. Under these assumptions, **BEVs clearly outperform both diesel and hydrogen trucks** in long-haul operation by 2030, while FCEVs remain more costly than BEVs but start approaching parity with diesel.

6.1.3 Long-haul - 2050

In the Base 2050 long-haul scenario (GVWR 38 t, cargo mass 20 t, 50% depot / 50% public charging, first registration year 2045), the purchase prices shown in Figure 12 amount to €118'807 for ICEV-d, €114'255 for BEVs, and €229'963 for FCEVs. The detailed cost breakdown in Figure 11 highlights amortised purchase costs of 0.0078, 0.0075, and 0.0151 €/t·km for ICEV-d, BEV, and FCEV respectively. Hydrogen trucks continue to bear component replacement costs (0.0030 €/t·km), while these remain negligible for ICEV-d and BEVs as 0 battery replacement over the truck's lifetime was selected.

Energy costs are 0.0206, 0.0311, and 0.0154 €/t·km respectively, reflecting declining hydrogen prices, while electricity charging tariffs are assumed constant across the years in Switzerland due to the absence of reliable projections. This assumption limits potential future cost reductions for BEVs, while favouring FCEVs in the long run. Maintenance (0.0102, 0.0068, 0.0095 €/t·km) and insurance (0.0012, 0.0012, 0.0024 €/t·km) remain lower for BEVs than for diesel and hydrogen trucks. BEVs also retain an infrastructure surcharge of 0.0023 €/t·km.

Cantonal and LSVA taxes are higher for ICEV-d (0.0573 €/t·km) compared to BEVs and FCEVs (0.0486 €/t·km). Driver wages remain the dominant contribution at 0.0332 €/t·km across all technologies. Residual credits are modest, ranging from 0.0005 for diesel to 0.0007 and 0.0014 for BEVs and FCEVs.

As reported in Figure 10, the resulting total cost of ownership converges to 0.1314, 0.1315, and 0.1272 €/t·km for ICEV-d, BEV, and FCEV respectively, corresponding to 2.628, 2.630, and 2.544 €/km. These results indicate that FCEVs achieve a slightly lower TCO than BEVs under these assumptions, primarily due to the constant electricity tariff assumption that prevents BEVs from realising long-term energy cost reductions.

A sensitivity analysis on truck lifetime reveals that this ranking reverses for shorter replacement cycles. When the lifetime is reduced to 8.5 years or less, BEVs achieve the lowest TCO, followed by FCEVs (see figure 13). In this case, the total cost of ownership amounts to 0.1336, 0.1334, and 0.1335 €/t·km for ICEV-d, BEV, and FCEV respectively, corresponding to 2.672, 2.668, and 2.669 €/km. This illustrates that shorter lifetimes penalise hydrogen trucks disproportionately, as their higher upfront and replacement costs are amortised over fewer operating years, while BEVs remain more resilient to this effect.

Furthermore, if the number of fuel cell replacements over the vehicle lifetime is set to 0 (instead of 1), the hydrogen storage mass is reduced from 80 kg to 60 kg, and the truck lifetime is kept at 15 years, the TCO of FCEVs drops well below that of BEVs and ICEVs, reaching only 12.32 ct./t·km (see fig. 14). Under these assumptions, the threshold for `truck_lifetime` becomes 3.5 years: once this value is reached, FCEVs consistently remain the lowest-cost option. This suggests that, by 2050, **FCEVs could emerge as the most competitive technology for long-haul applications**, provided fuel cell durability improves and hydrogen storage requirements decrease.

6.2 Regional trucks: cost breakdown by technology

6.2.1 Regional - base 2025

Using the illustrative input settings summarized in Table 1, but modified for a regional application with usage set to regional, `GVWR` set to 22 t, `cargo_mass` to 12 t, and depot charging only, the model produces the following results. The upfront purchase prices are reported in Figure 6, showing values of €129'490 for ICEV-d, €181'702 for BEV, and €561'521 for FCEV. The corresponding cost component breakdown is shown in Figure 3: amortised purchase costs of 4.82, 6.76, and 20.90 ct/t·km for ICEV-d, BEV, and FCEV respectively, with additional contributions from energy costs (3.43, 3.46, 6.68 ct/t·km), maintenance (1.45, 0.90, 1.35 ct/t·km), insurance (0.75, 1.06, 3.27 ct/t·km), and cantonal taxation (0.57, 0.47, 0.47 ct/t·km). For BEVs, depot infrastructure costs contribute an additional 0.29 ct/t·km. LSVA charges amount to 5.03, 1.03, and 1.03 ct/t·km respectively, while residual credits partially offset costs with 0.33, 0.47, and 1.43 ct/t·km. Driver wages dominate the overall structure at 18.88 ct/t·km across all powertrains.

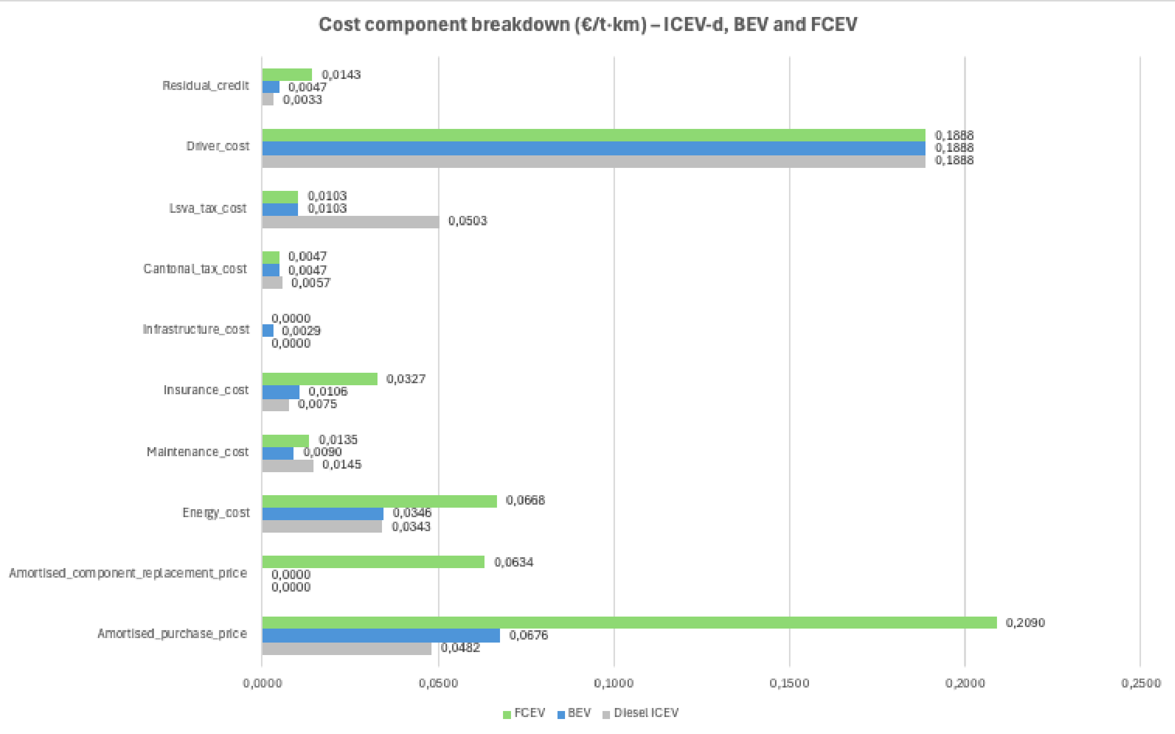

Figure 3: Comparison of cost components in €/t·km for ICEV-d, BEV, and FCEV (Regional - Base 2025).

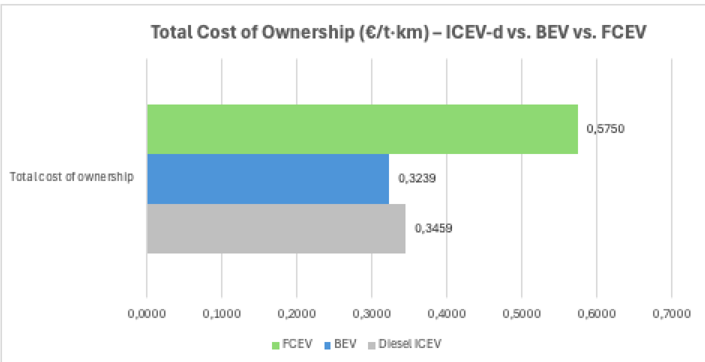

Figure 4: Total cost of ownership in €/t·km (Base 2025).

