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FUEL-CELL HYDROGEN LONG-HAUL TRUCKS IN EUROPE: A TOTAL COST OF OWNERSHIP ANALYSIS

Hussein Basma, Yuanrong Zhou, and Felipe Rodríguez

www.theicct.org

communications@theicct.org

twitter @theicct

THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

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For additional information:
International Council on Clean Transportation Europe
Fasanenstrasse 85, 10623 Berlin, Germany

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EXECUTIVE SUMMARY

Road freight activity is expected to grow continuously through 2050, offsetting the expected CO_2 reduction benefits mandated by heavy-duty vehicle (HDV) CO_2 standards in the European Union (EU). For the EU to reach its carbon neutrality goals by mid-century, more ambitious CO_2 reduction targets are warranted. Such a transition toward a low- and eventually a zero-carbon economy will require a shift from internal combustion engines to zero-emission HDV technologies. Fuel cell trucks are a decarbonization option that could help achieve these goals. However, the economic viability of this technology is still uncertain.

This study evaluates the total cost of ownership (TCO) of fuel cell electric trucks (FCETs), focusing on long-haul tractor-trailers, the highest-emitting HDV segment in the EU. The geographic scope of this study includes seven European countries—France, the United Kingdom, Germany, Italy, Spain, the Netherlands, and Poland—representing more than 75% of HDV registrations in the EU in 2020. The TCO is evaluated through a detailed analysis of the different costs facing truck operators, including truck acquisition costs, renewable electrolysis hydrogen and diesel fuel costs, maintenance costs, road tolls, and other country-specific taxes and levies. The analysis is conducted from a first-user perspective over a 5-year ownership period.

We arrive at the following key findings:

» **Fuel cell long-haul trucks can reach TCO parity with their diesel counterparts by 2030 in Europe if the at-the-pump green hydrogen fuel price is around 4 €/kg**. The break-even hydrogen price varies among the countries considered in this study; the highest break-even price is recorded in the United Kingdom at 5 €/kg, and the lowest is found in Poland at 3.5 €/kg. This disparity is driven by the country-specific diesel fuel prices, road tolls, and other taxes and levies. The break-even hydrogen prices to achieve total cost of ownership parity by 2030 between FCETs and diesel trucks are shown in Figure ES1.

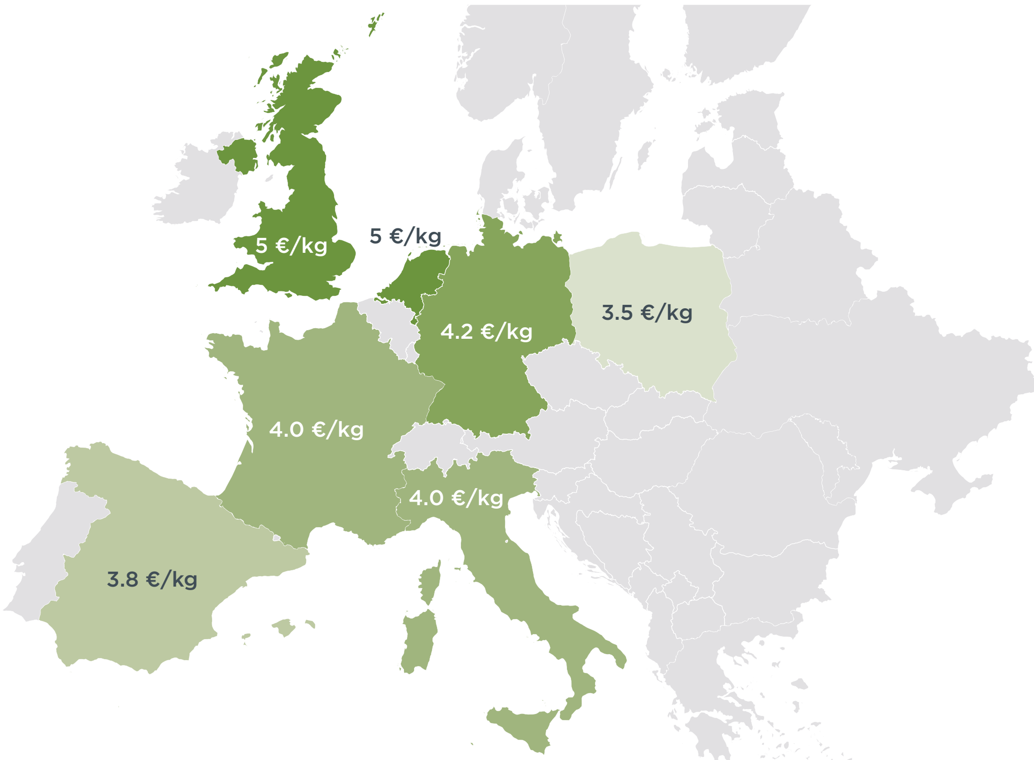

Figure ES1. Break-even hydrogen price to achieve total cost of ownership parity by 2030 between fuel cell electric and diesel trucks in selected countries.

» **Hydrogen fuel subsidies will be needed to justify the business case for FCETs in Europe during this decade**. The expected hydrogen fuel price is higher than the break-even price required to achieve TCO parity by 2030. Subsidies needed vary from 1.2 €/kg in the Netherlands to more than 4 €/kg in Italy and Germany, as shown in Figure ES2. The price of hydrogen fuel will be the primary driver of the technology's economic viability as the retail price gap between FCETs and diesel trucks is expected to narrow significantly by 2030.

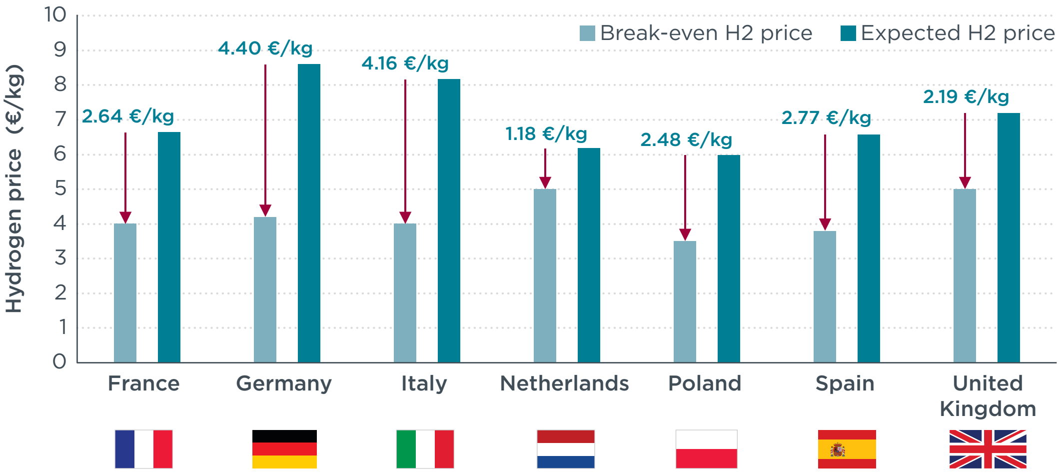

Figure ES2. Hydrogen fuel subsidy needed to achieve total cost of ownership parity between fuel cell electric trucks and diesel trucks by 2030, assuming onsite hydrogen production through renewable electrolysis

Based on these findings, we recommend the following:

» **Increase the ambition of the heavy-duty vehicle CO_2 standards as more stringent standards are needed to comply with the EU Climate Law**. Zero-emission trucks have the ability to replace the current diesel fleets, significantly reducing the heavy-duty vehicle sector CO_2 emissions. Greater stringency can provide certainty to invest in fuel cell trucks and other zero-emission technologies, which would help to elevate their market demand. This can ramp up the technology economies of scale, reducing its total deployment costs.

» **Expedite the implementation of the Eurovignette directive into national law and fully exempt zero-emission trucks from road tolls**. Road tolls are a significant contributor to the TCO of long-haul trucks in general. Similar to what is currently implemented in Germany, a 100% road toll waiver for zero-emission trucks can reduce the TCO of fuel cell trucks by 14% to 25% by the end of the decade, helping fuel cell trucks to achieve TCO parity with diesel trucks in France and the Netherlands. Furthermore, the proposed CO_2 charge of between 0.08 €/km and 0.16 €/km can narrow the TCO gap between fuel cell and diesel trucks.

» **Incentivize the purchase of zero-emission trucks and limit these incentives to their early market uptake phase**. Germany, France, and the Netherlands already provide purchase subsidies based on the retail price differential between fuel cell and diesel trucks. This can help reduce the TCO gap between the two technologies. Because these subsidies are designed on a price differential basis, they will decrease and eventually be phased out as the retail prices of zero-emission and diesel trucks become comparable. Although purchase premiums cannot cover the entire TCO gap between fuel cell and diesel trucks, they can significantly reduce the capital investment needed to ramp up market demand for the technology.

» **Incentivize demonstration projects of fuel cell trucks in real-world applications**. This would help in closing the existing knowledge gaps and address some uncertainties around the technology, mainly regarding fuel economy, refueling, and costs. This would help in identifying the real-world challenges that hinder wide-scale deployment of fuel cell trucks.

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INTRODUCTION

The European Union (EU) has committed to achieving climate neutrality by mid-century, as indicated by adoption of the European Climate Law (European Commission, 2021d). The transport sector, particularly heavy-duty vehicles (HDV), will contribute significantly to a European carbon-neutral economy. The growing preference for zero-emission vehicles (ZEV) has been evident in the light-duty vehicle (LDV) sector, with electric vehicles accounting for 11% of new sales in Europe in 2020 (Mock et al., 2021). Meanwhile, the HDV market in Europe remains dominated by fossil fuel-powered internal combustion engines, with ZEVs accounting for just 2% of sales in the same year (Basma & Rodríguez, 2021).

Electrifying the HDV sector becomes more important when considering the sector's long-term growth: road freight activity increased by an average of 1.8% per annum between 1995 and 2018, compared to 1.0% for road passenger activity over the same period (European Commission, 2020a). This growth in activity is expected to offset the benefits of CO_2 reduction driven by the HDV CO_2 standards in Europe, which mandate a 15% and 30% reduction in emissions by 2025 and 2030, respectively, relative to 2019. The net result is an 8% projected growth in emissions by 2050 (Mulholland et al., 2022). With more ambitious CO_2 reduction targets needed, ZE-HDVs will play a pivotal role in achieving the EU's climate neutrality goals.

Several ZE-HDV technologies exist with the potential to deliver real-world reductions in lifecycle greenhouse gas (GHG) emissions of trucks. These include battery-electric trucks (BETs), fuel cell electric trucks (FCETs), and overhead catenary trucks. While several truck manufacturers have already announced and deployed many BET and FCET models, high market demand has not materialized as there is a high level of uncertainty regarding the economic viability of these alternative technologies.

To assess the economic viability of ZE-HDVs, this study models the total cost of ownership (TCO) of fuel-cell electric long-haul trucks based on current state-of-the-art technology. It determines the current TCO disparity between this technology and its diesel counterpart. This TCO analysis is performed from a first-user perspective over a 5-year analysis period. The TCO analysis is based on detailed assumptions of current and future fixed and operating costs. A recently published ICCT study focused on the TCO of BETs in Europe (Basma, Saboori, et al., 2021). This report solely focuses on assessing the TCO of fuel-cell tractor-trailers. The study covers seven European countries accounting for more than 75% of the European HDV market (Diaz et al., 2021): France, the United Kingdom, Germany, Italy, Spain, the Netherlands, and Poland.

Finally, the study discusses the supporting incentives and policies required to overcome the existing TCO gap between fuel cell and diesel long-haul tractor-trailers during this decade. Such policies can stimulate market demand for the technology, especially during the early market uptake phase.

USE CASE DEFINITION

This study focuses on quantifying the total cost of ownership of fuel cell electric tractor-trailers in long-haul operations and comparing their economic performance to the performance of their diesel counterparts. The use case of interest looks at a long-haul application with a daily driving range of up to 660 km, which covers 95% of heavy-duty truck applications in Europe (Basma, Saboori, et al., 2021; Wentzel, 2020).

The diesel and fuel cell tractor-trailers' main technical specifications are presented in Table 1. The diesel vehicle is representative of a typical 4 x 2 tractor-trailer in long-haul operation in Europe, and the fuel cell vehicle is designed to perform similarly to the diesel vehicle, taking into account the currently available FCET models in Europe.[1]

Table 1. Technical specifications of the diesel and fuel cell tractor-trailers

	Diesel truck	Fuel cell truck
Axle configuration	4 x 2	4 x 2
Gross vehicle weight	40 tonnes	42 tonnes
Unladen weight [a)]	14.9–13.1 tonnes	14.9–12.6 tonnes
Maximum payload	25.1–26.9 tonnes	25.1–27.4 tonnes
Powertrain rated power	350 kW	350 kW
Fuel cell system power	-	180 kW
Transmission	12-speed	2-speed
Daily driving range	660 km	660 km
Battery size	-	72 kWh

a) The truck unladen weight is estimated using a bottom-up approach considering the expected technology improvement such as chassis light weighting as detailed in (Basma & Rodríguez, 2022).

The FCET's gross vehicle weight is 42 tonnes compared to the 40-tonne diesel tractor-trailer, thereby incorporating the two extra tonne exemption for zero-emission trucks granted in the HDV CO_2 standards in Europe. The maximum payload of the trucks varies as the trucks' curb weight decreases in the long term due to chassis lightweighting, which increases the payload capacity.

Compressed hydrogen gas at 700 bar is considered in this study. Liquid hydrogen is not common in road transportation and is thus not evaluated in this study. Finally, the FCET is equipped with a 72-kWh lithium-ion high-power battery to assist the fuel cell unit during peak power demand and to recover part of the vehicle's kinetic energy during braking.

The energy efficiency of both trucks is estimated through detailed vehicle energy consumption modeling and simulation using the commercial tool Simcenter Amesim (Siemens, 2020). The diesel vehicle model is simulated under VECTO[2]-like conditions, the official vehicle simulation model used to certify the CO_2 emissions of trucks (it does not cover fuel cell electric trucks). Consumption of diesel and hydrogen fuel is estimated by simulating the virtual models over the long-haul cycle at a low payload of 2.9 tonnes and a reference payload of 19.3 tonnes, as defined by VECTO. Detailed analysis of the technology can be found in Basma & Rodríguez (2022).

Diesel truck fuel consumption and FCET hydrogen consumption are shown in Figure 1. The diesel truck fuel consumption at the combined load (defined as 70-30% reference-low payload, according to HDV CO_2 standards) is around 30 l/100km, a number that has the potential to decrease to 23 l/100km by 2030 due to technology improvement

1 See Table 1 in (Basma & Rodríguez, 2022).

2 VECTO (Vehicle Energy Consumption calculation Tool) is the simulation tool that has been developed by the European Commission for determining CO_2 emissions and fuel consumption from HDVs.

as detailed in Delgado et al. (2017). The FCETs consume hydrogen fuel in the range of 8.3 kg/100km at combined load for truck model year 2022, a value that has the potential to decrease to ~ 6.1 kg/100km by 2030. More insight into the FCET's energy efficiency can be found in a separate vehicle technology analysis conducted by ICCT in Basma & Rodríguez (2022) and Basma, Beys, et al. (2021).

