



# Economic Viability of FCEV Long-Haul HD Transport •

A TCO Comparison of Classical & CO<sub>2</sub> Neutral  
Propulsion Systems.

Whitepaper

# Giving substance to reality.

## **Authors**

Arndt v. Gregory, SE

Dr Albert Neumann, SE

Peter Gillbrand, AVL

Martin Rothbart, AVL

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## Management Summary

The potential of hydrogen as an energy source for the automotive sector is currently a topic of considerable debate, with a host of publications reflecting the diversity of opinions there are on the subject. At Strategy Engineers we believe hydrogen has much to offer as a potential investment alternative.

In this document we compare the Total Cost of Ownership (TCO) of four different propulsion systems – ICE-diesel, BEV, ICE-hydrogen and FCEV-hydrogen – in the long-haul heavy-goods transport sector.

Our aim is to make clear why hydrogen-based propulsion systems offer a real alternative not just to the classic ICE-diesel drives but also to battery-powered vehicles. This is not just from the point of view of regulatory necessity but also, above all, because hydrogen-based systems make sound financial sense as well. As this report shows, a positive business case for investment in hydrogen cell-based technology already exists.

When considering the practical application of hydrogen as an alternative propulsion technology it is also necessary to consider the infrastructure requirements. In this study we examine two possible alternative hydrogen supplies and their potential in economic terms.