The resulting total cost of ownership is reported in Figure 4: 34.59, 32.39, and 57.50 ct/t·km for ICEV-d, BEV, and FCEV respectively, corresponding to 4.15, 3.89, and 6.90 €/km. Under these regional assumptions, **BEVs achieve a clear cost advantage** over both diesel and hydrogen trucks, while **FCEVs remain significantly less competitive**.

6.2.2 Regional – Base 2030

Using the same regional configuration as in the Base 2025 case (GVWR 22 t, cargo mass 12 t, depot charging only) but extended to the year 2030, the cost structure evolves as reported in Figure 5. Purchase prices fall substantially for BEVs and FCEVs, reaching €121'178 and €316'832 respectively, while diesel trucks remain close to €120'215. Amortised purchase costs converge between ICEV-d and BEV (4.47 and 4.51 ct/t·km), whereas FCEVs remain significantly higher at 11.79 ct/t·km. Component replacement costs continue to affect only FCEVs, adding 2.82 ct/t·km as one fuel cell replacement over lifetime was entered.

Energy costs are broadly similar to 2025 values, at 3.43, 3.46, and 5.31 ct/t·km for ICEV-d, BEV, and FCEV respectively. BEV-specific infrastructure costs remain modest (0.29 ct/t·km), while maintenance (1.45, 0.90, 1.35 ct/t·km) and insurance (0.70, 0.71, 1.85 ct/t·km) show only minor differences. Cantonal and LSVA charges continue to penalize ICEV-d the most, with LSVA at 5.03 ct/t·km compared to 1.03 ct/t·km for BEV and FCEV. Driver wages remain the dominant cost item (18.88 ct/t·km for all technologies).

Overall, the total cost of ownership decreases across powertrains, reaching 34.21, 29.85, and 42.54 ct/t·km for ICEV-d, BEV, and FCEV respectively, corresponding to 4.11, 3.58, and 5.10 €/km. Under these assumptions, **BEVs achieve a clear cost advantage** over diesel trucks by 2030, while FCEVs, though improved relative to 2025, remain significantly less competitive.

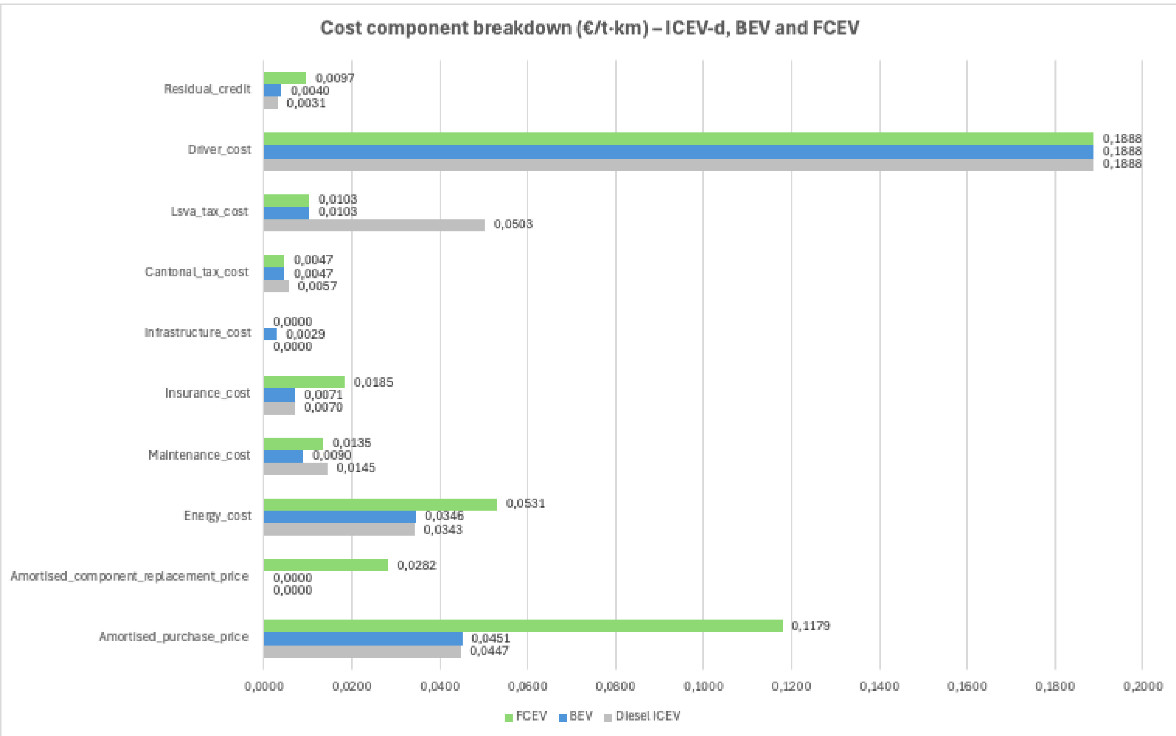

Figure 5: Comparison of cost components in €/t·km for ICEV-d, BEV, and FCEV (Regional - Base 2030).

6.2.3 Regional - Base 2050

For the regional case in the Base 2050 scenario, the model was run with the following settings: `usage = regional`, `canton = Zurich`, `scenario = Base`, `year = 2050`, `first_registration_year =`

`2045`, `GVWR = 22 t`, `cargo_mass = 12 t`, `truck_lifetime = 15 years`, `public_charging_share = 0%`, and `depot_charging_share = 100%`.

As shown in Figure 19, purchase prices amount to €123'156 for ICEV-d, €103'517 for BEVs, and €219'224 for FCEVs. The detailed breakdown of cost components is presented in Figure 18: amortised purchase costs fall to 0.0385 €/t·km for BEVs, compared to 0.0458 for ICEV-d and 0.0816 for FCEVs. Hydrogen trucks continue to face substantial mid-life replacement costs (0.0172 €/t·km), whereas diesel and BEVs avoid such expenditures.

Energy costs are stable for ICEV-d and BEVs (0.0343 and 0.0346 €/t·km), while FCEVs achieve the lowest value at 0.0257 €/t·km. BEV infrastructure costs, reflecting exclusive depot charging, add 0.0029 €/t·km. Maintenance and insurance remain lower for BEVs (0.0090 and 0.0060 €/t·km) compared to ICEV-d (0.0145 and 0.0072) and FCEVs (0.0135 and 0.0128). Cantonal taxation slightly penalises ICEV-d (0.0057 €/t·km) relative to BEVs and FCEVs (0.0047 €/t·km). LSVA charges remain an important driver, at 0.0553 €/t·km for diesel against 0.0469 for both BEVs and FCEVs. Driver wages dominate the overall cost structure at 0.1888 €/t·km across all powertrains. Residual credits provide a modest offset, ranging from 0.0032 for diesel to 0.0039 and 0.0079 for BEVs and FCEVs respectively.

As a result, the total cost of ownership reported in Figure 17 is 0.3484, 0.3276, and 0.3833 €/t·km for ICEV-d, BEV, and FCEV respectively, corresponding to 4.181, 3.932, and 4.599 €/km. Even, if we set the number of fuel cell replacements over the FCEV lifetime to 0 (instead of 1) and the hydrogen storage mass to 60 kg, **FCEV do not reach parity with diesel** in regional duty (36.04 ct./tkm). Under these assumptions, **BEVs retain a clear cost advantage** over diesel, while FCEVs remain the least competitive option in regional transport.

6.3 Discussion and validation of the results

Overall, our findings are consistent with the comparative evidence in Noll et al. (2022) and recent ICCT studies.

(i) Switzerland as a policy-driven outlier (LSVA). Noll *et al.* identify Switzerland as an anomaly where toll design (LSVA, weight– and class-based) reshapes TCO rankings: BETs become the least-cost option in HDT–LongHaul and FCETs move closer to competitiveness; nearly 40% of ICE-D TCO in Switzerland is due to tolls [6]. In our long-haul Base 2030 run (Zurich, GVWR 38 t, cargo 20 t), LSVA for ICEV-d is 5.21 ct./t·km out of 12.57 ct./t·km ($\approx$ 41%), mirroring Noll's magnitude. The same policy signal explains why BEVs lead already in 2025 and 2030, and why FCEVs approach parity by 2050 under optimistic hydrogen assumptions.

(ii) OPEX dominate commercial-vehicle TCO. Noll *et al.* show that OPEX parameters (tolls, energy, wages, O&M) account for ~75% of TCO across segments, with wages especially large in lighter-duty use [6]. Our results reproduce this structure: in all scenarios the driver cost is the single largest component (e.g., 3.32 ct./t·km in long-haul; 18.88 ct./t·km in regional), while LSVA and energy prices drive cross-technology gaps. The policy implication stressed by Noll, targeting OPEX (tolls, energy) is more effective than CAPEX-only support, is directly visible in our Swiss-specific outcomes.