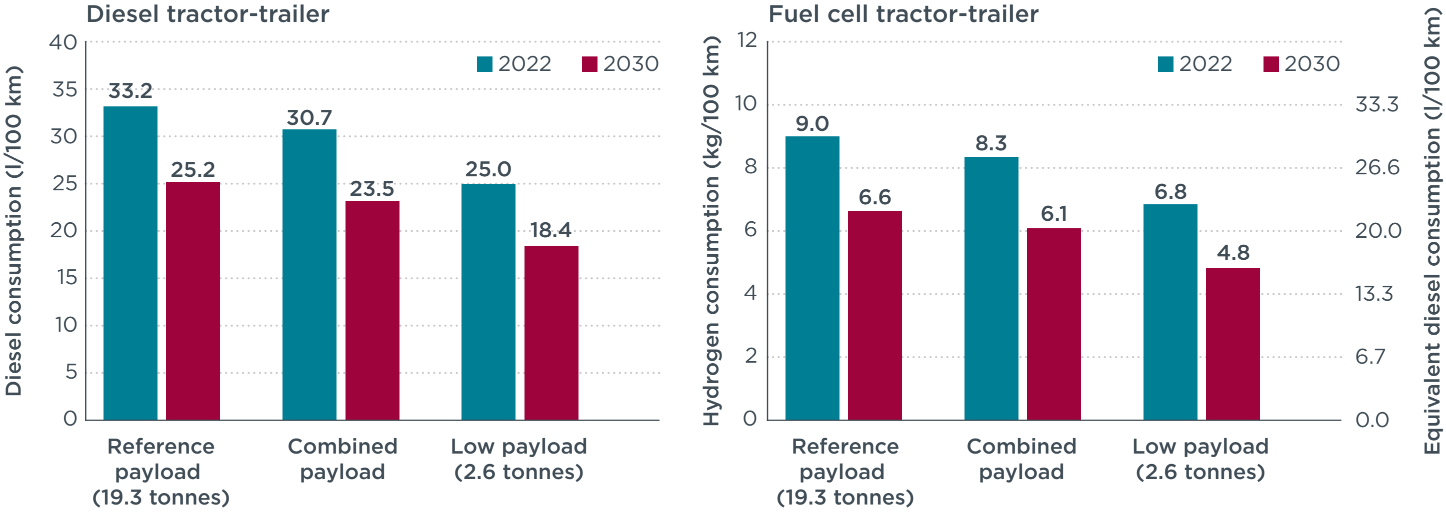

Figure 1. Diesel and hydrogen fuel consumption for tractor-trailers simulated over the long-haul cycle and at several payloads for truck model years 2022 and 2030

Although improvement in energy efficiency will allow smaller and lighter hydrogen tanks on board to meet a certain driving range design point, it is assumed that the hydrogen tank size will be maximized to attain the highest possible driving ranges. Given the truck geometry and volume constraints as discussed in Basma & Rodríguez (2022), the maximum storage capacity for a type IV 70 MPa hydrogen tank is 55 kg, resulting in a driving range of 650 km to 880 km between 2022 and 2030, based on the truck hydrogen fuel consumption under the combined payload as shown in Figure 1. This will be enough to cover the daily driving ranges of 660 km illustrated in this use case.

TOTAL COST OF OWNERSHIP MODELING

The total cost of ownership (TCO) of FCETs is evaluated for a first user over a 5-year period. In this section, the TCO methodology is explained. A previously published study by ICCT (Basma, Saboori, et al., 2021) describes in detail the adopted methods and assumptions to assess the TCO of diesel trucks and battery-electric trucks in Europe for tractor-trailer applications. This study will briefly recall some of those assumptions and key figures while giving more emphasis to FCET-specific costs such as the fuel cell unit, hydrogen tank, and hydrogen fuel.

FIXED COSTS

Truck fixed costs include the vehicle purchase cost, residual value, financing, taxes, and all expenses independent of the vehicle's kilometers driven.

Vehicle price and residual value

The cost of a diesel tractor-trailer today is estimated at €133,000, including the base glider and the trailer. In 2030, this cost is expected to increase to €145,000 due to improvements in road load technologies, diesel engine technology and emissions control systems (Meszler et al., 2018). Regarding the FCET cost, the vehicle retail price is directly related to the fuel cell unit rated power and hydrogen storage tank size. The FCET base glider direct manufacturing cost (DMC), excluding the power units (fuel cells and battery) and hydrogen storage tank, is detailed in Table 2 for a 2022 model year truck based on cost data provided by Ricardo Strategic Consulting (Anculle et al., 2022; Sharpe & Basma, 2022). The base glider DMC includes the chassis, power electronics, air compressor, steering pump, air conditioning and heating units, and battery thermal management systems. It is assumed that the costs of the components presented in Table 2 are fixed between 2022 and 2030. The trailer retail price is €33,000 today, and it is assumed to increase by €4,822 by 2030 due to the introduction of new road-load technologies (Meszler et al., 2018).

Table 2. Fuel cell electric truck base glider direct manufacturing costs in 2022-2030[3]

Component	Specifications	Cost multiplier (€/kW)	Total cost (€)
Chassis [a)]	-	-	25,375
Power electronics	350 kW	22.5	7,875
Air compressor [b)]	6 kW	1,250	7,500
Steering pump	9 kW	240	2,160
Air conditioning	10 kW	58	580
Heater	10 kW	63	630
Thermal management	350 kW	7.5	2,625
Total cost	-	-	46,745

a) This includes axles, suspension, wheels, steering, cab exteriors, and interiors.
b) This is the pneumatic braking system air compressor and not the fuel cell system air loop compressor. The latter's cost is included in the fuel cell system cost, as discussed below, in addition to the other balance of plant.

Based on a comprehensive meta-analysis of the purchase costs of ZE-HDVs conducted by ICCT (Sharpe & Basma, 2022), the DMC of the fuel cell unit, hydrogen storage tank, electric drive, and battery are summarized in Table 3. In 2020, the reported fuel cell unit DMC ranged widely, between 145 €/kW to 1,040 €/kW as thoroughly reviewed in (Sharpe & Basma, 2022). A mean value of 460 €/kW is considered in this study for truck model year 2022. This number is assumed to decrease to 170 €/kW in 2030, driven by the technology's increasing economies of scale. Similarly, the hydrogen

3 Data are provided in USD and a conversion rate of EUR 1 = USD 1.2 is used to express costs in EUR.

storage tank DMC in 2022 is estimated to be around 900 €/kg and is expected to decrease to 525 €/kg by 2030. The DMC of the electric drive (electric motor, inverter, and transmission) and the battery pack—assuming high-power battery prices—are also shown in Table 3.

Table 3. Direct manufacturing costs of fuel cell electric truck power unit and energy storage costs

Component	2022	2025	2030
Fuel cell unit	460 €/kW	340 €/kW	170 €/kW
Hydrogen tank	900 €/kg	660 €/kg	525 €/kg
Power battery	370 €/kWh	320 €/kWh	230 €/kWh
Electric drive	52 €/kW	29 €/kW	15 €/kW

In order to estimate the retail price of the truck, indirect costs should be considered in addition to the DMC. These indirect costs include research and development, overhead, marketing and distribution, warranty expenditures, and profit markups. These costs are considered by using indirect cost multipliers (ICMs) that multiply the DMC of the truck to estimate its retail price. The ICMs used in this study are defined by the U.S. EPA (EPA & DOT, 2016) and presented in Table 4. ICM of complexity level "High 1" is considered for the base glider components and the battery pack. For the fuel cell and hydrogen storage tank, ICM complexity level "High 2" is used to estimate the retail price.

Table 4. Indirect cost multipliers for technologies with a high technology complexity level

Complexity level	ICM	2022 [a)]	2030 (long-term)
High 1	**Warranty costs**	0.066	0.037
	Non-warranty costs	0.328	0.233
	Total	0.394	0.27
High 2	**Warranty costs**	0.079	0.056
	Non-warranty costs	0.451	0.312
	Total	0.53	0.368

[a)] The indirect cost multipliers (ICM) for truck model year 2022 are interpolated, assuming that the "short-term" ICM scenario defined in (EPA & DOT, 2016) corresponds to truck model year 2020.

Figure 2 shows the diesel and FCET retail price as a function of the model year between 2022 and 2030. For truck model year 2022, the difference exceeds €200,000, driven by the costly fuel cell unit in 2022, as shown in Figure 3, and by the price of the hydrogen tank to a lesser extent. By 2025, the retail price gap is reduced to almost €150,000, mainly due to the reduction in the fuel cell unit cost. In 2030, the FCET is expected to be only €60,000 more expensive than its diesel counterpart.

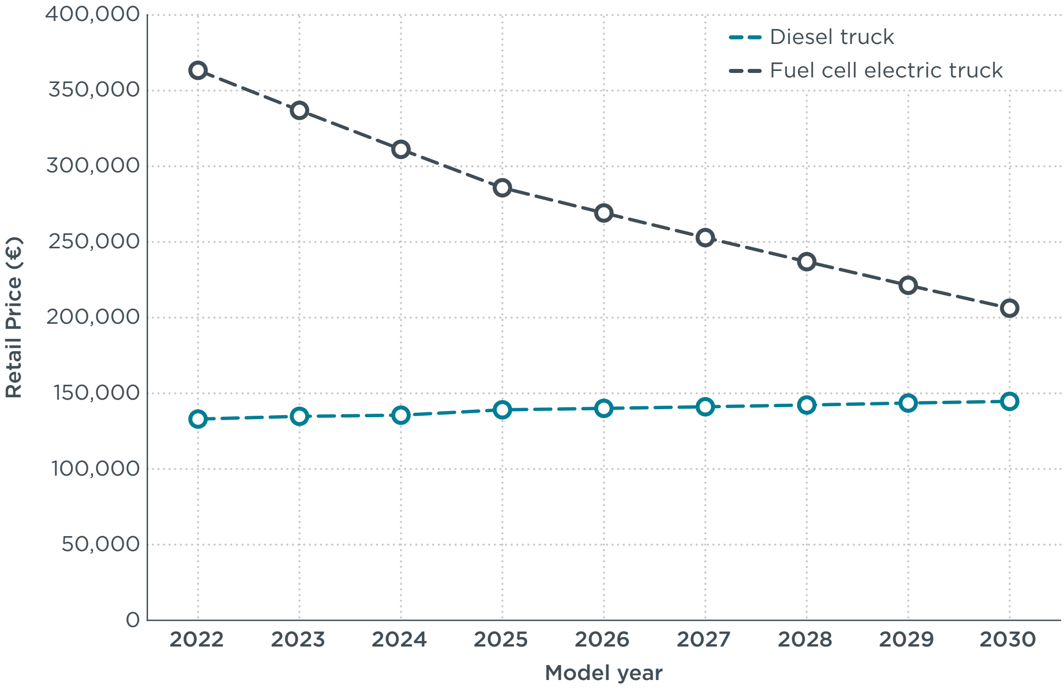

Figure 2. Estimated retail price of the diesel and fuel cell electric tractor-trailers between 2022 and 2030

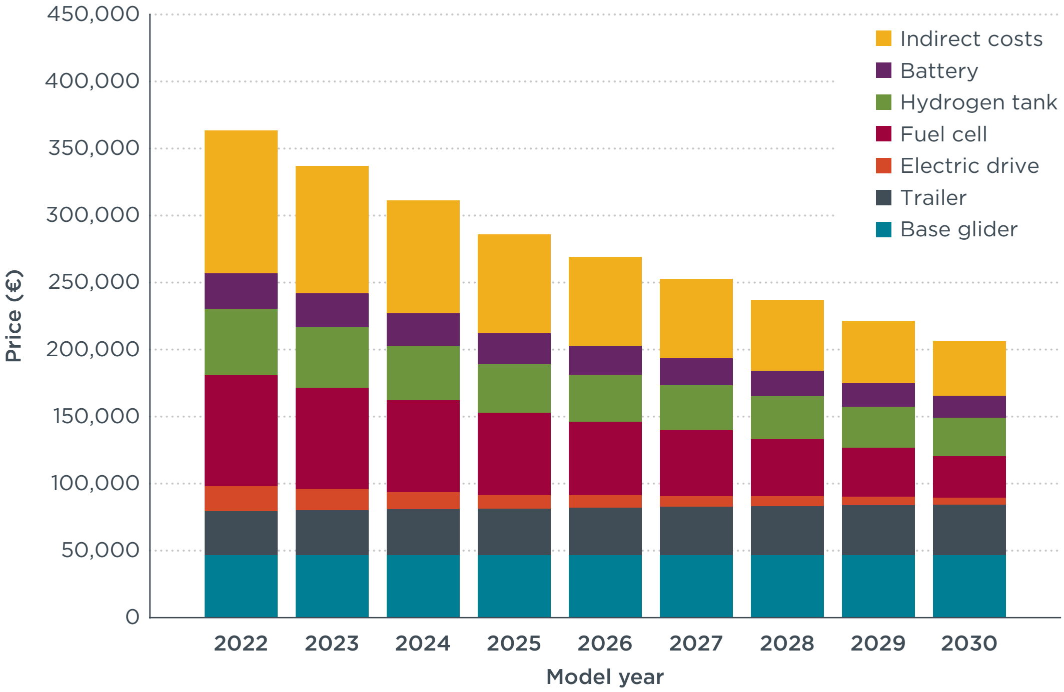

Figure 3. Fuel cell tractor-trailer retail price breakdown between 2022 and 2030

At the end of the 5-year analysis period, the truck salvage value is estimated using an analytical approach similar to Basma et al. (2022) and Mao et al. (2021). The diesel truck depreciation is assumed to be composed of a fixed annual depreciation rate of 7.5% and a variable depreciation rate as a function of the vehicle kilometers traveled (VKT) and truck lifetime. The lifetime VKT of tractor-trailers in Europe is assumed to be 1.2 million km (Meszler et al., 2018). Figure 4 shows the depreciation curves of the diesel tractor-trailers considered in this study. After five years of operation at an average annual mileage of 158,000 km, the truck has a residual value of 30%. The truck's annual VKT will be discussed in the 'Operating costs' section.