## 1. Introduction – The EU goal of CO<sub>2</sub> neutrality by 2050

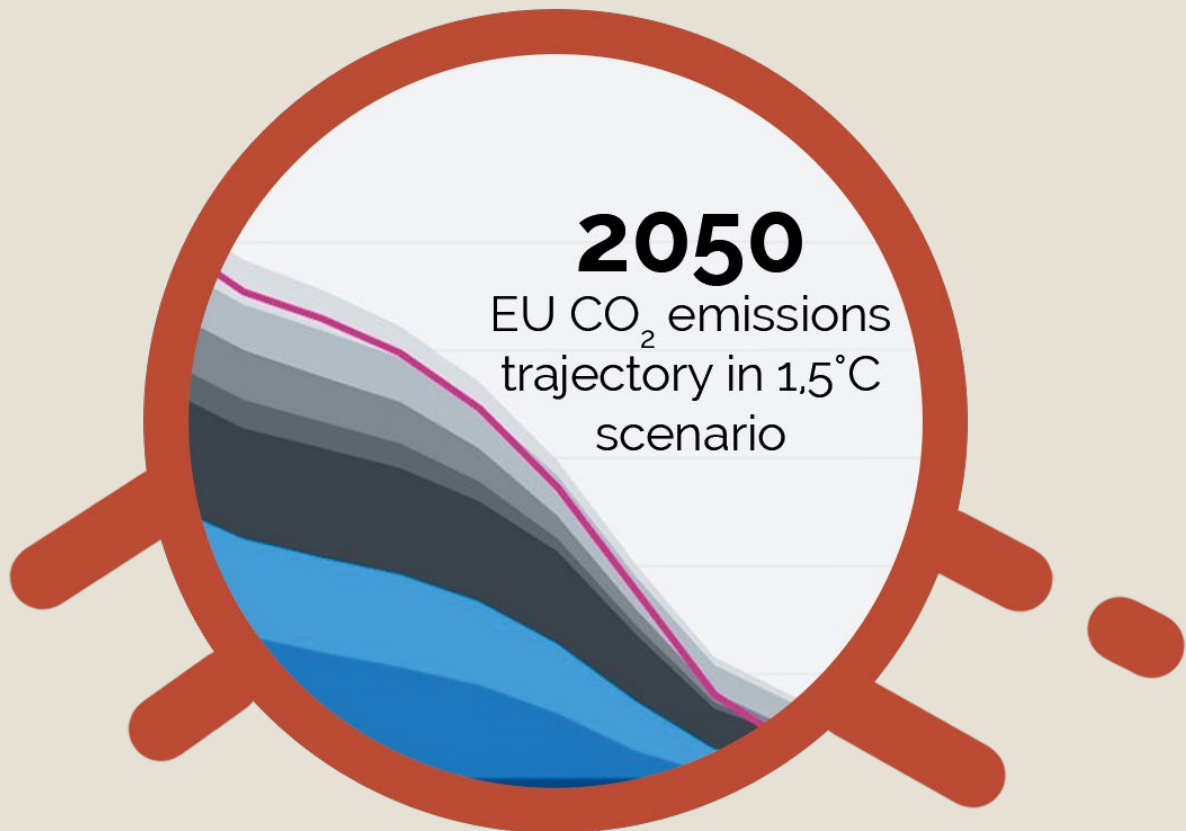


Figure 1: European Union CO<sub>2</sub> Commercial Vehicle Emission Targets



In early March 2020 the EU Commission set out how it intends to give legal effect to the European Union's political commitment to become carbon neutral by 2050. Starting in 2025, and building to full enforcement by 2030, for the first time the EU Commission is setting CO<sub>2</sub> emission targets for heavy-goods vehicles.<sup>1</sup> These emission targets are linked to penalty charges introduced by EU legislation, as shown in Figure 2.<sup>2</sup>

## 6% CO<sub>2</sub>

...is the share of total CO<sub>2</sub> emissions in Germany caused by road transport

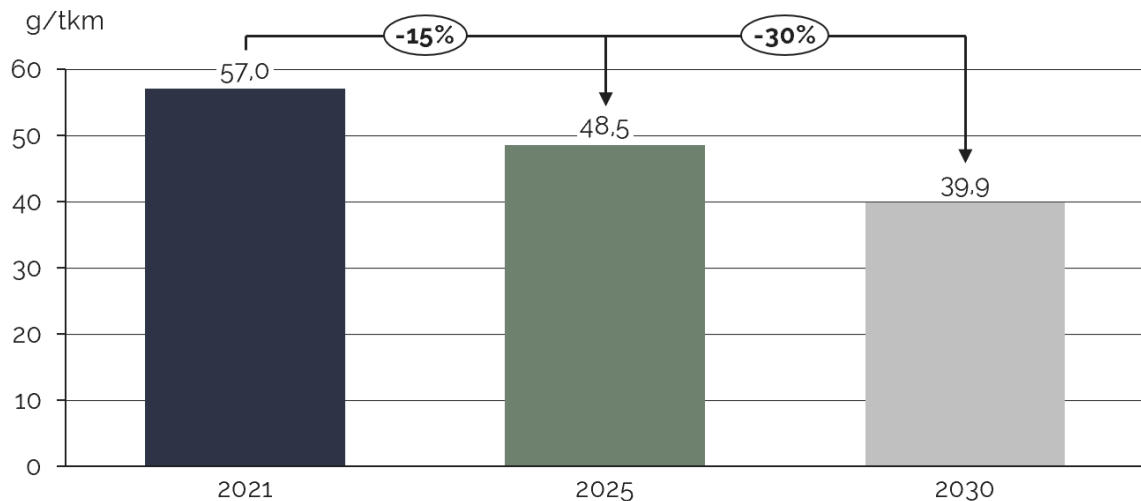


Figure 2: EU CO<sub>2</sub> Emission Targets relevant for Investment Penalty Charges

From 2025 onwards there will be a penalty of €4,250 per g/tkm for every tonne in excess of the CO<sub>2</sub> emissions limit of 48.5 g/tkm. This penalty will rise to €6,800 0 per g/tkm by 2030 for every tonne over the then reduced limit of 39.9 g/tkm. It is therefore imperative for all fleet operators to consider the current CO<sub>2</sub>-emission reduction targets in their long-term investment plans.

Heavy-duty trucks operating in the EU today consume on average ~57g CO<sub>2</sub> per tkm (2020-21). (This estimate is provided by the European Automobile Manufacturers Association (ACEA), based on production numbers in Q3 and Q4 2019<sup>3</sup>).