(iii) Technology ranking by duty cycle and horizon. For regional/MDT uses, both our model and Noll et al. find BEVs as the clear least-cost powertrain, with FCETs the most expensive [6]. In long-haul/HDT, our Base 2025 and Base 2030 results show BEVs beating diesel and hydrogen, again in line with Noll's Swiss bars. Looking ahead, ICCT's European assessment concludes BEVs remain the most cost-effective choice by 2030 under plausible price paths [16], which matches our Base 2030 ranking. By 2050, our Swiss long-haul Base case yields near parity BEV–FCEV, consistent with ICCT's finding that FCET parity requires optimistic hydrogen costs and durability while BEVs keep an efficiency/maintenance edge [12], [14].

(iv) Divergences in parity years. ICCT (2023) estimates parity relative to diesel as follows: for long-haul (800 km return-depot), BEVs by 2026 and FCEVs by 2036; for regional heavy-duty trucks, BEVs by 2023 and FCEVs by 2036 [16]. In our Swiss model, BEVs reach parity already in 2025 for both regional and long-haul, driven by the LSVA exemption that heavily penalises diesel. However, FCEVs do not reach parity in regional duty even by 2050 (remaining at 38.3 ct./t·km versus 34.8 for ICEV-d), while in long-haul they converge with BEVs in 2050. This confirms ICCT's projection that hydrogen requires very favorable assumptions to compete, and highlights that Swiss-specific cost drivers (LSVA, high public charging tariffs) accelerate BEV adoption but do not fully close the competitiveness gap for FCEVs in regional use.

(v) Benchmark vs. ICCT Europe (2030). Compared with the ICCT Europe baseline for 2030[16], our Swiss results are systematically higher in €/km, while preserving the same technology ranking (BEV < diesel < FCEV). For **regional delivery**, ICCT reports **BEV 0.83 €/km**, **diesel 0.98 €/km** and **FCEV 1.06 €/km**; our model for Zurich yields **BEV 3.58 €/km**, **diesel 4.11 €/km**, **FCEV 5.10 €/km**, i.e. about 4.3×, 4.2×, and 4.8× higher, respectively. For **long haul (return-to-depot, 800 km)**, ICCT finds **BEV 0.93 €/km**, **diesel 1.13 €/km**, **FCEV 1.24 €/km**; our Swiss run with inputs in table 1 gives **BEV 1.89 €/km**, **diesel 2.51 €/km**, **FCEV 2.29 €/km**, roughly 2.0×, 2.2×, and 1.8× higher. These gaps are expected for Switzerland, driven by (1) the LSVA heavy-vehicle fee and cantonal taxation embedded in our model, which substantially affect not only long-haul but also regional applications, (2) very high Swiss wage levels, with driver costs identical in our model for regional and long-haul duty cycles, yet appearing disproportionately high in regional duty (18.88 ct./t·km versus 3.32 ct./t·km in long-haul) due to normalization over much lower annual mileages, (3) lower annual mileages than in other European countries, which amplify fixed-cost contributions when expressed per kilometer, (4) higher public charging tariffs that directly increase BEV operational costs, and (5) above-average diesel and AdBlue prices, which further penalize ICEV-d. Together, these factors raise €/km values relative to EU-wide averages reported by ICCT (see Section 5.1).

Summary. While absolute TCO levels in our Swiss model are higher than European averages, driven by LSVA and cantonal taxation, higher wage levels, lower annual mileage, and elevated charging and fuel prices, the comparative ranking of technologies is consistent with Noll *et al.* (2022) and ICCT (2023). In regional duty, BEVs emerge as the least-cost option, with ICEV-d next and FCEVs remaining the most expensive. In long-haul duty, BEVs also lead in 2025 and 2030, ahead of diesel and FCEVs. By 2050, FCEVs approach parity with BEVs only in long-haul scenarios under optimistic assumptions (reduced hydrogen storage and no stack replacement), whereas in regional duty they remain significantly less competitive.

7 Conclusions and outlook

7.1 Summary of key findings

This study developed a parameterized and Swiss-adapted TCO model for heavy-duty trucks, enhancing the *Carculator* framework with explicit consideration of LSVA charges and cantonal vehicle taxes. The results provide several key insights:

- **Battery-electric trucks (BEVs)** emerge as the most cost-competitive option already in 2025, both for regional and long-haul applications, driven by LSVA exemptions and lower operating costs.
- In the **regional scope** (2030 and 2050), BEVs retain a clear and sustained cost advantage over both diesel and hydrogen, while FCEVs remain the least competitive option across the horizon.
- In the **long-haul scope**, BEVs dominate in 2025 and 2030, but by 2050 FCEVs can outperform BEVs under the assumption of constant Swiss electricity tariffs, highlighting the sensitivity of results to energy price trajectories.
- **Swiss-specific factors** significantly lift absolute cost levels compared to EU averages: (i) the LSVA fee, which is decisive in penalizing diesel vehicles until 2029; (ii) cantonal vehicle taxes, which add heterogeneity but limited aggregate impact; (iii) very high driver wages, especially influential under lower Swiss annual mileage; and (iv) public charging tariffs that remain substantially above European averages.

These findings underline that Swiss freight decarbonisation pathways are strongly shaped by regulatory instruments (LSVA exemptions) and cost structures that amplify differences between technologies. While BEVs appear as early cost leaders, FCEVs hold long-term potential under optimistic assumptions of hydrogen and fuel cell cost reductions.

7.2 Future research and tool extensions

Several extensions can strengthen the model and its policy relevance:

- **Refined projections.** Incorporating dynamic electricity price scenarios would improve the robustness of long-term competitiveness assessments.
- **Expanded scope.** Adding all cantons explicitly would capture the full heterogeneity of Swiss taxation and infrastructure conditions.
- **Technological detail.** Extending the model to include a broader set of battery chemistries beyond the currently implemented NMC, LFP, and NCA (e.g., LTO, Li–O_2, Li–S, SiB) would enhance technological realism. Likewise, introducing additional drivetrain and fuel options such as HVO, H_2-ICE (dual fuel or spark ignition), e-diesel, or bio-CNG would enable more comprehensive comparative insights.
- **Economic realism.** Discounting annual mileage in economic terms, acknowledging that each kilometre generates revenue for transported goods, would better align cost modelling with logistics operators' decision-making criteria.
- **Replacement vs. retrofitting.** Extending the model to compare full vehicle replacement with partial upgrades (e.g., retrofitting an existing ICEV with a battery module for hybrid operation) would provide operators with more granular investment strategies.
- **Carculator integration.** The updated parameter set can be fed back into *Carculator* to enhance its flexibility as a Europe-wide tool, while retaining the ability to zoom into the Swiss context.

Overall, this project highlights that BEVs are already competitive today, while FCEVs may represent a viable long-haul niche beyond 2040. The Swiss case illustrates how taxation can decisively alter competitiveness rankings, providing lessons for other European countries seeking to accelerate the freight sector's decarbonisation. Moreover, the developed TCO model demonstrates high flexibility: it can be readily used by logistics operators to explore alternative usage profiles thereby serving as a practical decision-support tool for investment planning and fleet strategy.

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A Appendix

List of abbreviations

- BEV = Battery Electric Vehicle. A vehicle or truck powered entirely by batteries and recharged from the electric grid.
- FCEV = Fuel-Cell Electric Vehicle. A vehicle or truck using a hydrogen fuel cell to generate electricity onboard.
- ICEV-d = Internal Combustion Engine Vehicle – diesel. Conventional vehicles or trucks running on diesel fuel.
- LSVA = *Leistungsabhängige Schwerverkehrsabgabe*. The Swiss heavy-vehicle fee, distance- and weight-based, exempting ZETs until 2029.
- RPLP = *Redevance Poids Lourds Proportionnelle aux Prestations*. The French equivalent of LSVA, a performance-based heavy vehicle fee.
- TCO = Total Cost of Ownership. The aggregated lifetime cost of a vehicle, combining CAPEX and OPEX, expressed here in €/t·km or €/km.
- ZET = Zero-Emission Truck. Refers to BEVs and FCEVs.

Excel model

The Excel workbook `TCO_model.xlsx` (ReadMe, UserInput, ScenarioData, FixedParameters, BatteryCosts, CantonalTax, LSVATax, TCO_ICEV/BEV/FCEV, Summary) is provided as supplementary material.

Tables and charts

This appendix provides the itemised tables for the two following technologies sheets used in the workbook: for ICEV-d (8) and FCEV (9), BEV beeing already represented in section 3.5. Moreover, below can be found the charts that highlight the results for different scenarios.