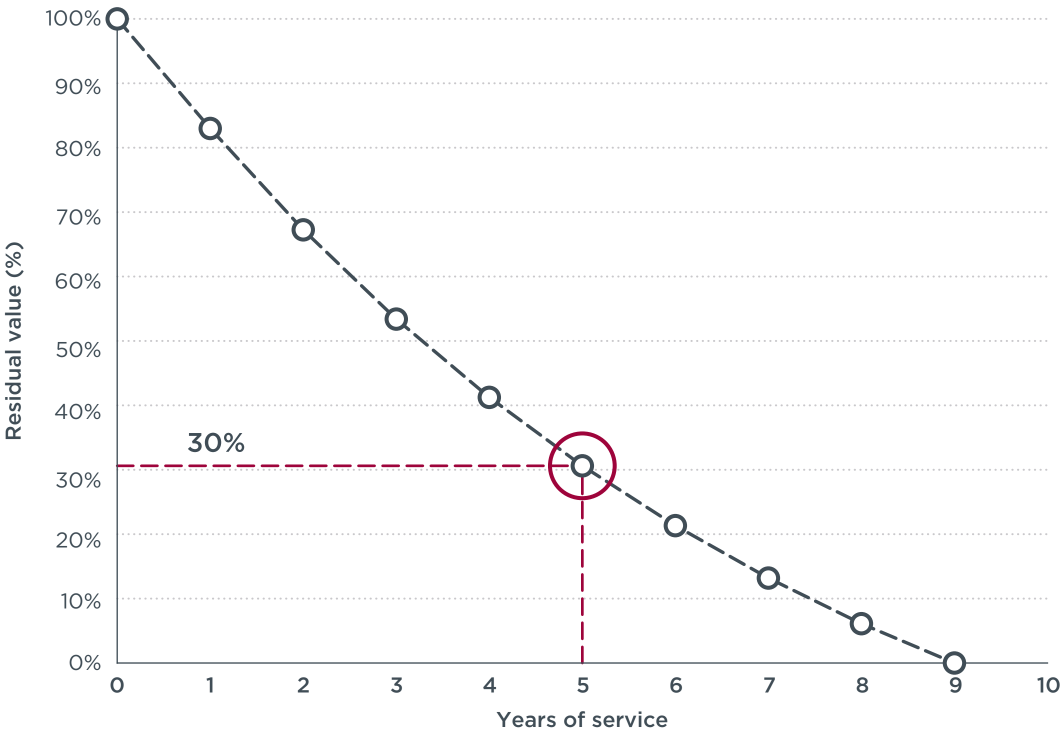

Figure 4. Tractor-trailer's depreciation curves as a function of service life, based on annual vehicle kilometers traveled

Several components have potential second-life marketability, like batteries and fuel cell units. The FCET base glider and electric powertrain componentry are assumed to depreciate in a manner similar to the diesel truck. Regarding the fuel cell unit, its durability allows for 15,000 hours of operation today, a number that could reach 22,000 hours by 2030 (Anculle et al., 2022). The number of operating hours for the cumulative vehicle kilometers traveled over the analysis period is divided by the average vehicle speed during operation, resulting in roughly 11,300 hours of operation. This translates to a 25% fuel cell unit residual value for truck model year 2022 assuming linear depreciation. With the expected improvement in the fuel cell unit durability by 2030, reaching 22,000 hours, the fuel cell unit salvage value will reach 49%. No battery replacement is needed over the first five years of operation, and battery residual value is estimated at 15% of its original price (Burke & Zhao, 2017). As for the hydrogen storage system, it is assumed that the tanks have a lifetime of 5,000 charge/discharge cycles (Pohl & Ridell, 2019). The fuel cell truck of interest in this study is subject to 1 charge/discharge cycle during the day. Over five years of operation for 312 days per annum, this results in roughly 1,500 charge/discharge cycles yielding a residual value of 70%.

Table 5. Summary of fuel cell tractor-trailers residual values after 5 years of operation

Component	Salvage value after 5 years	
	Truck model year 2022	Truck model year 2030
Fuel cell electric truck base glider and e-drive	30%	30%
Fuel cell system	25%	49%
Battery	15%	15%
Hydrogen tank	70%	70%

FINANCING, TAXES, AND VIGNETTE

The truck purchase cost is assumed to be financed over five years (first user analysis period) with a loan interest rate of 2% paid at the start of each year.

Table 6 summarizes the truck registration and ownership taxes in each country considered in this study and highlights the fixed annual vignettes for road taxes to be paid by truck operators. It is worth mentioning that most of the EU member states considered in this study adopt distance-based road vignettes, as will be explained later.

Table 6. Summary of truck registration and ownership taxes (Schroten et al., 2019) and fixed vignettes

Country	Registration tax (€)	Ownership tax (€/year)	Fixed vignettes (€/year)
Germany	0	929	-
France	800	950	-
Italy	1,500	1,000	-
Spain	0	850	-
Poland	290	1,300	-
Netherlands	0	0 [a)]	1,250 [b)]
United Kingdom	0	550	1,170 [c)]

[a)] (Belastingdienst, 2022)
[b)] (Eurovignette, 2022),
[c)] (UK Department for Transport, 2018)

OPERATING COSTS

Truck operating costs are directly related to truck mileage over the analysis period. Figure 5 shows the evolution of the truck annual mileage—referred to as annual vehicle kilometers traveled (AVKT)[4] in this study—as a function of the truck service year according to the EU TRACCS database (Emisia, 2013). The resulting truck average AVKT is around 158,000 km for the first-user analysis.

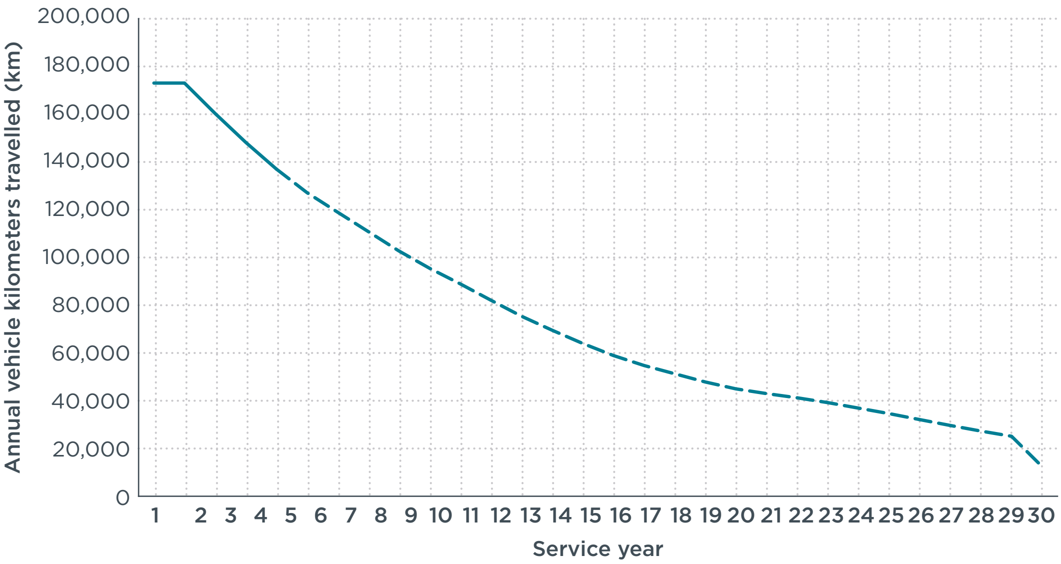

Figure 5. Truck annual mileage as a function of service years (long-haul applications)

4 The available TRACCS database does not distinguish between long and short-haul operations. This has been modified based on the trip length distribution. Refer to Basma, Saboori, et al. (2021) for more details.

HYDROGEN PRICE

This study provides the at-the-pump hydrogen price produced domestically in all seven European countries. While the EU is also planning to import hydrogen from other world regions (European Commission, 2022b), the cost of imports is beyond the scope of this study and will be assessed in a forthcoming ICCT study. Hydrogen price as a fuel at the pump consists of hydrogen production cost including the cost needed for compressing hydrogen to 700 bar, hydrogen transport cost if needed, and fueling station cost, i.e., dispensing cost. In reality, the at-the-pump price shall also include a fuel tax, which we exclude from our estimates because we assume that EU policymakers would exempt hydrogen from fuel taxes, in addition to offering other incentives in order to meet hydrogen infrastructure deployment goals.[5] In particular, the Commission's proposed Energy Taxation Directive allows renewable hydrogen to be taxed at the lowest tax rate (European Commission, 2021a). In this study, we provide estimates of hydrogen prices for each of the seven European countries during the 2022–2035 timeframe, in Euros per kilogram of hydrogen (€/kg). These estimates are based on a cost model previously developed within the ICCT (Zhou & Searle, 2022).

Renewable electrolysis hydrogen, also known as "green" hydrogen, is produced from renewable electricity (RE) using electrolysis. The European Commission is supporting green hydrogen in multiple policies. In particular, the proposed revision to the recast Renewable Energy Directive (REDII) requires 2.6% of the energy used in the transport sector to be renewable fuels of non-biological origin, which includes green hydrogen (European Commission, 2021b). A previous ICCT study modeled green hydrogen production costs in EU countries, and we derive the numbers from that study (Zhou & Searle, 2022). Green hydrogen can be produced from central or decentralized facilities. Decentralized production means that hydrogen is produced onsite at a fueling station so that no hydrogen transportation is needed from the production site to the fueling station, as would be the case with central production. While central production can benefit from economies of scale that enable a lower hydrogen production cost, decentralized production avoids the costly and inefficient transport of hydrogen. This study assumes decentralized green hydrogen production in all seven European countries. Therefore, green hydrogen price at the pump is the sum of green hydrogen production cost and the dispensing cost.

Table 7 summarizes the hydrogen production that includes compression costs between 2022 and 2035 in the seven European countries considered in this analysis.

Table 7. Hydrogen production cost in Europe including cost of compression to 700 bar

	Green Hydrogen (€/kg)		
Country	2022	2030	2035
France	5.47	4.45	4.15
Germany	7.68	6.41	6.10
Italy	7.95	5.98	5.65
Netherlands	4.85	3.98	3.71
Poland	4.63	3.77	3.50
Spain	5.26	4.36	4.10
United Kingdom	5.90	4.98	4.71

Hydrogen fueling station: European Commission (2021c) provides estimates of fueling station capital and operational costs from 2020 to 2050. We converted the numbers into per kg hydrogen costs using corresponding fueling station capacity and lifetime as described in that document. Figure 6 shows the amortized hydrogen

5 Ragon et al., (2022)

fueling station cost between 2022 and 2035 at different utilization rates. In the early years, the hydrogen fueling station will probably not be utilized to its full capacity. For the baseline scenario in this study, we assume utilization rates of 30% in 2022, 50% in 2030, and 70% in 2035, following the assumptions in previous studies (Hydrogen Council, 2020; Zhou & Searle, 2022).

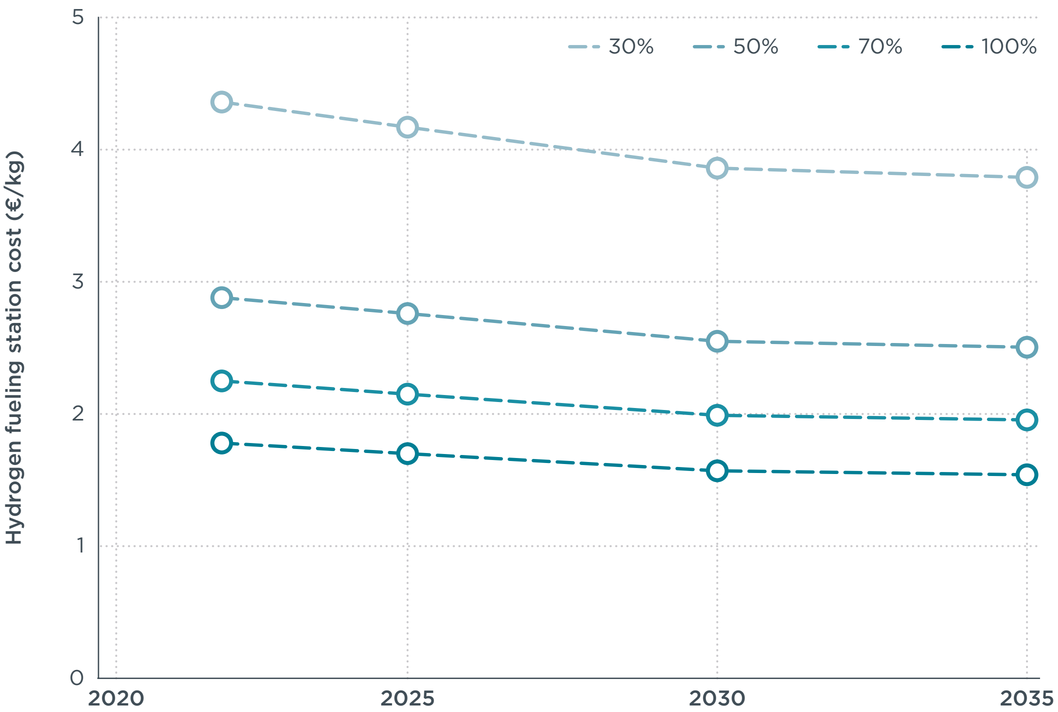

Figure 6. Amortized hydrogen fueling station cost between 2022 and 2035 at different utilization rates. Case of a small hydrogen station with a capacity of 400 kg/day.

The final at-the-pump hydrogen price is the sum of hydrogen production and compression costs and fueling station costs as presented in Figure 7. Germany and Italy have the highest green hydrogen prices but for different reasons. For Germany, it is because of the high grid fee that hydrogen producers pay when receiving electricity from the grid. For Italy, the renewable resources of solar and wind are not abundant and thus lead to a relatively high renewable electricity cost.

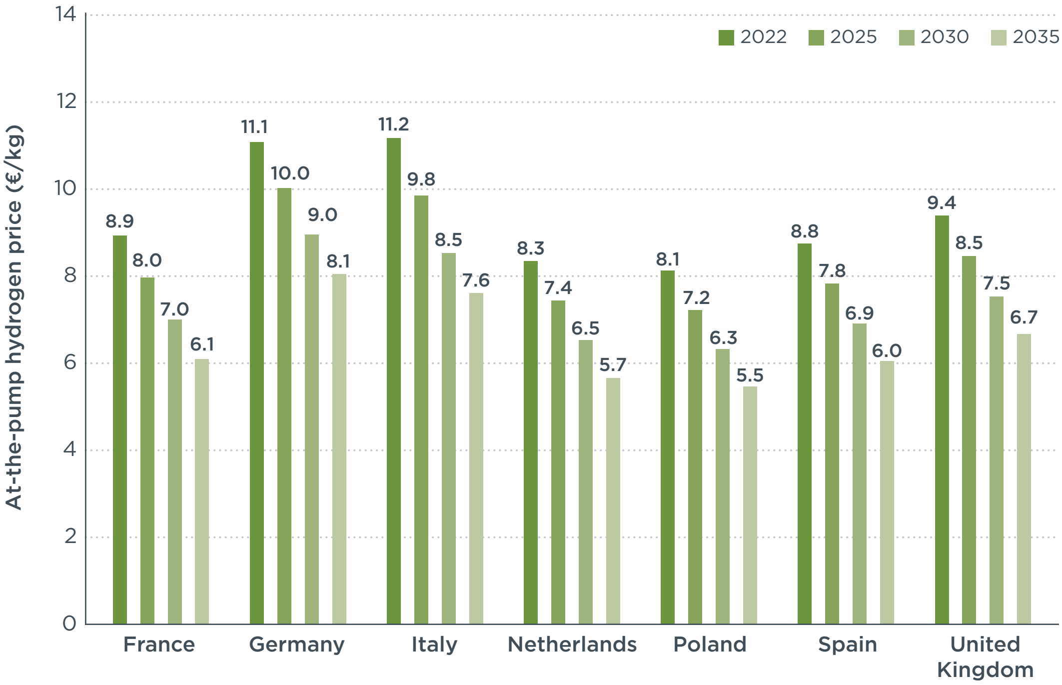

Figure 7. At-the-pump green hydrogen price between 2022 and 2035 for several European countries assuming the following hydrogen refueling station utilization rates (30% in 2022, 40% in 2025, 50% in 2030, and 70% in 2035).