Assuming no changes in fuel consumption and CO<sub>2</sub> emission levels between today and 2025, this would result in a 15% overrun of the limit value in 2025, corresponding to ~ 8.5 g/tkm CO<sub>2</sub>, resulting in a

## -30% CO<sub>2</sub>

...is the EU Target of CO<sub>2</sub> emission reduction in commercial vehicle sector from mid 2020 to 2030

<sup>1</sup> European Commission: Reducing CO<sub>2</sub> emissions from heavy-duty vehicles. 2019

<sup>2</sup> European Commission: Reducing CO<sub>2</sub> emissions from heavy-duty vehicles. 2019

<sup>3</sup> ACEA: CO<sub>2</sub> emissions from heavy-duty vehicles – Preliminary CO<sub>2</sub> baseline (Q3-Q4 2019). 2020

## 2040

...is the very last year in which anyone will invest in an ICE-based transport fleets.

financial penalty of around €36,350 – i.e. an increase in the operating cost of the truck of around 36%.

The planned further tightening of the CO<sub>2</sub> limit in 2030 will bring a 30% reduction in fuel consumption and CO<sub>2</sub> emission levels compared to today. Again assuming no changes in the truck performance, this would equate to an excess of 17.1 g/tkm CO<sub>2</sub>. Furthermore, this excess would be subject to the higher € 6,800,-- per g/tkm penalty. The resulting penalty of €116,500 would be more than twice as high (~+116%) as the acquisition cost of the truck or ~59% higher than the investment (truck + penalty = € 136,350) that would have been required in 2025.

Against this regulatory background, manufacturers are naturally seeking to optimize the efficiency of ICE engine technology to offset these competitive disadvantages. At the same time, they are also increasing their efforts to develop alternative drive technologies. It is important to keep in mind that, assuming a payback period of approx. 10 years for vehicles in fleet operation, come 2040, if not before, fleet operators will no longer invest in conventional ICE drive technology.

This whitepaper shows that changes in the propulsion technology, from classic drives to alternative drives, is already both possible and realistic, not just to meet these new regulatory requirements, but also from a purely economic perspective. In this whitepaper we focus on the two key options: hydrogen as the basis of fuel cell electric propulsion (FCEV) and hydrogen combustion propulsion technology (H<sub>2</sub>-ICE). Our aim is to provide an informed starting point for discussion on FCEV-based propulsion technology and its technological/economic potential.



## 2. TCO comparison of classical & CO<sub>2</sub> neutral propulsion systems for long-haul heavy-duty transportation



The lack of a widespread refuelling infrastructure and the high costs of fuel cell-based truck technology compared to its proven diesel counterparts appear to be the main obstacles. It remains to be clarified whether and to what extent these are the real barriers to start a hydrogen-based change of propulsion technology for long haul heavy duty transportation.

Our analysis compares the conventional drivetrain technology based on ICE-diesel with three alternative drive systems: Battery electric propulsion (BEV) and the two hydrogen-based propulsion systems (H<sub>2</sub>-ICE & FCEV).