Table 8: ICEV–diesel itemised cost build-up (illustrative run with the user inputs from table 1, Base 2025)

Parameter	Value	Unit	Formula	Comment
glider_cost (C_{glider})	43 571.20	€	$m_{\text{glider}} \cdot c_{\text{glider,kg}}$	Chassis/glider
lightweighting_cost ($C_{\text{lightweight}}$)	346.41	€	$m_{\text{glider}} \cdot \lambda \cdot c_{\text{light,kg}}$	λ: lightweighting factor
combustion_powertrain_cost ($C_{\text{combustion,pt}}$)	20 180.00	€	$P_c \cdot c_{c,\text{kW}}$	Engine + transmission
exhaust_treatment_cost (C_{exhaust})	15 840.00	€	$P_c \cdot c_{\text{exh}} \cdot m_{\text{kerb}}$	SCR/DPF system
power_battery_cost (C_{starter})	10 000.00	€	$P_b \cdot c_{b,\text{kW(ICEV)}}$	Starter battery
diesel_tank_cost (C_{tank})	462.00	€	$m_{\text{fuel}} \cdot c_{\text{tank,kg}}$	Fuel tank
energy_cost (C_{energy})	2.06E-02	€/t·km	$\frac{FC_{\text{diesel}}}{100} \cdot p_{\text{diesel}} \cdot \frac{1}{m_{\text{cargo}}}$	Fuel cost per t·km
purchase_price (C_{purchase})	121 858.68	€	$\mu_{\text{high1}} \cdot (C_{\text{glider}} + C_{\text{lightweight}} + C_{\text{combustion,pt}} + C_{\text{exhaust}} + C_{\text{starter}} + C_{\text{tank}})$	With ICM markup
amortisation_factor (AF)	1.28E-01	–	$\frac{i}{1-(1+i)^{-L}}$	i: discount rate, L: lifetime
amortised_purchase_price ($C_{\text{amort,purchase}}$)	7.98E-03	€/t·km	$\frac{C_{\text{purchase}} \cdot AF}{km_{\text{year}} \cdot m_{\text{cargo}}}$	Annualised CAPEX
adblue_cost (C_{AdBlue})	1.42E-02	€/km	$\frac{FC_{\text{diesel}}}{100} \cdot \rho_{\text{diesel}} \cdot \alpha_{\text{AdBlue}} \cdot p_{\text{AdBlue}} \cdot \gamma_{\text{CHF-EUR}}$	DEF fluid cost (€/km)
maintenance_cost (C_{maint})	1.02E-02	€/t·km	$\frac{c_{\text{maint,ICEV}} + C_{\text{AdBlue}}}{m_{\text{cargo}}}$	Includes AdBlue cost
insurance_cost (C_{ins})	1.25E-03	€/t·km	$\frac{C_{\text{purchase}} \cdot c_{\text{ins,yr}}}{km_{\text{year}} \cdot m_{\text{cargo}}}$	Proportional to CAPEX
driver_cost (C_{driver})	3.32E-02	€/t·km	$\frac{c_{\text{driver,yr}}}{km_{\text{year}} \cdot m_{\text{cargo}}}$	Very high in CH
cantonal_tax_cost ($C_{\text{tax,cantonal}}$)	1.61E-03	€/t·km	model-specific	Zurich case
lsva_tax_cost ($C_{\text{tax,LSVA}}$)	5.21E-02	€/t·km	model-specific	Federal LSVA, pre/post-2028 split
residual_credit (C_{residual})	5.52E-04	€/t·km	$C_{\text{amort,purchase}} \cdot f_{\text{res}} \cdot (1+i)^{-L}$	End-of-life resale credit
total_cost_per_tkm	1.26E-01	€/t·km	sum of €/t·km items	Total cost of ownership

Table 9: FCEV itemised cost build-up (illustrative run with the user inputs from table 1, Base 2025)

Parameter	Value	Unit	Formula	Comment
glider_cost (C_{glider})	43 571.20	€	$m_{\text{glider}} \cdot c_{\text{glider,kg}}$	Chassis/glider
lightweighting_cost ($C_{\text{lightweight}}$)	346.41	€	$m_{\text{glider}} \cdot \lambda \cdot c_{\text{light,kg}}$	λ: lightweighting factor
electric_powertrain_cost ($C_{\text{electric,pt}}$)	19 200.00	€	$P_e \cdot c_{e,\text{kW}}$	Motor + inverter
energy_battery_cost ($C_{\text{bat,energy}}$)	4 365.00	€	$E_{\text{bat}} \cdot c_{\text{bat,kWh}}$	Buffer battery (energy)
power_battery_cost ($C_{\text{bat,power}}$)	6 962.00	€	$P_{\text{bat}} \cdot c_{\text{bat,kW}}$	Buffer battery (power)
battery_cost (C_{battery})	11 327.00	€	$C_{\text{bat,energy}} + C_{\text{bat,power}}$	Total battery pack
fuel_cell_cost (C_{fc})	229 005.00	€	$P_{\text{fc}} \cdot c_{\text{fc,kW}}$	Fuel cell stack system
hydrogen_tank_cost ($C_{\text{H2,tank}}$)	90 080.00	€	$m_{H_2} \cdot c_{\text{tank,kg}}$	Compressed H_2 tanks
energy_cost (C_{energy})	4.01E-02	€/t·km	$\frac{f_{H_2}/100 \cdot p_{H_2}}{m_{\text{cargo}}}$	H_2 consumption per t·km
battery_replacement_cost ($C_{\text{bat,repl}}$)	0.00	€	$E_{\text{bat}} \cdot c_{\text{bat,kWh}} \cdot n_{\text{bat}}$	No replacement in Base 2025
fuel_cell_replacement_cost ($C_{\text{fc,repl}}$)	229 005.00	€	$P_{\text{fc}} \cdot c_{\text{fc,kW}} \cdot n_{\text{fc}}$	One stack replacement
component_replacement_price ($C_{\text{repl,price}}$)	336 408.35	€	$\mu_{\text{high1}} C_{\text{bat,repl}} + \mu_{\text{high2}} C_{\text{fc,repl}}$	With ICM markups
purchase_price (C_{purchase})	569 087.20	€	$\mu_{\text{high1}}(C_{\text{glider}} + C_{\text{lightweight}} + C_{\text{electric,pt}} + C_{\text{battery}}) + \mu_{\text{high2}}(C_{\text{fc}} + C_{\text{H2,tank}})$	Initial CAPEX
amortisation_factor (AF)	1.28E-01	–	$\frac{i}{1-(1+i)^{-L}}$	i: discount rate, L: lifetime
amortised_purchase_price ($C_{\text{amort,purchase}}$)	3.73E-02	€/t·km	$\frac{C_{\text{purchase}} \cdot AF}{km_{\text{year}} \cdot m_{\text{cargo}}}$	Annualised CAPEX
maintenance_cost (C_{maint})	9.50E-03	€/t·km	$\frac{c_{\text{maint,FCEV}}}{m_{\text{cargo}}}$	Specific to fuel cell trucks
insurance_cost (C_{ins})	5.84E-03	€/t·km	$\frac{C_{\text{purchase}} \cdot c_{\text{ins,yr}}}{km_{\text{year}} \cdot m_{\text{cargo}}}$	Proportional to CAPEX
driver_cost (C_{driver})	3.32E-02	€/t·km	$\frac{c_{\text{driver,yr}}}{km_{\text{year}} \cdot m_{\text{cargo}}}$	High in CH
cantonal_tax_cost ($C_{\text{tax,cantonal}}$)	1.45E-03	€/t·km	model-specific	Zurich case
lsva_taxable_years	6.00	years	$\max(0; \min(y_0 + L - 1; 2028) - y_0 + 1)$	Exempt until 2029
lsva_tax_cost ($C_{\text{tax,LSVA}}$)	1.07E-02	€/t·km	$\frac{\text{lsva\_taxable\_years} \cdot c_{\text{LSVA}}}{L} \cdot \frac{\text{GVWR}}{m_{\text{cargo}}}$	Federal LSVA fee
amortised_compo_repl_price ($C_{\text{amort,repl}}$)	1.12E-02	€/t·km	$\frac{C_{\text{repl,price}} \cdot (1+i)^{-L/2} \cdot AF}{km_{\text{year}} \cdot m_{\text{cargo}}}$	Mid-life replacement
residual_credit (C_{residual})	2.13E-03	€/t·km	$C_{\text{amort,purchase}} \cdot f_{\text{res}} \cdot (1+i)^{-L}$	End-of-life resale credit
total_cost_per_tkm	1.47E-01	€/t·km	sum of €/t·km items	Total cost of ownership