Diesel price

The price of diesel fuel is composed of the prices of crude oil extraction, refining, and distribution, along with excise duties, and value-added taxes (VAT). Table 8 shows the diesel fuel prices in 2021 in each of the European countries considered in this study, according to the Diesel Price Index (2022). VAT and part of the excise duty are extracted from diesel fuel prices as they are refundable for commercial fleet operators (Vitalis, 2022). Due to the highly uncertain projections of diesel fuel prices through 2030, we assume several scenarios for the diesel fuel price evolution as presented in the results section. In addition, diesel fuel prices in the first quarter of 2022, as shown in Figure 8, recorded a 30% to 50% increase in March 2022 relative to 2021 annual average prices. The impact of such a price spike on the TCO will be examined later in the results section.

Table 8. Diesel fuel prices per liter in 2021 in European countries of interest in this study

Country	Gross price (€)	VAT rate	VAT (€)	Excise duty refund in 2021 (€)	Net price with tax refunds (€)
Germany	1.38	19 %	0.22	0	1.16
France	1.46	20 %	0.24	0.16	1.06
Italy	1.52	22 %	0.27	0.21	1.03
Netherlands	1.54	21 %	0.27	0	1.27
Poland	1.17	23 %	0.21	0	0.95
Spain	1.23	21%	0.22	0.048	0.97
United Kingdom	1.61	20 %	0.27	0	1.34

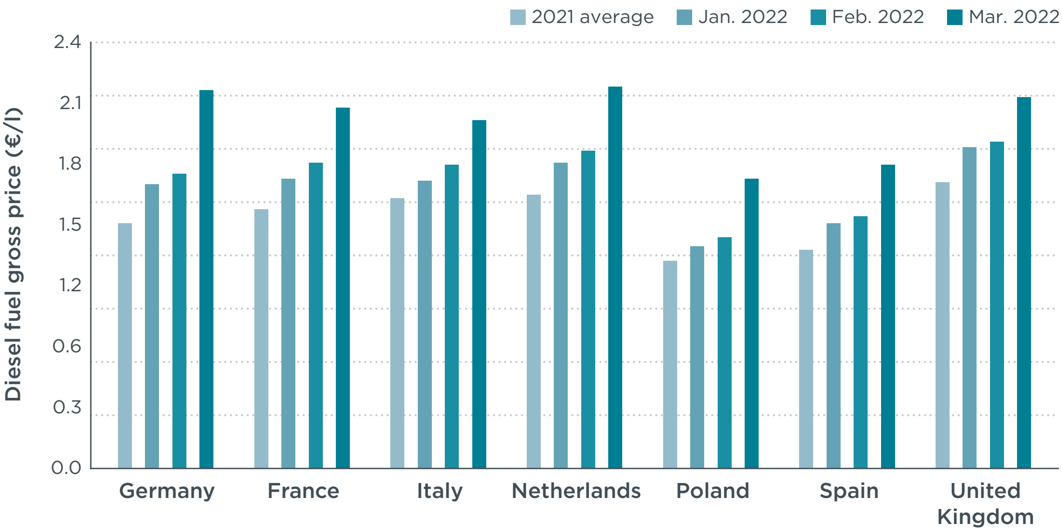

Figure 8. Evolution of diesel fuel gross price in several European countries between 2021 and the first quarter of 2022.

MAINTENANCE COSTS

Estimates of the maintenance costs of diesel tractor-trailers are shown in Table 9. Maintenance costs for diesel trucks include typical repairs and regular preventive maintenance; refilling of fluids such as oil, lubricants, and AdBlue; and tire changes. The total maintenance cost of a FCET is assumed to be the same as that of its diesel equivalent today. By 2030, this cost is expected to drop due to the learning curve effect of advanced new technologies, resulting in a 25.5% reduction (Wang et al., 2022). The total maintenance cost of a diesel truck, 18.5 €/100 km, is assumed constant for all model years, while that of the FCET, at 18.5 €/100 km today, is expected to fall to 13.78 €/km in the future.

Table 9. Maintenance cost breakdown for diesel and fuel cell tractor-trailers

Item	Cost (€/100 km)		
	Diesel	Fuel cell	
		2022	2030
Fluids (oil and lubricants) [a]	0.75	-0%[d]	-25.5%[d]
AdBlue refueling [a]	0.55		
Tires: front and driven axles [a]	2.47		
Tires: trailer [b]	2.73		
Repair and preventive maintenance [c]	12		
Total	18.5	18.5	13.78

[a] (Lastauto Omnibus, 2018)
[b] (Braun, 2016)
[c] (Kleiner & Friedrich, 2017)
[d] (Wang et al., 2022)

ROAD TOLLS

Most EU member states except the UK and the Netherlands adopt distance-based road tolls regulated by the Euro vignette directive, depending on the truck class and emissions category. Table 10 summarizes the distance-based road tolls in the EU member states considered. The government of the Netherlands intends to introduce distance-based road tolls as of 2024; meanwhile, an annual fixed rate of 1,250 €/year still applies for trucks with GVW above 12 tonnes (Eurovignette, 2022). In the United Kingdom, an annual fixed rate of 1,000 £/year has been applied since 2019 (UK Department for Transport, 2018). However, the government has suspended all tolls until 31 July 2023 because of the coronavirus (COVID-19) (UK Department for Transport, 2022).

Table 10. Summary of distance-based road tolls in EU member states

Country	Tolls (€/km)
Germany [a)]	0.183
France [b)]	0.320
Italy [c)]	0.190
Spain [b)]	0.160
Poland [d)]	0.055
Netherlands [e), f)]	0.15

[a)] (Bundesamt für güterverkehr, 2021)
[b)] (Schroten et al., 2019)
[c)] (autostrade.it, 2020)
[d)] (Poland Ministry of Infrastructure, 2020)
[e)] (Government of the Netherlands, 2020)
[f)] The Dutch Cabinet intends to introduce a 0.15 €/km road toll on all heavy goods vehicles exceeding of 3.5 tonnes as of 2024. The plans still await parliamentary approval.

RESULTS AND DISCUSSION

The results section is divided into four main parts:

» A key findings section in which the TCO of diesel and FCET are compared without considering any policy intervention, to reflect the actual technology cost. The section also includes a break-even analysis to calculate the needed hydrogen fuel price to reach TCO parity in each country. Finally, the section analyzes the impact of diesel fuel and hydrogen prices on the time needed for FCETs to achieve TCO parity with diesel trucks.

» A policy measures section where the impact of several possible policy interventions is examined.

» A sensitivity analysis section highlighting the impact of some main parameters and assumptions on the TCO gap between FCET and its diesel counterpart.

» A design choice section highlighting the impact of fuel cell stack size on the TCO.

KEY FINDINGS

Baseline scenario: fixed diesel fuel prices between 2022 and 2030, and renewable electrolysis hydrogen production

Figure 9 shows the TCO net present value of fuel cell and diesel tractor-trailers as a function of year of purchase calculated over the first 5 years of ownership, considering fixed diesel fuel prices between 2022 and 2030 in the seven European countries considered in this study. The diesel fuel prices considered in this section represent the 2021 yearly average prices in each country, as discussed earlier. In general, the TCO of the diesel truck is stable over the entire analysis period with a slight decrease driven by improvement in the truck diesel fuel economy despite the increase in the truck retail price due to stricter emission regulations as discussed in the "Use case definition" section. In the case of the Netherlands, the diesel truck TCO increases between 2022 and 2024 then stabilizes beyond 2024. This is driven by the assumption of road tolls in the Netherlands as distance-based road tolls are expected to be introduced in 2024, and until then, fixed vignettes are considered resulting in a lower TCO.

The TCO of FCETs decreases significantly between 2022 and 2030 across all countries, driven by the following three main factors:

Reduction in the FCET retail price as shown earlier in Figure 2 (~ €360,000 in 2022 compared to ~ €210,000 in 2030).

Reduction in the at-the-pump hydrogen fuel price between 2022 and 2035 as shown earlier in Figure 7 (8-11 €/kg in 2022 compared to 5-8 €/kg in 2035). This reduces the truck's operational expenses.

Improvement in the FCET energy efficiency results in improved fuel economy, as presented earlier in Figure 1 (~ 27% reduction in hydrogen fuel consumption between 2022 and 2030 – more details can be found in Basma & Rodríguez (2022)). This also results in reduced operational expenses.

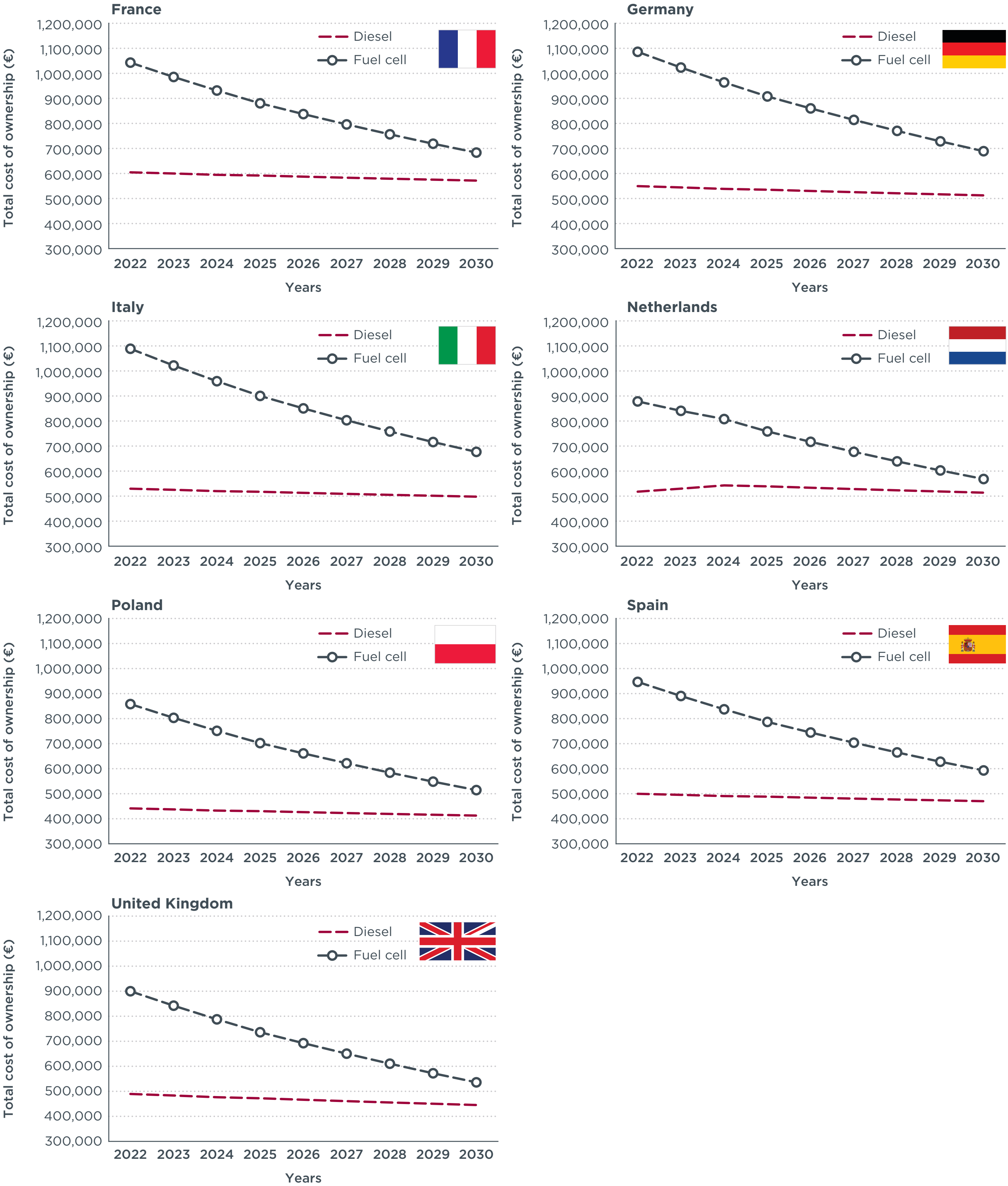

Figure 9. Net present value of TCO of fuel cell and diesel tractor-trailers as a function of year of purchase, calculated over the first 5 years of ownership and assuming fixed diesel fuel prices between 2022 and 2030, without policy intervention

Despite the significant reduction in their TCO, FCETs will not achieve TCO parity with their diesel counterparts before 2030 in any of the countries considered in this study. Nonetheless, the TCO gap between the two technologies is significantly narrowed by 2030, ranging from €55,000 for trucks operating in the Netherlands to €180,000 for trucks operating in Germany and Italy. A higher TCO gap for trucks purchased in 2030 implies that FCETs will require more time to achieve TCO parity with diesel trucks over the next decade in those countries. Table 11 summarizes the 5-year TCO gap between FCETs and diesel trucks, for trucks purchased in 2030.

Table 11. Five-year total cost of ownership gap between fuel cell and diesel tractor-trailers for trucks purchased in 2030 without policy intervention

Country	France	Germany	Italy	Netherlands	Poland	Spain	United Kingdom
TCO gap in 2030	+16% (€112,000)	+30% (€177,000)	+32% (€179,000)	+ 6% (€55,000)	+20% (€102,000)	+21% (€123,000)	+16% (€91,000)

To better understand the difference in the TCO of FCETs among the different countries considered in this analysis, Figure 10 shows the TCO breakdown in each country for trucks purchased in 2022, 2025, and 2030. In general, the TCO gap in 2022 is driven primarily by the significantly higher fuel price for the FCET, almost 3 times higher than that of the diesel truck. This behavior is not common for alternative vehicle technologies when compared to internal combustion engine vehicles. Nonetheless, the high cost of producing hydrogen fuel and the limited energy efficiency improvement[6] for the FCET powertrain relative to the diesel powertrain result in higher operational expenses for the FCET. To a lesser extent, the truck net cost, including the truck purchase price and residual value, is another reason for the high TCO gap in 2022. This dynamic is observed in all countries. By 2030, the higher FCET fuel cost becomes almost the only driver behind the TCO gap as net costs become comparable for the two truck technologies.