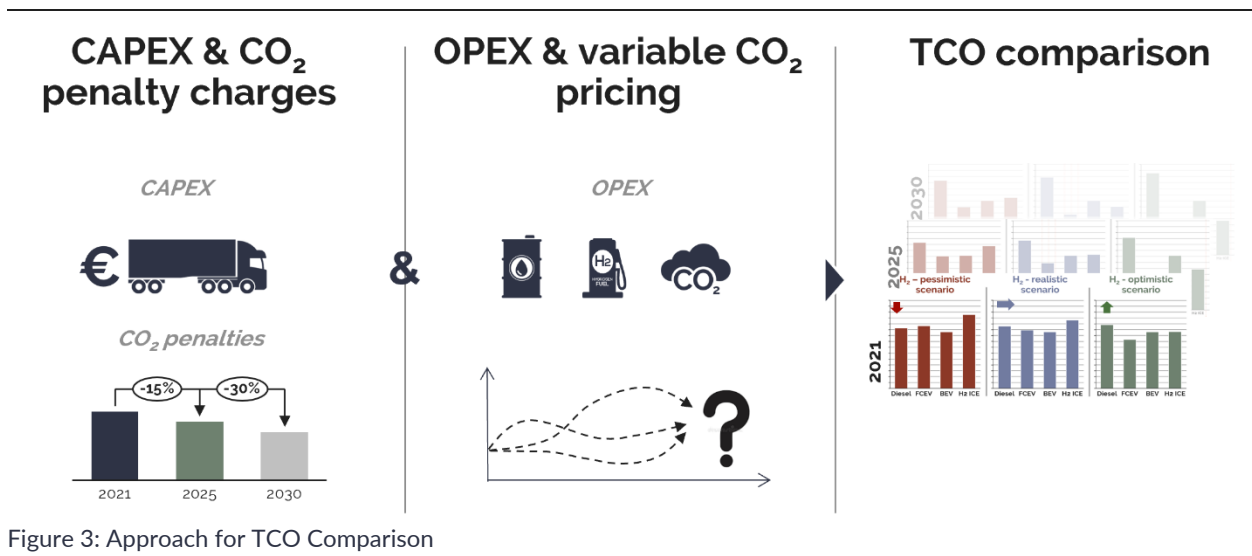


Figure 3: Approach for TCO Comparison

The TCO approach in this document considers the necessary investment (CAPEX) including, in the case of conventional diesel technology, any CO<sub>2</sub> investment penalties. On the OPEX side, the report includes all variable costs, comprising those of fuel, CO<sub>2</sub> emission taxes, maintenance costs and toll charges.

Investments in rapidly developing technical environments, such as alternative drive technologies, are characterised by significant future price degradations<sup>4</sup>. Key components of alternative propulsion technologies (e.g. fuel cells, H<sub>2</sub> tanks, power electronics and batteries) will become substantially cheaper in the years to come as these technologies benefit from increasing production volumes and growing market shares. Anticipating these economies of scale, in this report we analyse the likely investments (CAPEX) at three points in time: 2021, 2025 and 2030.

<sup>4</sup> Kühnel, Hacker, & Görz: Oberleitungs-Lkw im Kontext. 2018

So as to anticipate possible future price developments in of the commodities (OPEX) we elaborated three different scenarios per date of investment, thus in total 9 scenarios. The scenarios differ in the extent to which they economically support hydrogen technologies as a propulsion concept.

## 2.1 CAPEX: Essential elements of the investment costs

based on tractor units for 40-ton tractor-trailer combinations. An annual mileage of 140.000 km and a 10 year vehicle lifetime are assumed for all analysed drive systems.

9

...is number of different scenarios the present report analyses (3 investment points in time, with 3 scenarios each)

H <sub>2</sub> FCEV		BEV	
E-engine power	350 kW	E-engine power	350 kW
Battery capacity (FCEV)	75 kWh	Battery capacity	500 kWh
H <sub>2</sub> tank capacity (350 bar)	75 kg	Energy consumption	125 kWh/100 km
Hydrogen consumption	8 kg/100 km	Range	400 km
Range (H <sub>2</sub> / electric)	940 / 60 km		
	€ 185.101,-		€ 177.601,- <sup>2</sup>
	€ 134.163,-		€ 100.000,-
H <sub>2</sub> ICE		Diesel	
Engine power	240 kW	Engine power	350 kW
H <sub>2</sub> tank capacity (350 bar)	75 kg	Diesel tank capacity	1.000 l
Fuel consumption	10 kg/100 km	Fuel consumption	34 l/100 km
Range	750 km	Range	2.941 km

Figure 4: Technical Specifications of Analysed Concepts

Aside from the differences in powertrains and energy storage systems, the vehicles are assumed to be identical. It should be noted that with different powertrain concepts currently at different stages of maturity, they each require different levels of investment. The lowest required investment in 2021 would be a diesel at ~€100,000, followed by the H<sub>2</sub>-ICE propulsion at about €134,000. At the present time an investment in BEV or H<sub>2</sub>-FCEV propulsion technologies would be significantly more expensive, at ~€ 178,000 for BEV and €185,000 for FCEV-powered vehicles.