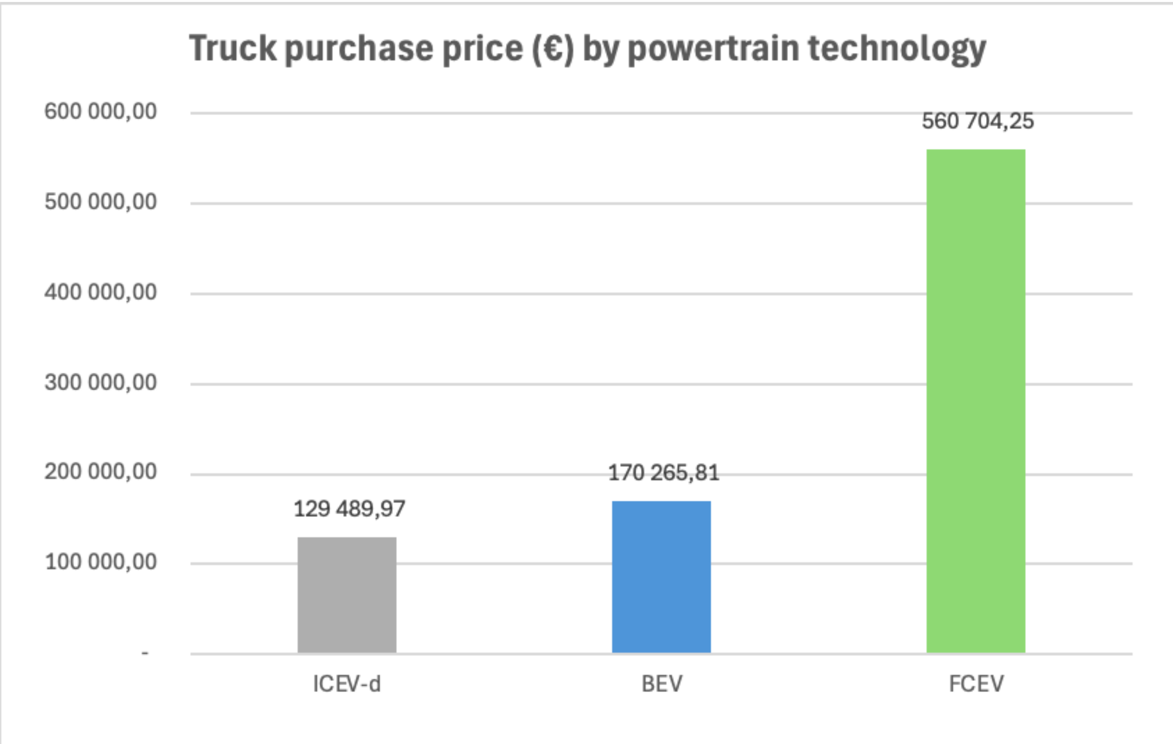

Figure 6: Regional truck purchase price (€) by powertrain technology (Regional - Base 2025)

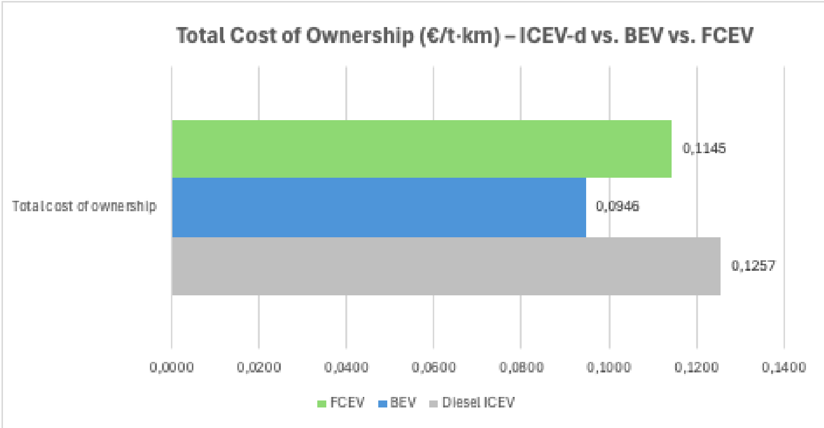

Figure 7: Total Cost of Ownership (€/t·km) – ICEV-d vs. BEV vs. FCEV (long haul - base 2030)

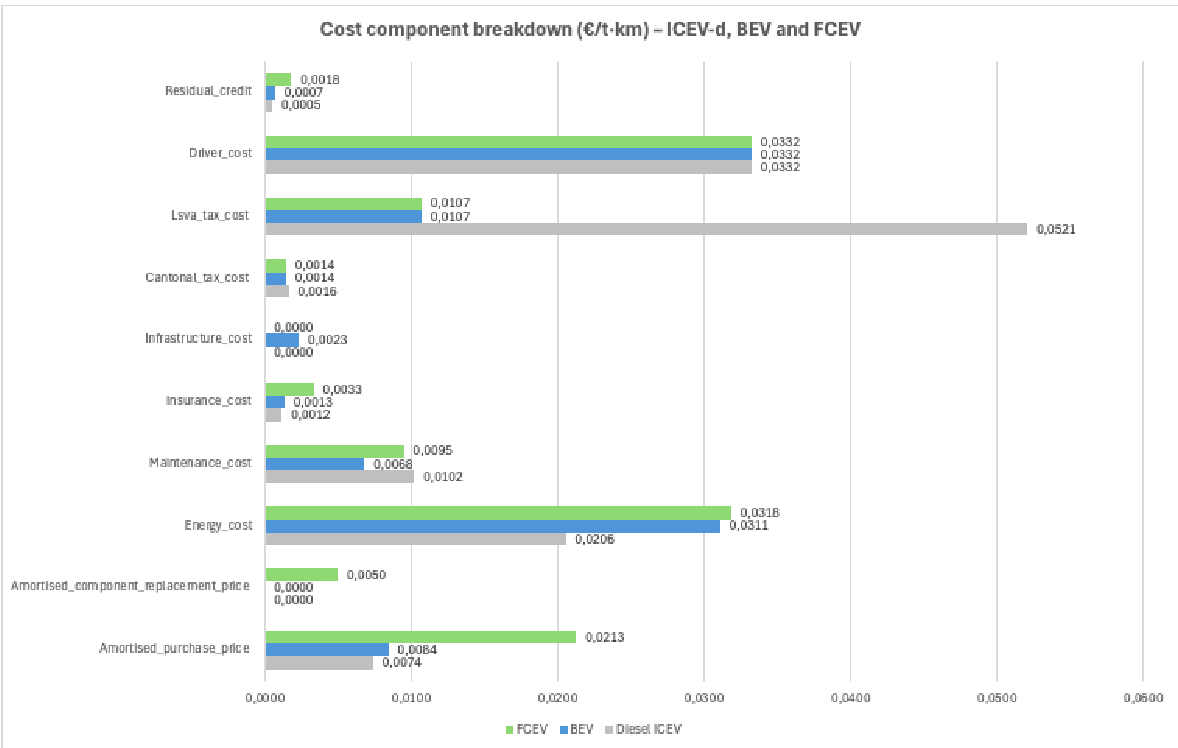

Figure 8: Cost component breakdown (€/t·km) – ICEV-d, BEV and FCEV (long haul - base 2030)