In 2030, FCETs operating in the Netherlands and United Kingdom will have the lowest TCO gap among all countries. In the case of the Netherlands, this is due to a combination of high diesel prices and low expected hydrogen prices compared to other European countries. In the case of the United Kingdom, although hydrogen prices by 2030 are not likely to be among the lowest in Europe, the lower TCO gap relative to other countries is driven by the high diesel fuel prices, reaching 1.6 €/liter as a yearly average in 2021, the highest among the countries considered in this analysis. FCETs operating in Poland also witness a relatively narrow TCO gap by 2030, around €80,000. This is driven by the expected low hydrogen prices in Poland during the 2030-2035 timeframe, which are expected to be around 5.5-6.3 €/kg, the lowest hydrogen fuel prices in the countries considered in this analysis. On the other hand, FCETs operating in Germany and Italy record the highest TCO gap relative to diesel trucks by 2030, primarily driven by the high expected hydrogen fuel price in 2030 in these countries, ranging between 8 and 9 €/kg in the 2030-2035 timeframe.

6 A detailed technology analysis previously conducted by ICCT (Basma & Rodríguez, 2022) has shown that FCETs record a mere 10% improvement in energy efficiency over the VECTO long-haul cycle.

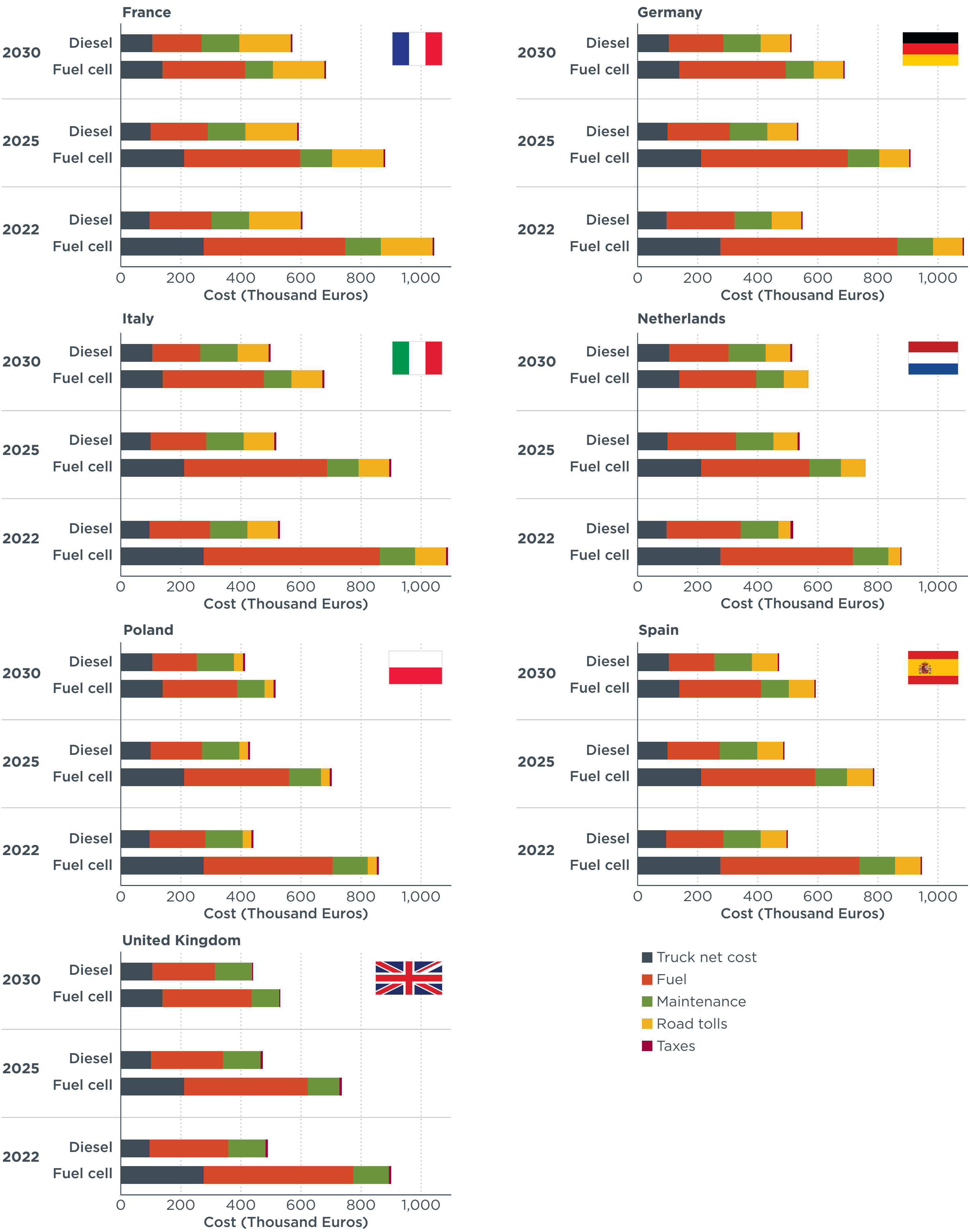

Figure 10. Country-specific TCO breakdown for trucks purchased in 2022, 2025, and 2030, without policy intervention.

Break-even analysis

As presented in the previous section, FCETs will not reach TCO parity with their diesel counterparts during this decade across the countries considered in this analysis. One of the main factors for this behavior is the high at-the-pump hydrogen fuel price. This section conducts a break-even analysis examining several scenarios for hydrogen prices to determine the break-even at-the-pump hydrogen price so that FCETs can reach TCO parity with diesel trucks during this decade. Figure 11 shows the TCO net present value of fuel cell and diesel tractor-trailers, as a function of the year of purchase, calculated over the first 5 years of ownership, considering fixed 2021 average diesel fuel prices between 2022 and 2030 and several scenarios for the at-the-pump hydrogen fuel price ranging between 3 €/kg to 6 €/kg and considered fixed over the analysis period. The TCO of FCETs decreases for lower hydrogen fuel prices resulting in an earlier parity with diesel trucks.

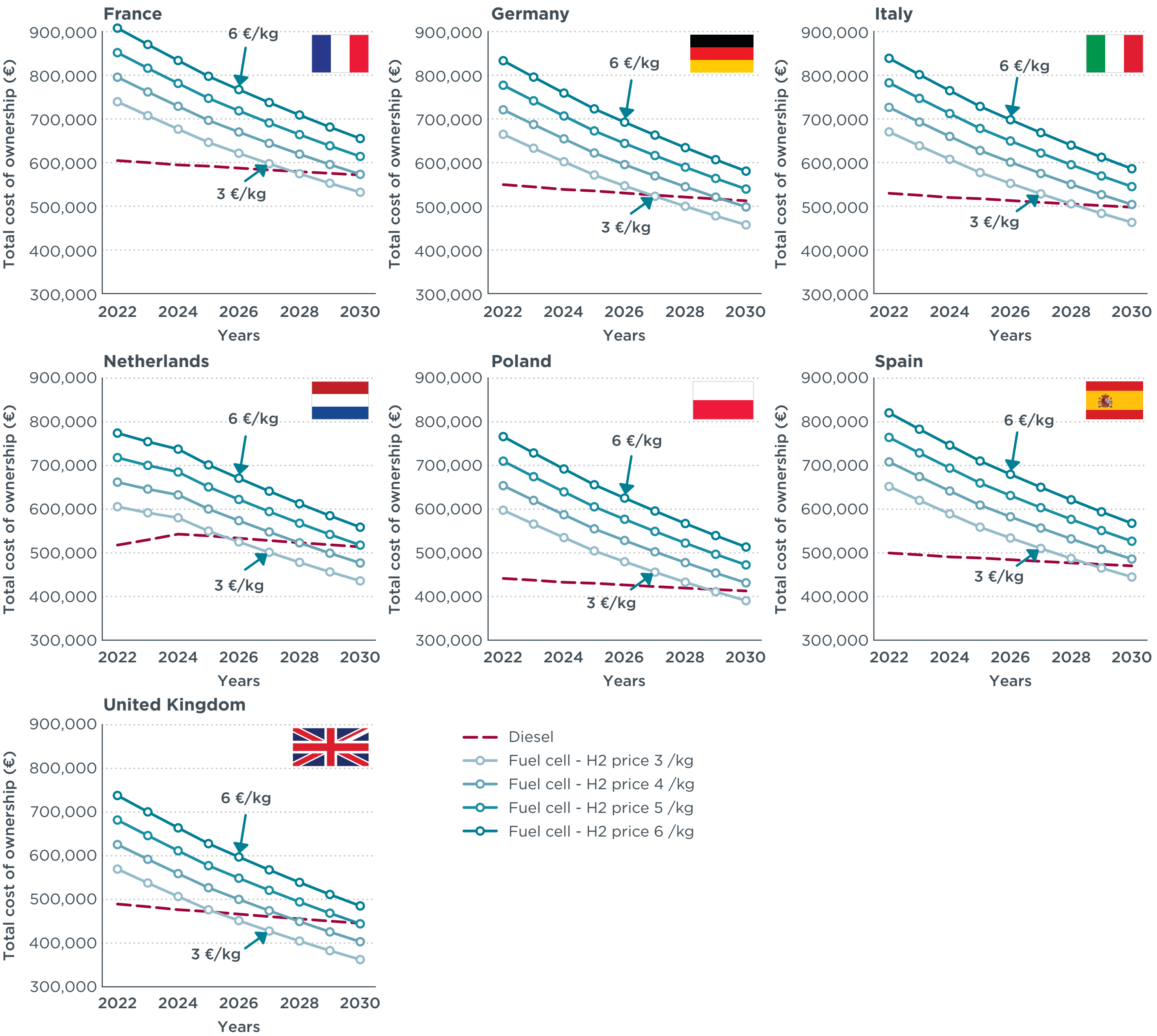

Figure 11. Net present value of TCO of fuel cell and diesel tractor-trailers as a function of year of purchase, calculated over the first 5 years of ownership and assuming fixed diesel fuel prices between 2022 and 2030 without policy intervention and with various levels of at-the-pump hydrogen fuel prices.

Figure 12 summarizes the break-even at-the-pump hydrogen price to achieve TCO parity by 2025 and 2030 between fuel cell and diesel tractor-trailers in all the countries considered in this study. For TCO parity in 2030, the lowest hydrogen break-even price is recorded in Poland at ~ 3.5€/kg, mainly driven by the lower diesel prices in Poland, making it difficult for FCETs to achieve TCO parity with their diesel counterparts. On the other hand, the highest hydrogen break-even price is recorded in the Netherlands and the United Kingdom at 5 €/kg, also driven by the diesel fuel prices in these countries as they record the highest prices among all countries considered in this study. A higher break-even price implies a relatively less costly transition from diesel trucks toward FCETs in these countries. For a 2025 TCO parity, significantly lower break-even hydrogen prices are needed, ranging from 1.5 to 3 €/kg. This is mainly driven by the expected higher retail price for FCETs in 2025 relative to 2030.

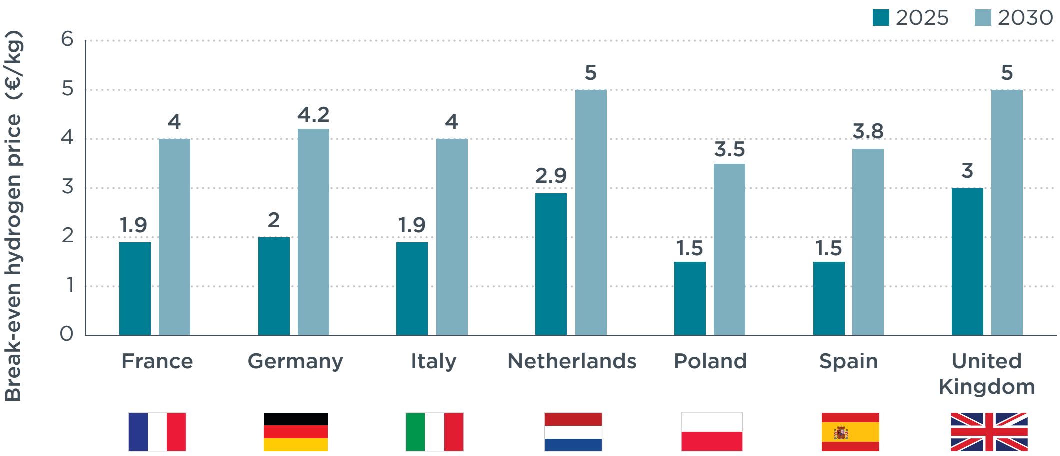

Figure 12. Break-even at-the-pump hydrogen price to achieve TCO parity by 2025 and 2030 between fuel cell and diesel tractor-trailers, without policy intervention.

Figure 13 shows the break-even and expected[7] at-the-pump hydrogen fuel price in the seven countries considered in this study for trucks purchased in 2025 and 2030. The difference between the expected and the break-even hydrogen fuel price for a 2025 FCET purchase year ranges from 4.18 €/kg in the case of the Netherlands to 7.42 €/kg in the case of Italy. In other words, if FCETs are to achieve TCO parity with their diesel counterparts by 2025, a 4.18 €/kg hydrogen fuel subsidy is needed in the Netherlands and a 7.42 €/kg hydrogen fuel subsidy is needed in Italy. For a 2030 purchase year FCET, significantly lower subsidies are needed to reach TCO parity, with diesel trucks calculated at around 1.18 €/kg in the Netherlands and 4.16 €/kg in Italy.

7 The expected hydrogen price for trucks purchased in a particular year is calculated as the average of our modeled yearly hydrogen prices from the year of purchase until five years after that (trucks purchased in 2025: average hydrogen price between 2025 and 2030; trucks purchased in 2030: average hydrogen price between 2030 and 2035).