But costs are already falling sharply. We expect a price decline for the Fuel Cell propulsion system as a whole of 22.5% between now and 2025. The largest price declines we see are for the battery (-37.5%), the fuel cell (-22%), and the H<sub>2</sub> tank system (-20%).

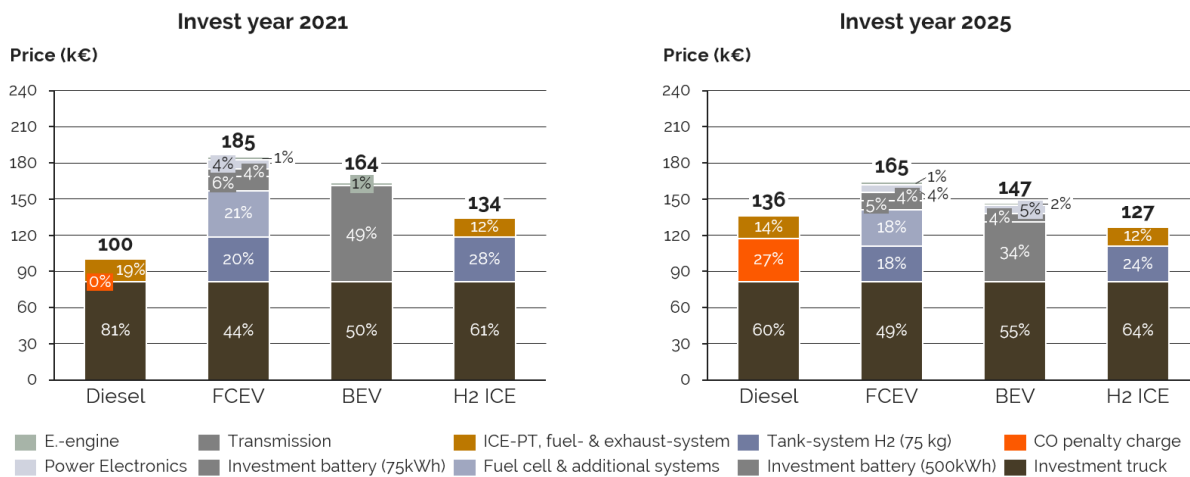


Figure 5: CAPEX Comparison Propulsion Systems

**40% → 7 %**

...is the decline in the average price gap between diesel and alternative drive systems between 2021 and 2025

As a result, the described price development of alternative drive systems in combination with increasing investment costs in classic diesel ICE technology based on rising CO<sub>2</sub> penalty charges leads to a significant decrease in the average price gap (40% in 2021 down to 7% in 2025) between alternative- and diesel-drive technology.

## 2.2 OPEX: Components of variable costs

Variable costs considered in this TCO analysis consist of fuel and maintenance costs as well as CO<sub>2</sub> pricing. Apart from accounting for a declining battery price for replacement after about 500,000 km, we assume that maintenance costs remain stable over the entire period under consideration. Energy costs, however, are assumed to be subject to significant price variability.

### Decarbonisation leads to peak-oil price scenarios

Assuming a progressive decarbonisation of the global economy, our analysis considers three oil price scenarios. All three show substantial rises occurring between now and 2030. In the most positive scenario, from the perspective of alternative fuel technologies, the oil price changes little over the following decade. In the H<sub>2</sub>-realistic and H<sub>2</sub>-pessimistic scenarios, after peaking in 2030 prices are expected to fall to varying degrees, tending to bring conventional propulsion technologies back towards more competitive price levels.<sup>5</sup>