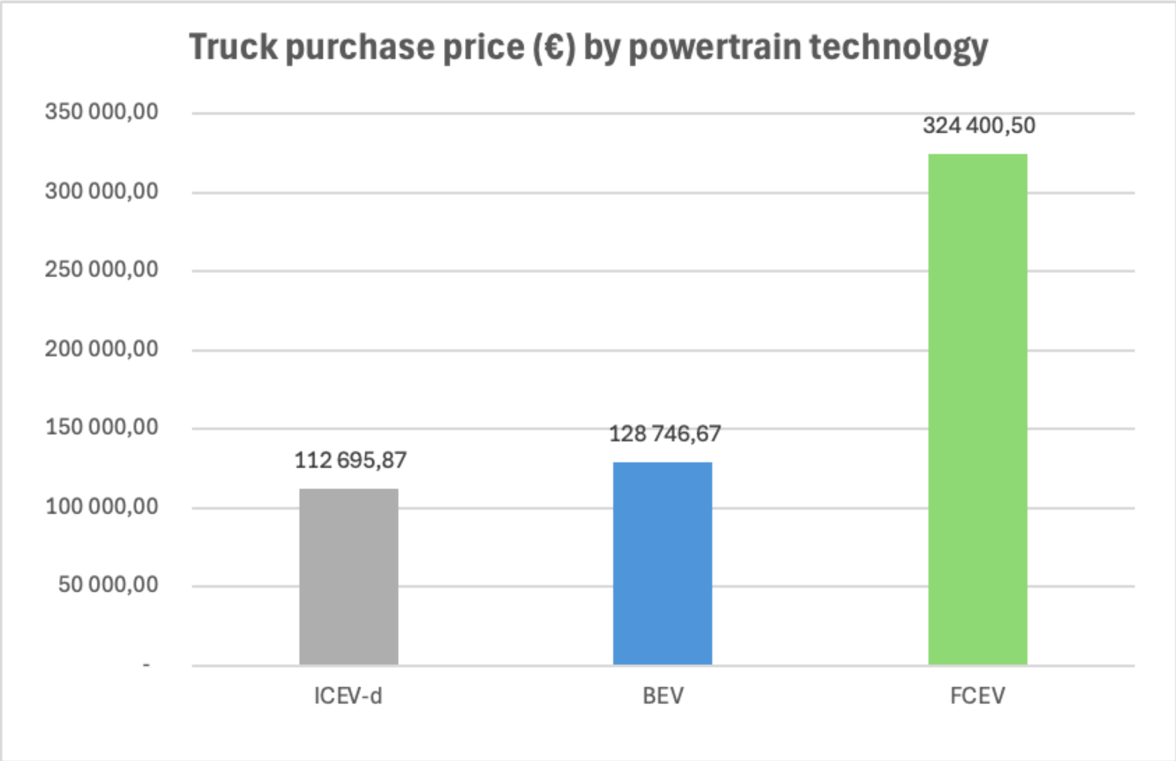

Figure 9: Truck purchase price (€) by powertrain technology (long haul - Base 2030)

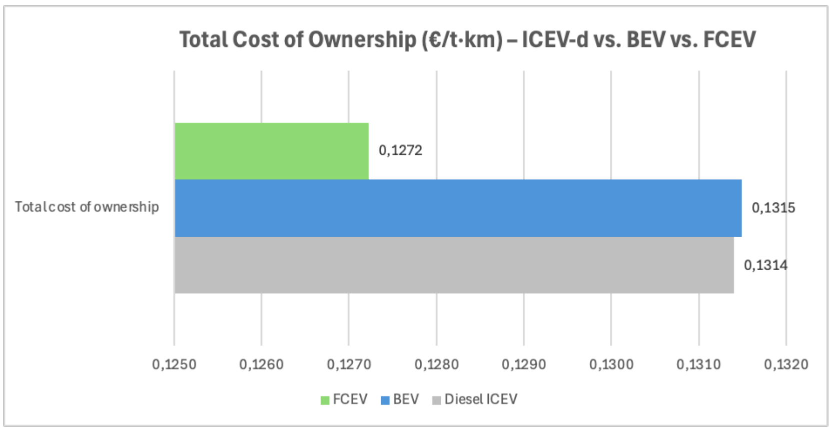

Figure 10: Total Cost of Ownership (€/t·km) – ICEV-d vs. BEV vs. FCEV (long haul - base 2050)

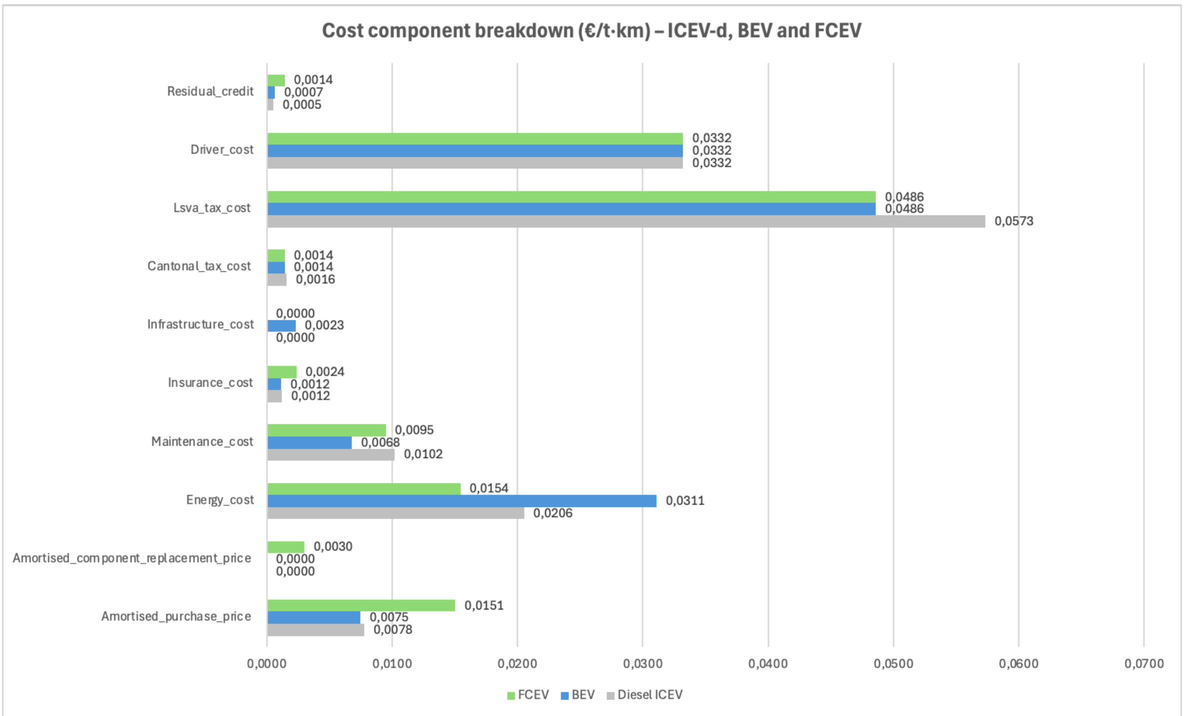

Figure 11: Cost component breakdown (€/t·km) – ICEV-d, BEV and FCEV (long haul - base 2050)

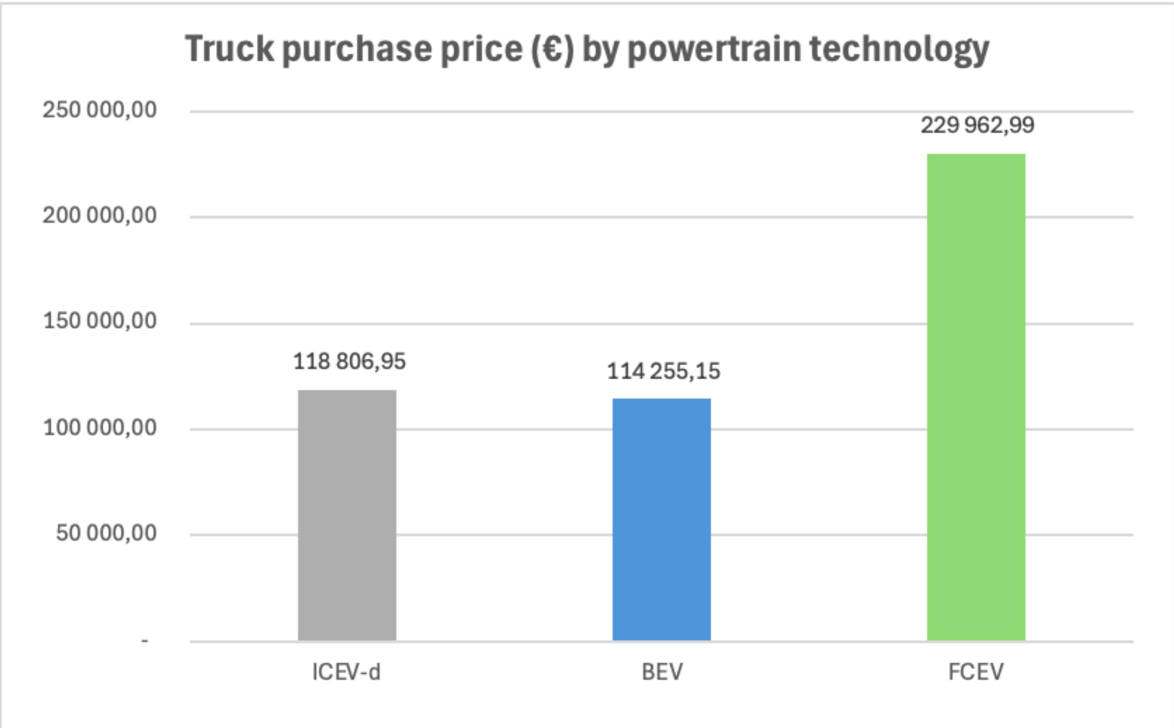

Figure 12: Truck purchase price (€) by powertrain technology (long haul - Base 2050)