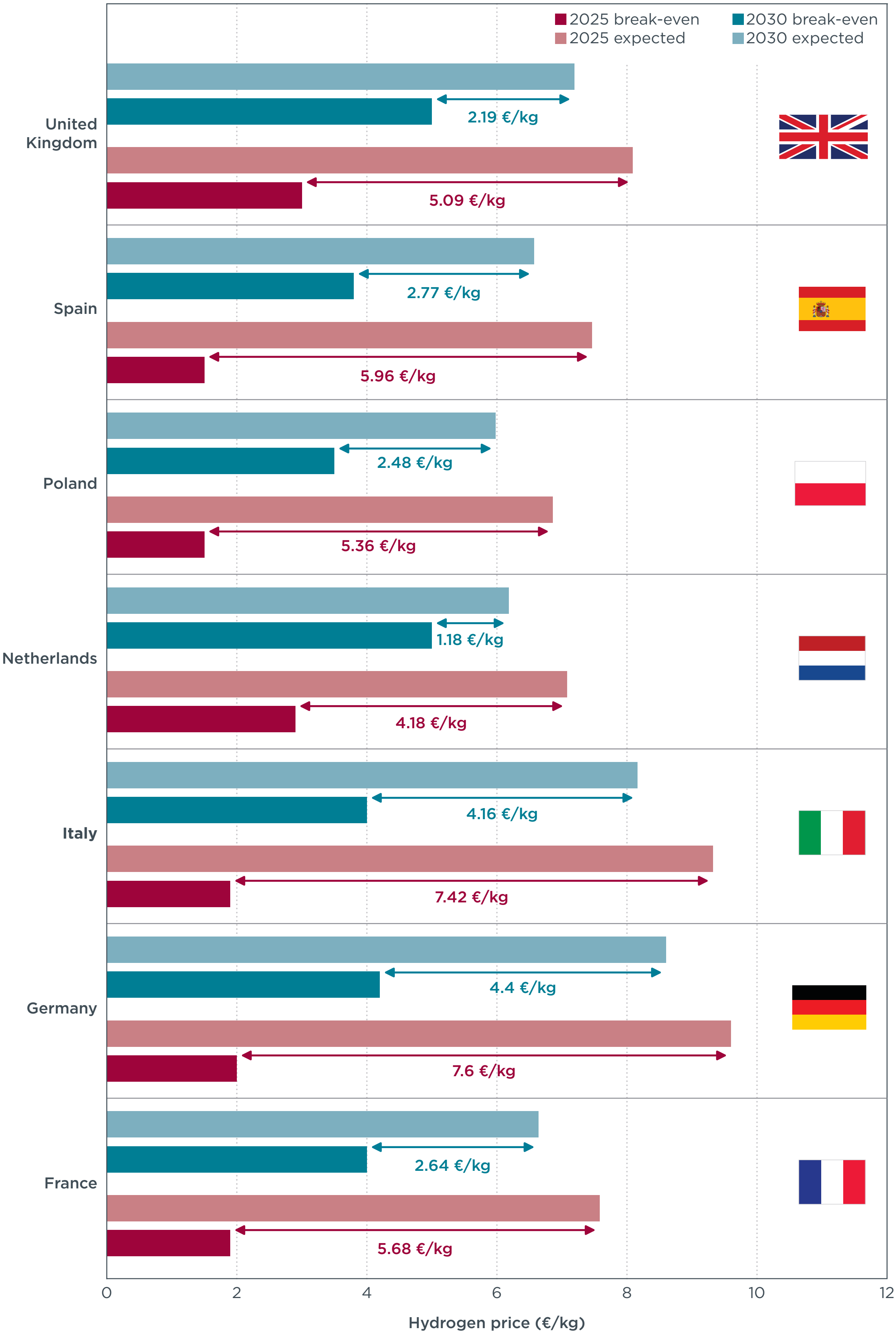

Figure 13. Break-even and expected at-the-pump hydrogen price for trucks purchased in 2025 and 2030, without policy intervention.

Impact of diesel and hydrogen fuel prices

The analysis in the previous section uses the 2021 average diesel prices in the countries studied. However, with the staggering increase in diesel fuel prices worldwide during the first quarter of 2022 (refer to Figure 8), a sensitivity analysis highlighting the impact of this price spike is needed.

In addition, the EU has ambitious hydrogen goals, as outlined in its 2020 Hydrogen Strategy communication (European Commission, 2020b). The Commission's proposed revision to the recast Renewable Energy Directive (REDII) includes an ambitious target: that 2.6% of total transport energy be renewable fuels of non-biological origin, including green hydrogen (European Commission, 2021b). The Commission has also proposed targets for the deployment of hydrogen fueling stations in cities and highways in its proposed revision of the Directive on the deployment of the alternative fuels infrastructure (European Commission, 2021c). It can thus be expected that EU member states will need to take substantial and robust measures to achieve these targets. However, at the current stage, it is not clear how many subsidies will be proposed by European countries.

Without policy incentives, it is unlikely that hydrogen will reach the cost parity level estimated in this study. The difference between the break-even and expected price in Figure 15 can provide some insights for policymakers when considering subsidies for hydrogen. When designing such a policy instrument, it is also crucial to support only low-GHG hydrogen that aligns with the EU's decarbonization targets, such as green hydrogen; rather than providing support for all kinds of pathways, some of which are not necessarily low-GHG, such as blue hydrogen—hydrogen made from fossil gas combined with carbon capture and storage (Zhou et al., 2021).

This section examines the impact of diesel and hydrogen fuel prices on the TCO parity year between FCETs and their diesel counterparts. Figure 14 shows the TCO parity between FCETs and diesel trucks at different diesel and hydrogen fuel prices. The oblique contours in the figure refer to the year of TCO parity for the two technologies. The diesel fuel prices vary between 0.8 €/l and 2.4 €/l, representing the price spectrum between January 2020 and March 2022. Hydrogen fuel prices vary between 3 €/kg and 9 €/kg, the hydrogen fuel price range required to achieve TCO parity during this decade.

Variations in hydrogen and diesel fuel prices significantly affect the year when FCETs and diesel trucks achieve TCO parity. TCO parity could be reached in 2022 if some extreme and unlikely scenarios are considered, such as a combination of high diesel fuel prices exceeding 1.8 €/l accompanied by low hydrogen fuel prices below 5.5 €/kg.

Figure 14 highlights the diesel fuel price spike in 2022, showing March 2022 diesel fuel prices for the countries considered in this analysis. These higher diesel fuel prices help FCETs achieve earlier TCO parity with their diesel counterparts. In other words, the break-even hydrogen fuel price becomes higher as diesel fuel prices increase. For example, in the case of Germany (DE), considering the 2021 net average diesel fuel price of 1.16 €/l, i.e., excluding VAT and excise duties that can be refunded, the break-even hydrogen price to achieve TCO parity by 2025 is below 3 €/kg. On the other hand, considering Germany's March 2022 net diesel fuel prices reaching almost 1.8 €/l, the break-even hydrogen price for a 2025 TCO parity would be between 4€/kg and 4.5 €/kg. This highlights how the recent price spike in diesel fuel prices may create a favorable environment to transition towards a fossil-free HDV sector by means of zero-emission HDVs powered by renewable electricity, or renewable electrolysis in the case of FCETs.

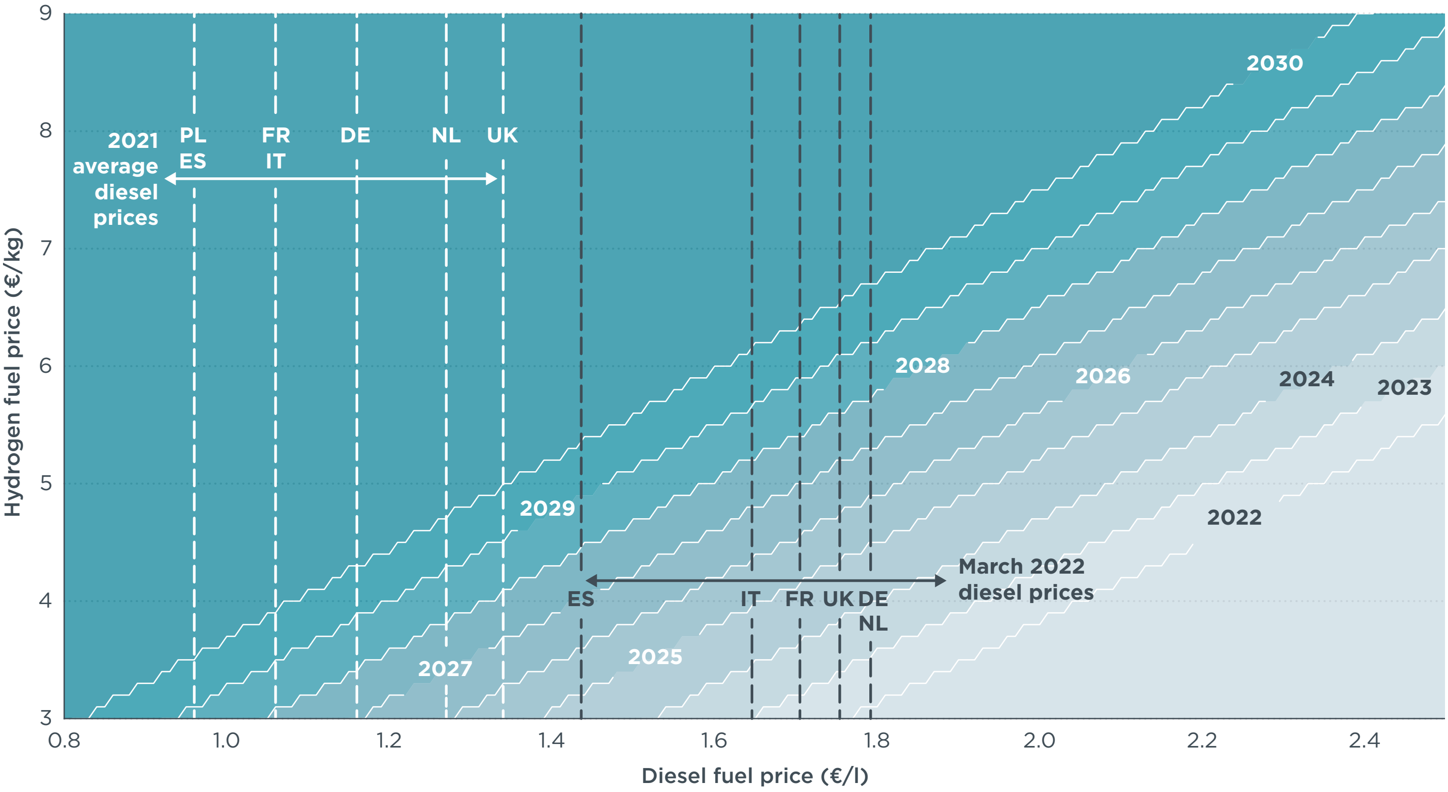

Figure 14. Total cost of ownership parity sensitivity to diesel and hydrogen fuel prices without policy intervention (PL: Poland, ES: Spain, FR: France, IT: Italy, DE: Germany, NL: The Netherlands, UK: United Kingdom)

ANALYSIS OF POLICY MEASURES

This section examines the impacts of different policy measures on the TCO parity between fuel cell and diesel tractor-trailers. These include measures that are actually in place today, planned measures, and hypothetical measures. Note that the assumption regarding exempting hydrogen fuel production from taxes still holds in this section. The following policy measures are considered:

» Purchase subsidies for fuel cell trucks (in place)
» Partial or full exemption of road tolls for fuel cell trucks (in place or planned, depending on the country)
» Addition of CO_2 external cost to road tolls (planned)
» Potential subsidies on H_2 fuel price (hypothetical).

Purchase subsidies for fuel cell trucks

Table 12 summarizes the currently offered purchase subsidies for alternative truck technologies in each of the countries considered in this study. These subsidies are exclusive for fuel cell tractor-trailers with a certain GVW. Other technologies, like battery-electric, hybrid, and natural gas trucks and other truck classes are subject to different subsidies.

Table 12. Summary of purchase subsidies for fuel cell trucks in the countries studied

Country	Subsidy
Germany [a]	**80%** of the difference in truck acquisition cost relative to an equivalent diesel truck capped at **€550,000** for trucks whose GVW is above 30 tonnes.
France [b]	**65%** of the difference in truck acquisition cost relative to an equivalent diesel truck capped at **€150,000** for trucks whose GVW is above 26 tonnes.
Italy [c]	**€24,000** fixed subsidy for trucks whose GVW is above 7 tonnes.
Spain [d]	Fixed subsidy for trucks belonging to N3 class whose GVW is above 16 tonnes, depending on the business size: large business (€130,000), medium business (€160,000) and small business (€190,000). A medium business is considered in this study to have **€160,000** in fixed subsidies.
Poland [e]	**30%** of truck acquisition cost difference relative to an equivalent diesel truck for trucks belonging to N3 class with GVW above 12 tonnes. The subsidy is capped at zl200,000 (~ **€42,600** assuming the following exchange rate zl1 = €0.21.
Netherlands [f]	A differential subsidy as a function of the truck acquisition cost difference relative to an equivalent diesel truck depending on the business size: large business (20% of cost difference capped at €72,700), medium business (28.5% of cost difference capped at €102,300) and small business (37% of cost difference capped at €131,900). A medium business is considered in this study with **28.5%** of cost difference subsidy capped at **€102,300**.
United Kingdom [g]	The grant covers 20% of the purchase price, up to a maximum of £16,000 available only for the first 250 orders placed. A maximum grant rate of £6,000 will apply when that limit is exceeded. It is assumed that the limit has already been exceeded and thus a fixed subsidy of £6,000 (~ **€7,000** assuming the following exchange rate £1 = €1.17) is considered.

a) (Bundesamt für Güterverkehr, 2021)
b) (Ministère de la Transition écologique, 2022)
c) (Ministero delle infrastrutture e della mobilità sostenibil, 2021)
d) (Ministerio de Transportes, Movilidad & y Agenda Urbana, 2022)
e) (Ministerstwo Energii, 2019)
f) (Ministerie van Infrastructuur en Waterstaat, 2021)
g) (Department for Transport, 2020).

Figure 15 shows the impact of purchase subsidies on the FCET's TCO and time to parity relative to diesel trucks. The left panels show the evolution of the trucks' retail prices, while the right-hand side panels show the TCO evolution. Only France, Germany, and Spain are presented in this section as they offer the highest purchase subsidies, while other countries provide much lower subsidies, as shown earlier in Table 12. It is assumed that purchase subsidies will remain in place until 2030 although it is unlikely to be the case as these subsidies are budget-limited and also time-limited. Nonetheless, this will provide insights into how different purchase subsidy designs and amounts affect the TCO of FCETs.

The subsidies offered significantly reduce the FCET retail price. For FCET purchase year 2022, the retail price is reduced by €150,000 in France, €180,000 in Germany, and €160,000 in Spain. Subsidies in France and Germany decrease with time as they are differential subsidies estimated based on the purchase price difference between the two technologies; and the FCET retail price is expected to decrease continuously until the end of the decade. In Spain, the subsidies are fixed, thus they remain constant throughout the entire analysis period. This significantly reduces the FCET retail price, making it even cheaper to purchase than its diesel equivalent, as of 2025.

This reduction in the FCET retail price positively impacts the FCET TCO. However, this reduction is not enough to make FCETs cost-competitive with diesel trucks during this decade, except for FCETs operating in Spain, where TCO parity might be achieved by 2030, assuming the current fixed premium of €160,000 per FCET remains in place, which is unlikely.

Purchase subsidies do not significantly drive the TCO of FCETs. Even if the FCET retail price becomes equal to or cheaper than its diesel counterpart, the fuel expenses of the FCET are expected to remain higher than diesel truck fuel expenses at least until the end of the decade, considering the expected hydrogen fuel prices (check the TCO breakdown presented earlier in Figure 10). This would counteract the benefits of retail price reduction through purchase subsidies. Nonetheless, the role of purchase subsidies could be significant in reducing the FCETs' TCO if these subsidies are increased or coupled with some hydrogen fuel subsidies as presented earlier in the "Break-even analysis." In addition, such subsidies could lower investment barriers for fleet owners or investors as "access to capital" is identified as a main challenge for decarbonizing HDV fleets during the early market uptake phase.

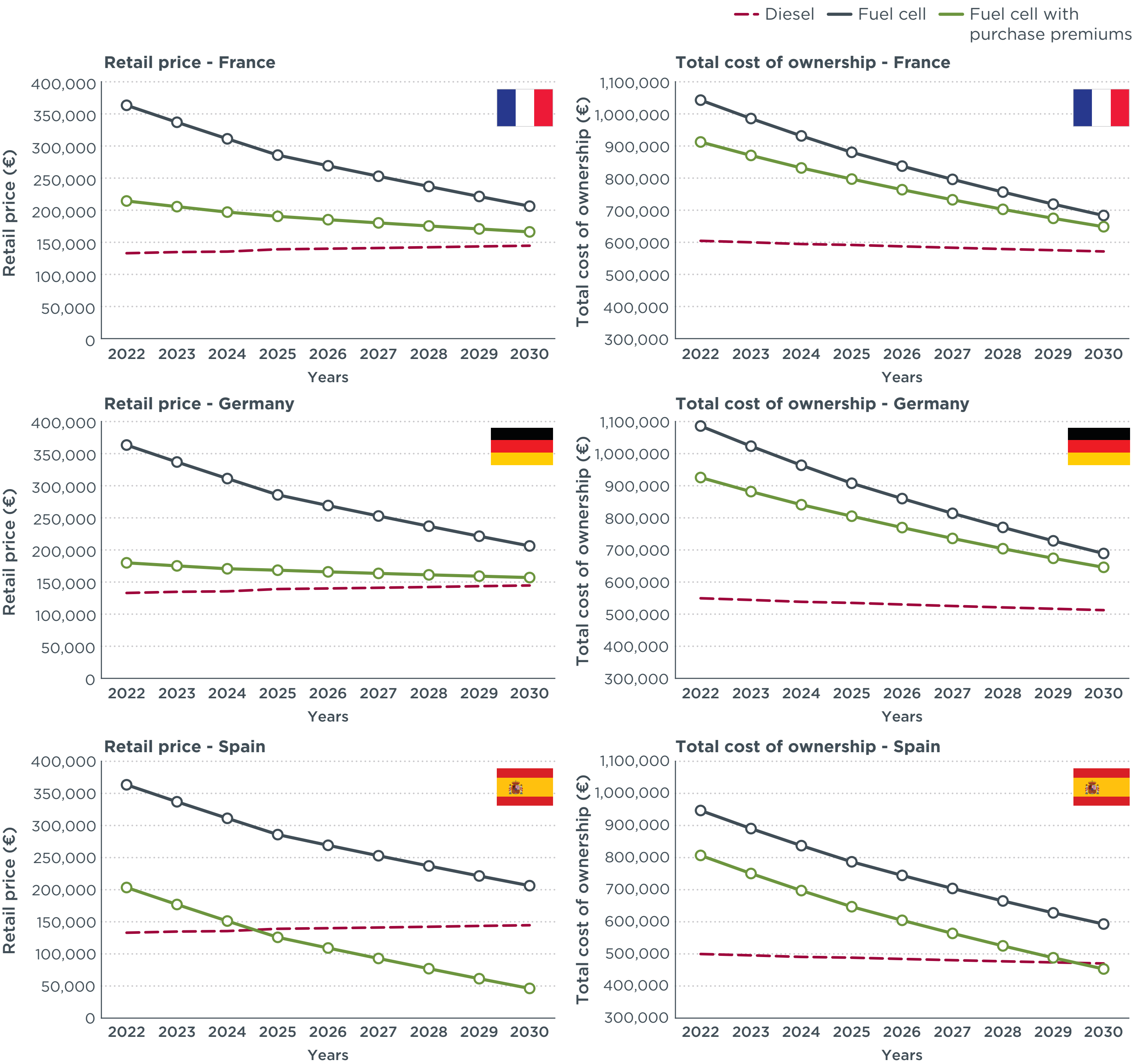

Figure 15. Impact of purchase subsidies on the TCO of fuel cell tractor-trailers

Partial or full exemption of road tolls for fuel cell trucks

The recent amendment (DIRECTIVE (EU) 2022/362) (European Commission, 2022a) to the Eurovignette directive inserted an additional article (*Article 7ga*) stating that member states shall reduce infrastructure charges (road tolls) for zero-emission vehicles by 50%–75%. Germany has already fully exempted zero-emission HDVs from such charges. The impact of such a policy intervention on the TCO parity-time between FCETs and diesel trucks is assessed in this section.

Table 13 shows the impact of exempting fuel cell tractor-trailers from road tolls on the TCO time to parity relative to their diesel counterparts. Three scenarios of road toll exemptions are considered: 50%, 75%, and 100% exemption. Only FCETs operating in France and the Netherlands record a shift in the TCO parity year, achieving parity by the end of the decade. In the case of France, a 100% road toll exemption may allow FCETs to reach TCO parity by 2029, without the need for any additional purchase subsidies or hydrogen fuel subsidies. If coupled with other policy measures, this could have a very positive impact on the TCO of FCETs operating in France.

It is worth mentioning that although this policy measure could play a vital role during the early market uptake phase of ZE-HDVs by reducing their TCO gap relative to diesel trucks, extending it for long periods may jeopardize road infrastructure funding in the future depending on the market share of ZE-HDVs. Thus, such exemption should be limited in duration.

Table 13. Impact of exempting fuel cell tractor-trailers from road tolls on TCO time to parity relative to their diesel counterparts.

Country	France	Germany	Italy	Netherlands	Poland	Spain	United Kingdom
TCO parity—baseline	> 2030						
TCO parity with 50% road toll exemption	> 2030						
TCO parity with 75% road toll exemption (% TCO reduction by 2030)	**2030 (-19%)**	> 2030 (-11%)	> 2030 (-11%)	**2030 (-11%)**	> 2030 (-4%)	> 2030 (-11%)	> 2030 **(-)**
TCO parity with 100% road toll exemption (% TCO reduction by 2030)	**2029 (-25%)**	> 2030 (-14%)	> 2030 (-15%)	**2030 (-14%)**	> 2030 (-6%)	> 2030 (-15%)	> 2030 **(-)**

Addition of external-cost charges for co$_2$ emissions

The recent amendment (DIRECTIVE (EU) 2022/362) (European Commission, 2022a) to the Eurovignette directive restates in *Article 7c* that member states may introduce an external-cost charge regarding CO_2 emissions from HDVs in addition to the currently available infrastructure charges (road tolls). The reference charge for a EURO VI HDV with a GVW above 32 tonnes is 8 cents/km for trucks belonging to emission class 1, which is assumed to be the case for the diesel truck in this study. *Article 7cb* of the same directive states that member states may apply a higher external-cost charge for CO_2 emissions limited to no more than twice the reference value, which would be 16 cents/km. The impact of such policy intervention on the TCO parity-time between FCETs and diesel trucks is assessed assuming that 80% of the trucks' VKT are subject to these charges.

Table 14 shows the impact of adding external-cost charge for CO_2 emissions on the TCO time to parity between fuel cell and diesel tractor-trailers. Marginal benefits are observed under this policy intervention regarding the FCET's TCO time to parity, compared with their diesel counterparts. Even at a high 0.16 €/km charge, FCETs will not achieve TCO parity during this decade except in the Netherlands, despite the significant reduction in the TCO gap.

Table 14. Impact of adding external-cost CO_2 emissions charge to TCO time to parity, for fuel cell and diesel tractor-trailers

Country	France	Germany	Italy	Netherlands	Poland	Spain	United Kingdom
TCO parity -baseline	> 2030						
TCO parity with 0.08 €/km external-cost CO2 charge	> 2030						
TCO parity with 0.16 €/km external-cost CO2 charge	> 2030	> 2030	> 2030	**2029**	> 2030	> 2030	> 2030

In addition, the '"Fit for 55" package suggests extending the European Emission Trading System (ETS) to include the road transport sector which will be covered by a new, separate emissions trading system. This new ETS for road transport will mainly cover fuel suppliers and will become operational as of 2025. Proper carbon pricing can accelerate the shift from fossil-based transport.

Summary of policy measures impact

In addition to the previously analyzed policy measures, a 3 €/kg hydrogen fuel subsidy is also considered in this section. The impact of these policy measures on the TCO is presented in Figure 16 and Figure 17, showcasing FCETs operating in Germany in 2025 and 2030.

For a model year 2025 FCET, a combination of the mentioned policy measures will be needed for FCETs to reach a lower TCO relative to diesel trucks as shown in Figure 16. This is mainly driven by the very wide TCO gap between the technologies, reaching approximately €400,000. Providing a hydrogen subsidy of around 3€/kg would have the strongest impact on FCETs' TCO compared to the other examined policy measures. Such subsidies can reduce the FCET TCO by almost €150,000, significantly reducing the cost gap between fuel-cell and diesel trucks. By 2030, a lower level of policy intervention will be needed to overcome the TCO gap between the truck technologies; nonetheless, the needed policy support would still be significant.

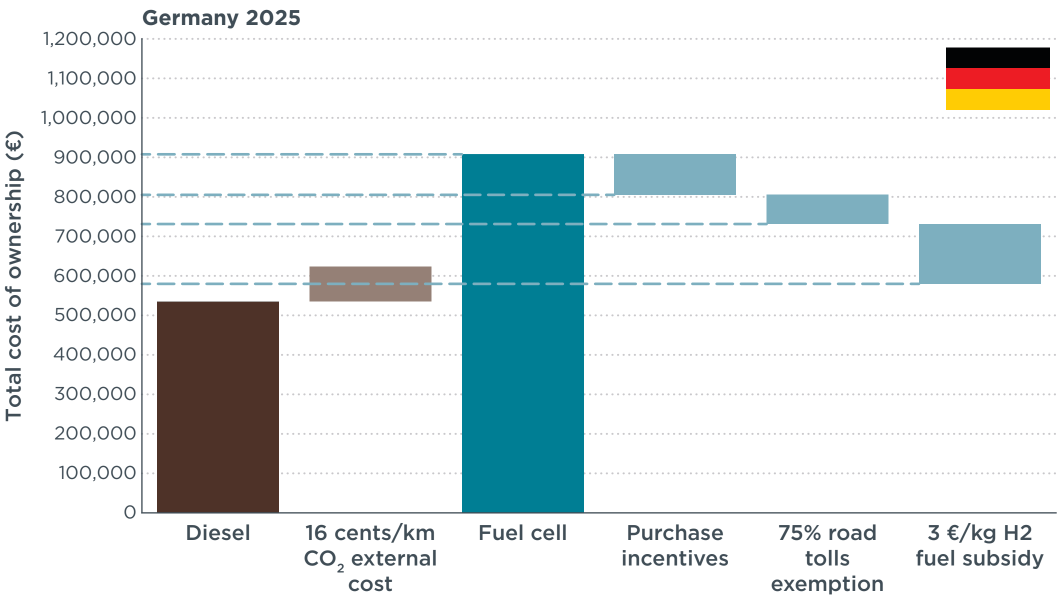

Figure 16. Impact of several policy measures on the TCO of fuel cell tractor-trailers, Germany, purchase year 2025

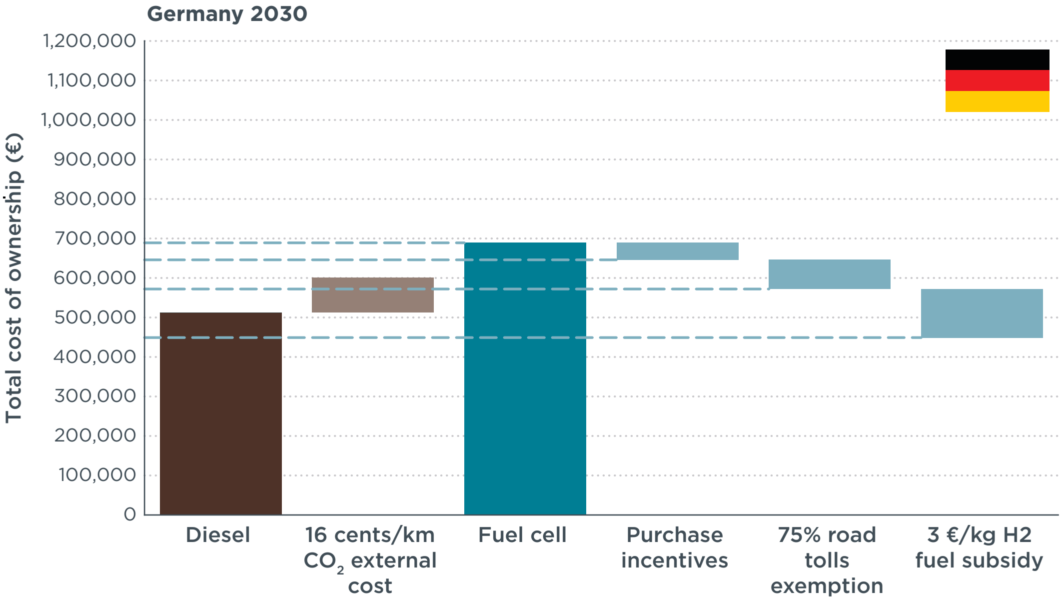

Figure 17. Impact of several policy measures on the total cost of ownership of fuel cell tractor-trailers, Germany, purchase year 2030

SENSITIVITY ANALYSIS

This section examines the impact of key parameters on the TCO of the two truck technologies. The sensitivity analysis focuses on five main parameters which are varied between extremums as summarized Table 15. The fuel cell and hydrogen tank cost ranges are adopted from a previous meta-analysis of zero-emission truck costs conducted by ICCT (Sharpe & Basma, 2022). The annual mileage range is representative of extreme scenarios for tractor-trailers, and corresponds to 400 km and 800 km daily. Ranges for hydrogen and diesel fuel prices are derived based on the data provided in the 'Hydrogen price' and 'Diesel price' sections. The minimum value of the hydrogen fuel price is an optimistic scenario with a 3€/kg subsidy relative to the reference scenario. The analysis focuses on FCETs purchased in 2030.

Table 15. Summary of sensitivity analysis parameters. Technology parameters are representative of a 2030 truck model year.