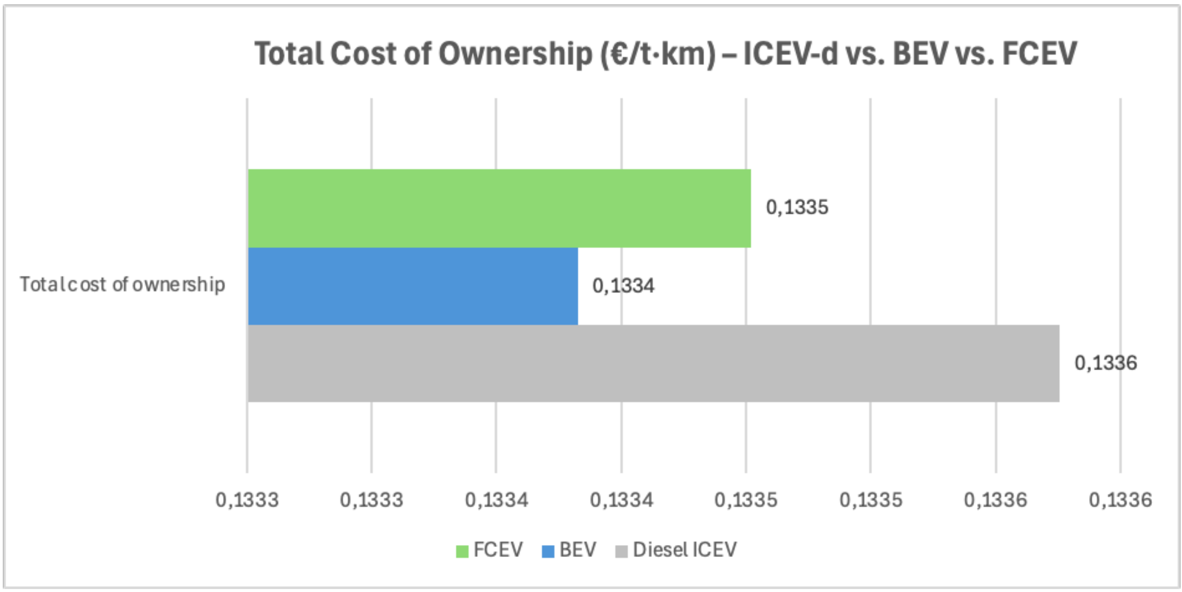

Figure 13: Total Cost of Ownership (€/t·km) – ICEV-d vs. BEV vs. FCEV for Base 2050 (long-haul) with truck lifetime of 8,5 years and first registration: 2045)

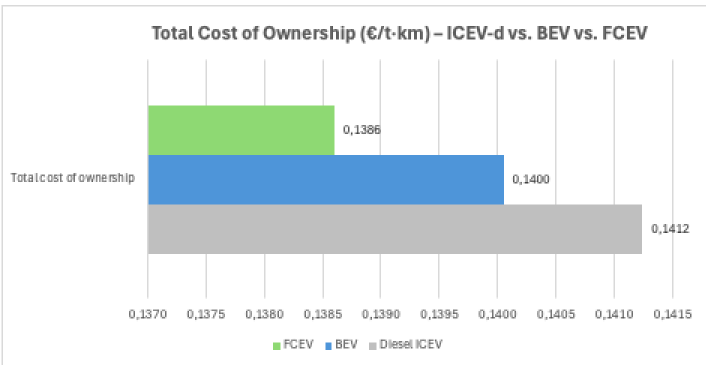

Figure 14: Total Cost of Ownership (€/t·km) – ICEV-d vs. BEV vs. FCEV for Base 2050 (long-haul) with truck_lifetime= 15 (years), first_registration =2045, fuel_cell_lifetime_replacements=0 and hydrogen_mass=60kg

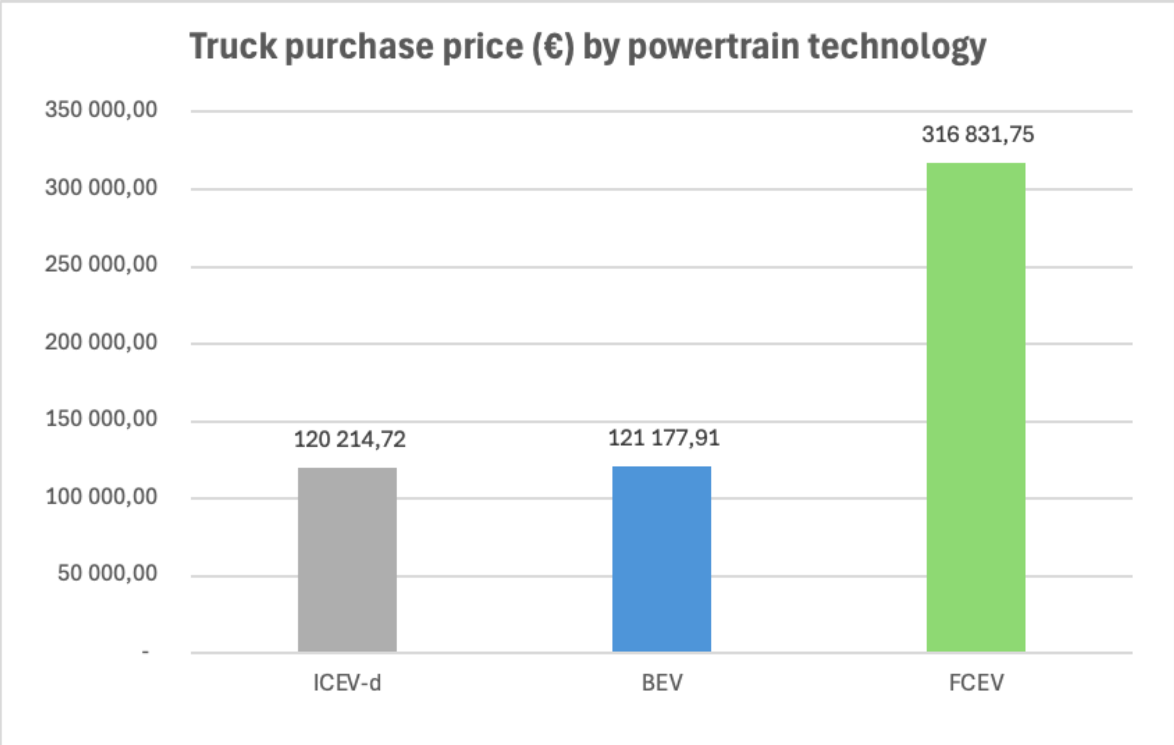

Figure 15: Truck purchase price (€) by powertrain technology (regional - Base 2030)

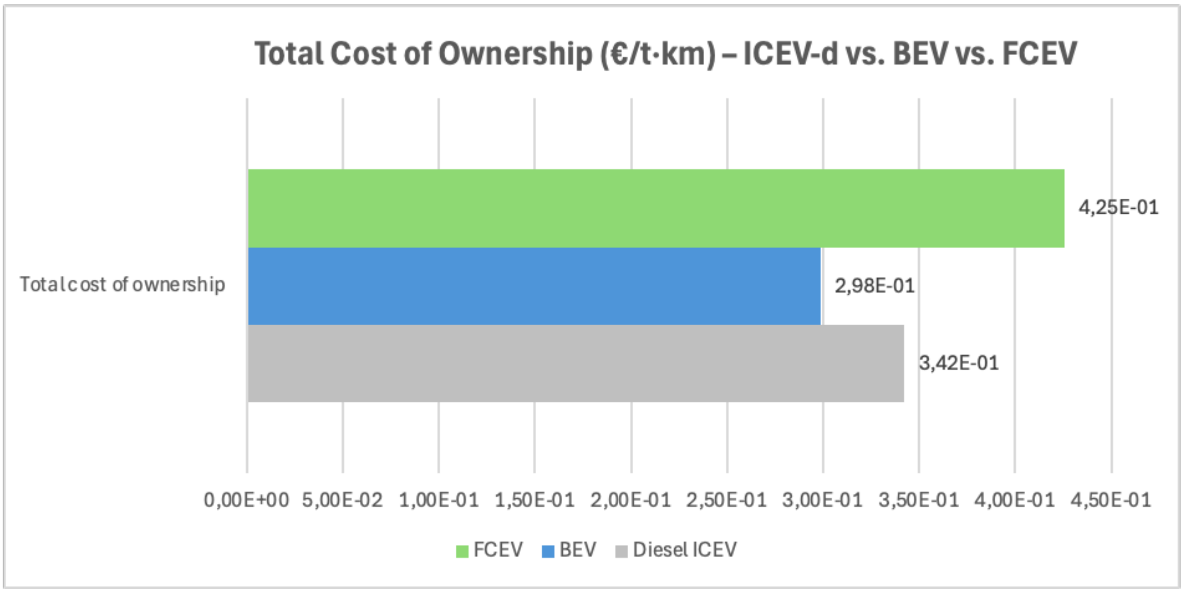

Figure 16: Total Cost of Ownership (€/t·km) – ICEV-d vs. BEV vs. FCEV (regional - base 2030)