Parameter	Min	Reference	Max
Fuel cell cost	50 €/kW	170 €/kW	525 €/kW
Hydrogen tank cost	250 €/kg	525 €/kg	900 €/kg
Annual mileage	100,000	158,000	200,000
Hydrogen fuel price	4 €/kg	7 €/kg	10 €/kg
Diesel fuel net price	1 €/l	1.2 €/l	1.7 €/l

The results of the sensitivity analysis are summarized in Figure 18. The price of hydrogen fuel remains the most influential parameter that drives the TCO gap between FCET and diesel trucks, as thoroughly discussed in the previous sections. The fuel cell stack cost could also drive the TCO gap especially if the technology economies of scale do not ramp up by the end of the decade, which could result in high stack costs. In a similar manner to the hydrogen fuel price, diesel fuel price is a significant contributor to the TCO gap driven by the high-mileage long-haul truck experience. To a lesser extent, the annual mileage and the hydrogen tank cost do not have a significant impact on the TCO gap between FCETs and diesel trucks. Nonetheless, it is worth mentioning that the TCO gap increases at higher annual mileages. In other words, the more kilometers a FCET covers, the wider its TCO gap relative to diesel. This is an uncommon behavior for alternative vehicle technologies as they are mainly cheaper to operate, which would compensate for more expensive investment cost. This behavior is mainly driven by the high hydrogen fuel price and by the mere enhancement in energy efficiency of FCET powertrains relative to diesel powertrains. More details on energy efficiency can be found in (Basma & Rodríguez, 2022).

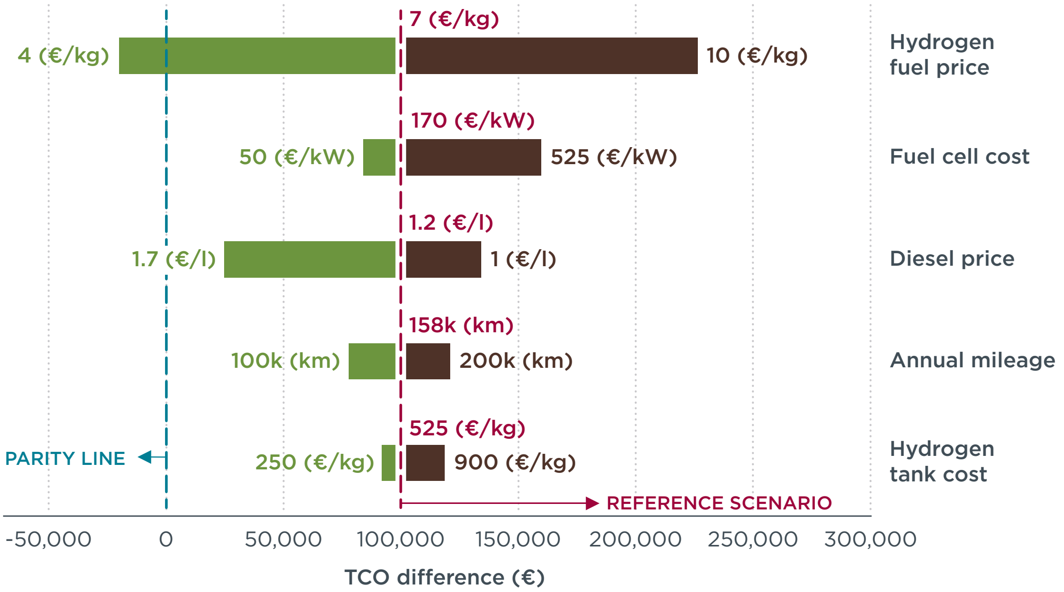

Figure 18. Impact of several parameters on the total cost of ownership (TCO) gap between fuel cell and diesel trucks. Results correspond to a 2030 truck model year.

IMPACT OF FUEL CELL STACK SIZE

The cost of the fuel cell stack is a major component of the truck's retail price and can have a significant impact on the TCO of FCETs as shown in the previous section. Larger fuel cell stacks in terms of rated power can only make the already costly technology more expensive. Nonetheless, larger fuel cell stacks can operate relatively more efficiently as fuel cells mainly achieve peak efficiencies and low-to-medium power loads. Thus, larger fuel cell stacks provide the flexibility to operate at more efficient operating points. Consequently, the hydrogen fuel consumption of FCETs equipped with larger stacks will be lower. Table 16 shows the FCET hydrogen fuel consumption for different fuel cell stack sizes at different payloads for current and future technologies obtained from detailed vehicle simulations developed in a previous ICCT study (Basma & Rodríguez, 2022). FCETs can achieve up to 7% reduction in fuel consumption if they are equipped with oversized fuel cell stacks.

Table 16. Fuel cell truck hydrogen fuel consumption for different fuel cell stack sizes at different payloads, current and future technologies

		Hydrogen fuel consumption (kg/100 km)		
	Fuel cell stack size	Reference payload	Low payload	Combined payload
Current technology (2022)	Rated power: **180 kW**	9	6.8	8.3
	Rated power: **300 kW**	8.2	6.5	7.7 **(- 7.2%)**
Future technology (2030)	Rated power: **180 kW**	6.6	4.8	6.1
	Rated power: **300 kW**	6.3	4.5	5.71 **(- 6.5%)**

The impact of oversized fuel cell stacks on the TCO is summarized in Figure 19 and Figure 20 for truck model years 2025 and 2030 in Germany, respectively. The oversized fuel cell stack provides 6% to 7% fuel cost reduction. On the other hand, the truck net cost—which is the difference between the truck retail price and its salvage value after

5 years of ownership—is 13% to 24% higher in the case of an oversized fuel cell stack. These two factors combined counteract each other resulting in no significant variation in the TCO of the truck.

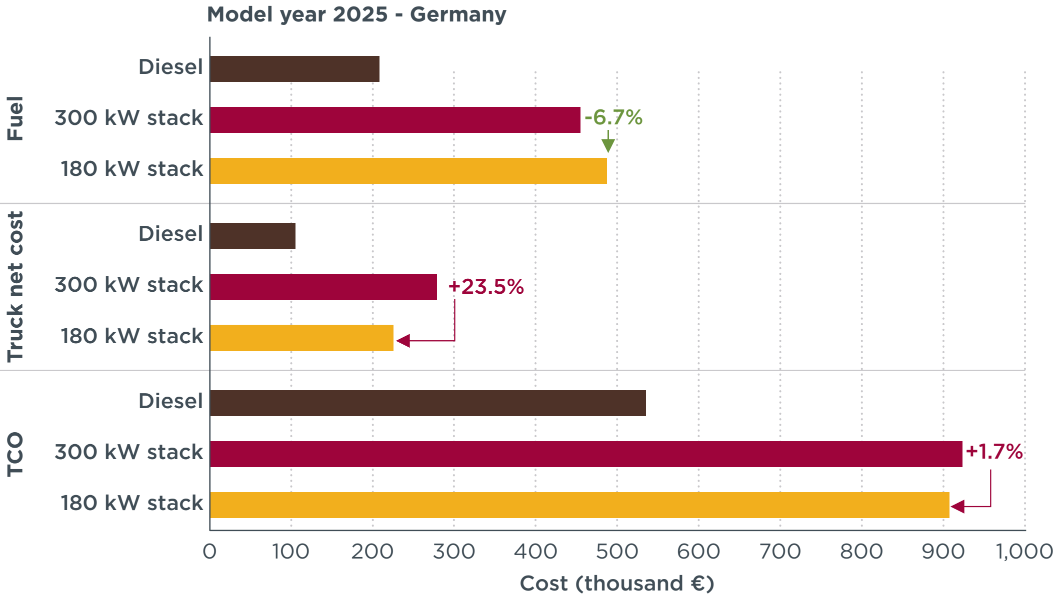

Figure 19. Impact of oversized fuel cell stack on the total cost of ownership, Germany, truck purchase year 2025

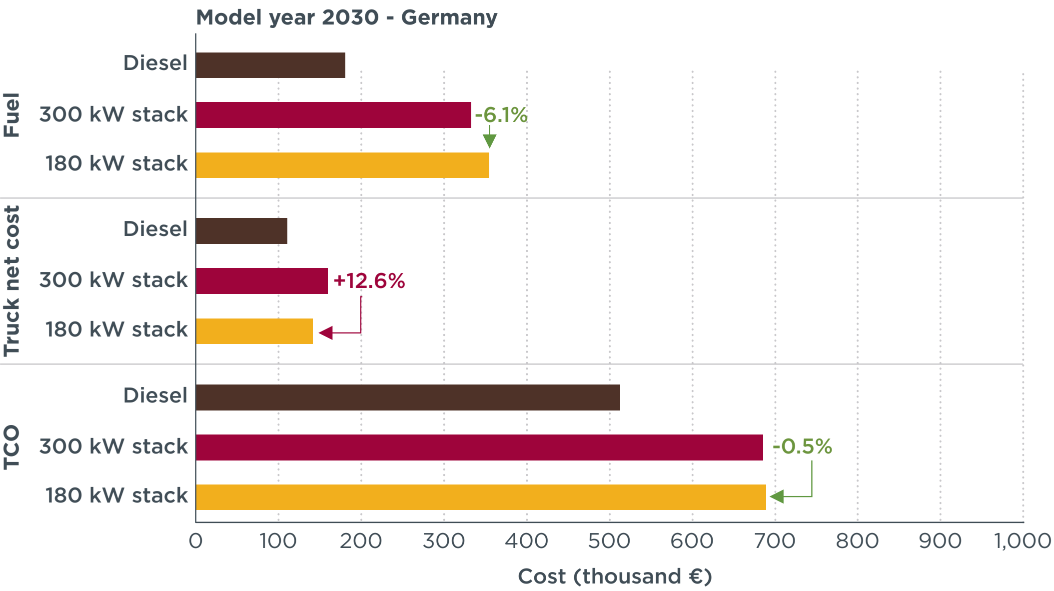

Figure 20. Impact of oversized fuel cell stack on the total cost of ownership, Germany, truck purchase year 2030

CONCLUSIONS AND POLICY RECOMMENDATIONS

This study evaluated the TCO of fuel cell long-haul tractor-trailers in seven European countries, including France, the United Kingdom, Germany, Italy, Spain, the Netherlands, and Poland. The study quantifies the TCO from a first-user perspective assuming a holding period of 5 years. We arrive at the following main conclusions:

» **Fuel cell long-haul trucks would need significant policy support to reach TCO parity with diesel trucks by the end of the decade**. The TCO of FCETs is expected to remain higher than that of diesel trucks by 2030. Exempting FCETs from road tolls can help them achieve TCO parity by 2029 in France and the Netherlands. However, FCETs will struggle to achieve TCO parity during this decade without significant policy support.

» **The price of hydrogen fuel is the primary driver of the economic viability of fuel-cell electric trucks in Europe**. The fuel costs of FCETs are expected to be three times higher than those of an equivalent diesel truck today. These will decrease by 2030 and become 1.8 times higher, driven by the expected improvement in the FCET fuel economy and the reduction in hydrogen fuel price. The retail prices of FCETs and diesel trucks are expected to be within the same range by 2030, making fuel costs the main TCO driver at that time.

» **A break-even hydrogen price of around 5 €/kg is needed for fuel-cell electric trucks to reach TCO parity with their diesel counterparts by 2030 given 2021 average diesel fuel prices**. Lower FCET operational expenses are required to offset the higher technology investment cost relative to diesel trucks. The break-even hydrogen price varies among the countries considered in this study. FCETs operating in the United Kingdom would require a break-even hydrogen price of 5.6 €/kg by 2030, while trucks operating in Spain and Poland would require a lower break-even hydrogen price of 4 €/kg.

» **Hydrogen fuel subsidies would likely be necessary to make fuel cell electric trucks financially viable for truck operators at least until 2035**. The price of hydrogen fuel in 2030 is expected to be higher than the required break-even price to achieve TCO parity between FCETs and diesel trucks by the end of the decade. Hydrogen fuel subsidies will be necessary in this case throughout the entire analysis period in this study (2022–2035). The needed subsidies vary among the countries considered in this study ranging from 1.2 €/kg in the Netherlands to greater than 4 €/kg in Italy given 2021 average diesel fuel prices. There are several EU proposals that may require member states to provide hydrogen subsidies, but the magnitude of such subsidies is still unknown at the moment.

» **Purchase incentives do not significantly cover the TCO gap between fuel cell electric trucks and their diesel counterparts**. Generous purchase incentives are already provided for ZE-HDVs in several European countries today. While such incentives can significantly reduce the retail price gap between FCETs and their diesel counterparts, the higher hydrogen fuel costs of FCETs offset these benefits.

Based on these findings, we recommend the following:

» **Increase the ambition of heavy-duty vehicle CO_2 standards as early as 2030**. The HDV CO_2 standards should be more stringent to comply with the EU Climate Law. Alternative zero-emission truck technologies are capable of replacing the current diesel fleets, providing a significant reduction in CO_2 emissions if their market share ramps up quickly. More stringent CO_2 standards can provide the needed certainty to invest in fuel cell trucks, increasing the demand for the technology. This can accelerate the technology improvement and ramp up its economies of scale, reducing the total deployment costs of the technology.

» **Expedite the implementation of the Eurovignette directive into national law and fully exempt zero-emission trucks from road tolls**. A 100% waiver on road tolls, similar to what is implemented in Germany, can reduce the TCO of fuel cell trucks by 14% to 25% by the end of the decade, helping fuel cell trucks to achieve TCO parity with diesel trucks in France and the Netherlands. This policy measure should be closely monitored not to jeopardize the road infrastructure funding in the future depending on the market share of zero-emission trucks that will be exempted from road tolls.

Tailpipe CO_2 emission charges can be an effective measure to penalize polluting diesel trucks. The proposed CO_2 charge of between 0.08 €/km and 0.16 €/km can narrow the TCO gap between fuel cell and diesel trucks.

» **Incentivize the purchase of zero-emission trucks and limit these incentives to their early market uptake phase**. Implementing a differential purchase premium calculated based on the retail price difference between a zero-emission truck and its diesel equivalent, similar to what is currently implemented in Germany, France, and the Netherlands, can reduce the TCO gap between fuel cell trucks and their diesel counterparts. Such premiums will decrease and eventually be phased out as the retail prices of zero-emission and diesel trucks become comparable, driven by the expected increase in economies of scale that may reduce the cost of some major components such as fuel cell units and hydrogen tanks.

While these purchase premiums cannot cover the entire TCO gap between fuel cell and diesel trucks, they can significantly reduce the needed capital investment to ramp up market demand for the technology, as access to capital is identified as a key barrier facing the technology's deployment.

» **Provide fiscal incentives for renewable electricity used for hydrogen production**. The price of hydrogen fuel is the primary driver of the TCO of fuel cell trucks. Such incentives can reduce the at-the-pump green hydrogen price, narrowing the TCO gap between fuel cell and diesel trucks. Battery-electric trucks would also benefit from such incentives. Further, the at-the-pump hydrogen fuel price can be directly incentivized through policy measures such as grant support for capital costs and subsidies.

» **Extend the European Emissions Trading Systems (ETS) to cover transport as suggested by the "Fit for 55 package."** Proper carbon pricing can reduce the TCO gap between fuel cell and diesel trucks by penalizing polluting trucks. Germany already has a carbon pricing scheme and other member states are encouraged to implement a similar ETS for road transport.

» **Incentivize demonstration projects of fuel cell trucks in real-world applications**. Such demonstration projects can close the existing knowledge gaps when it comes to the technology potential of fuel cell trucks such as the truck fuel economy and refueling time and can clearly demonstrate the technology's economic viability. This would help in identifying the real-world challenges hindering the technology's market deployment.

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