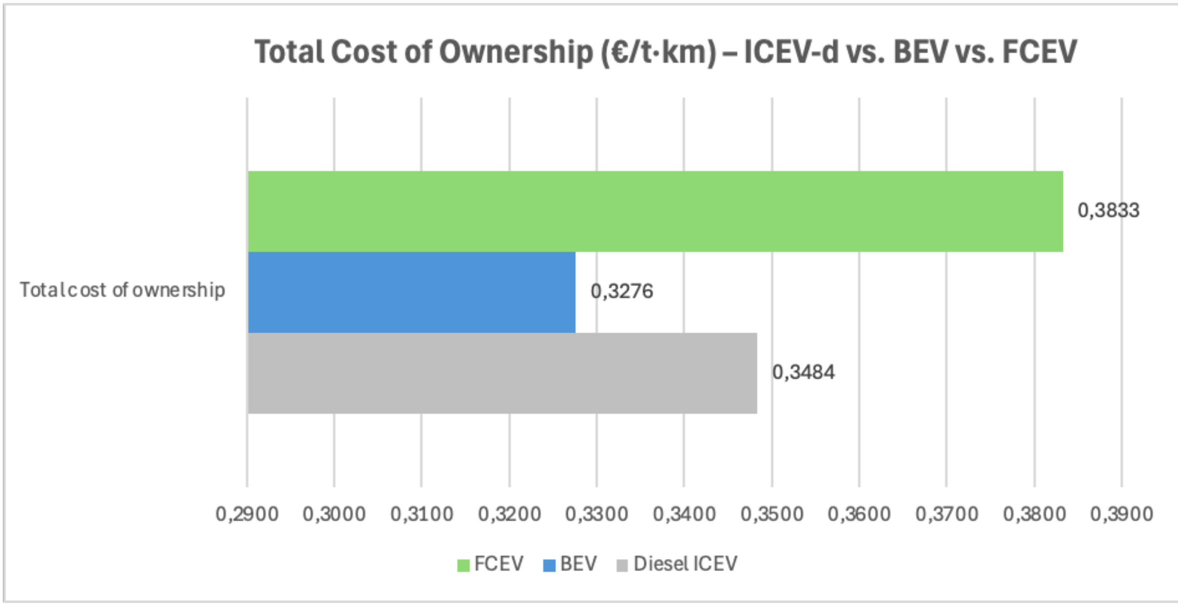

Figure 17: Total Cost of Ownership (€/t·km) – ICEV-d vs. BEV vs. FCEV (regional - base 2050)

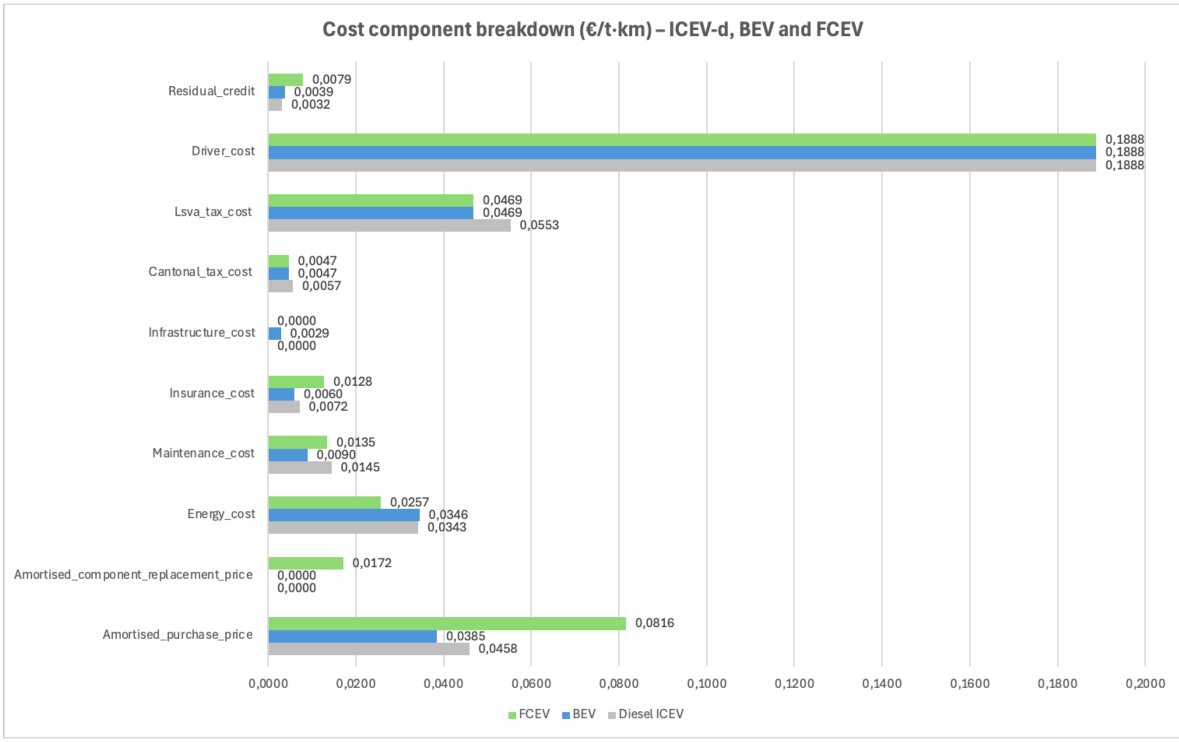

Figure 18: Cost component breakdown (€/t·km) – ICEV-d, BEV and FCEV (regional - base 2050)

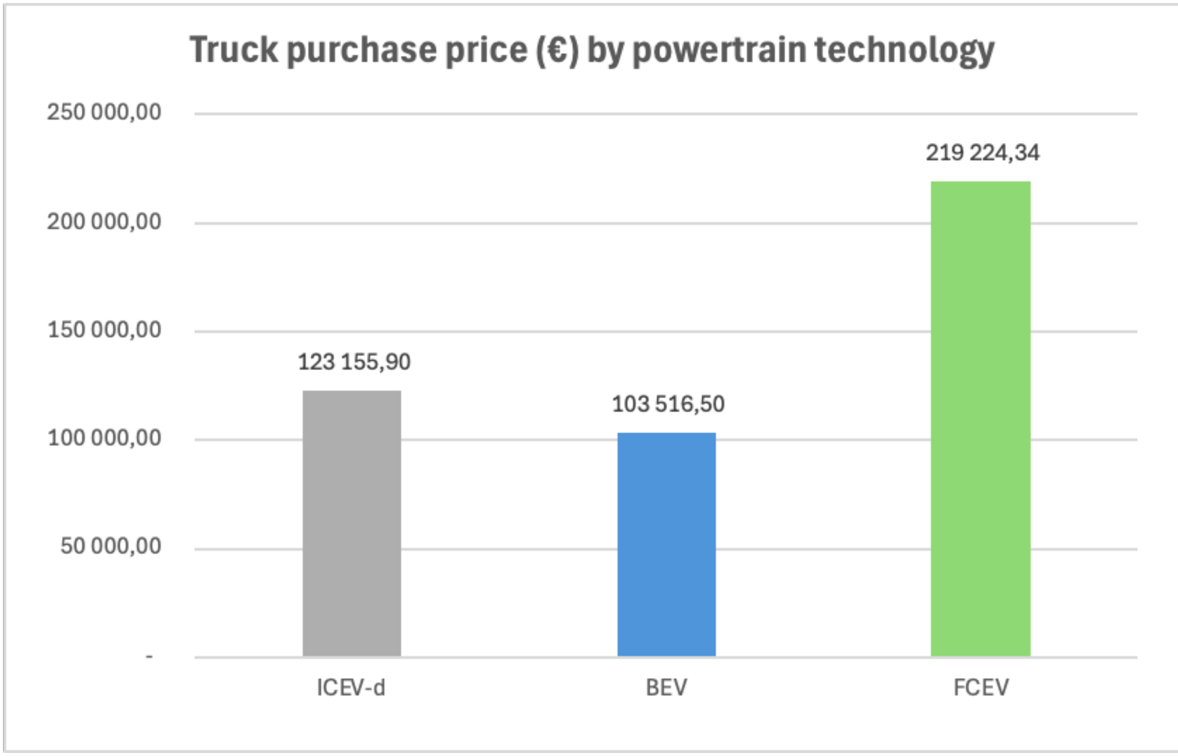

Figure 19: Truck purchase price (€) by powertrain technology (regional - Base 2050)