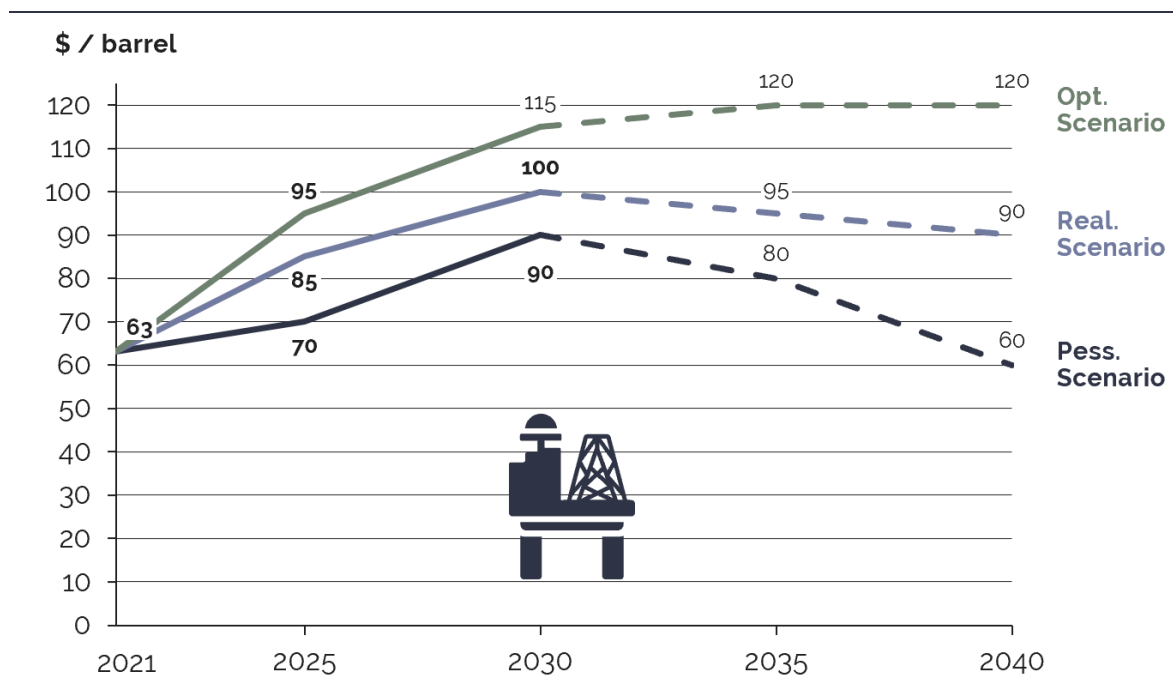


Figure 6: Oil Price Development

<sup>5</sup> Helbling, Ragwitz, Fleiter, Groos, Härle, Held, Wietschel: Eine Wasserstoff-Roadmap. 2019

## 2.3 CO<sub>2</sub> fuel pricing development 2021 – 2040

In early October 2020, the German parliament approved the introduction of CO<sub>2</sub> pricing for the transport sector.<sup>6</sup> The CO<sub>2</sub> pricing that has been decided upon begins with a comparatively moderate price control of carbon-based fuels.

€25/t  
CO<sub>2</sub>

...is the current CO<sub>2</sub> emission fee, as of January 1<sup>st</sup>, 2021. From January 1<sup>st</sup>, 2025 this fee will

Although not called a tax, the CO<sub>2</sub> pricing being imposed is in effect an energy tax (e.g. Section 2 of the German Fuel Emissions Trading Act (BEHG)).<sup>7</sup> When a fuel covered by the new CO<sub>2</sub> pricing regulations becomes available for purchase the trader or producer must buy an emissions certificate from the German Emissions Trading Authority (DEHSt) at the Federal Environment Agency. The Fuel Emissions Trading Act sets the prices for emissions allowances until 2025. In 2021, the price is set at €25 per tonne of CO<sub>2</sub> and this will increase to €50 per tonne of CO<sub>2</sub> in 2025.

Starting in 2026, emissions certificates will be auctioned, within a price band that will apply of between €55 and €65 per tonne of CO<sub>2</sub>. From 2027 onwards the price will be determined in the open market.

This has direct cost implications for consumers. With one litre of diesel generating 2.68 kg CO<sub>2</sub> that will increase the cost at the pump by 6.7 € cents per litre, obviously doubling to 13.4 € cents per litre when the CO<sub>2</sub> charge rises to €50 in 2025.

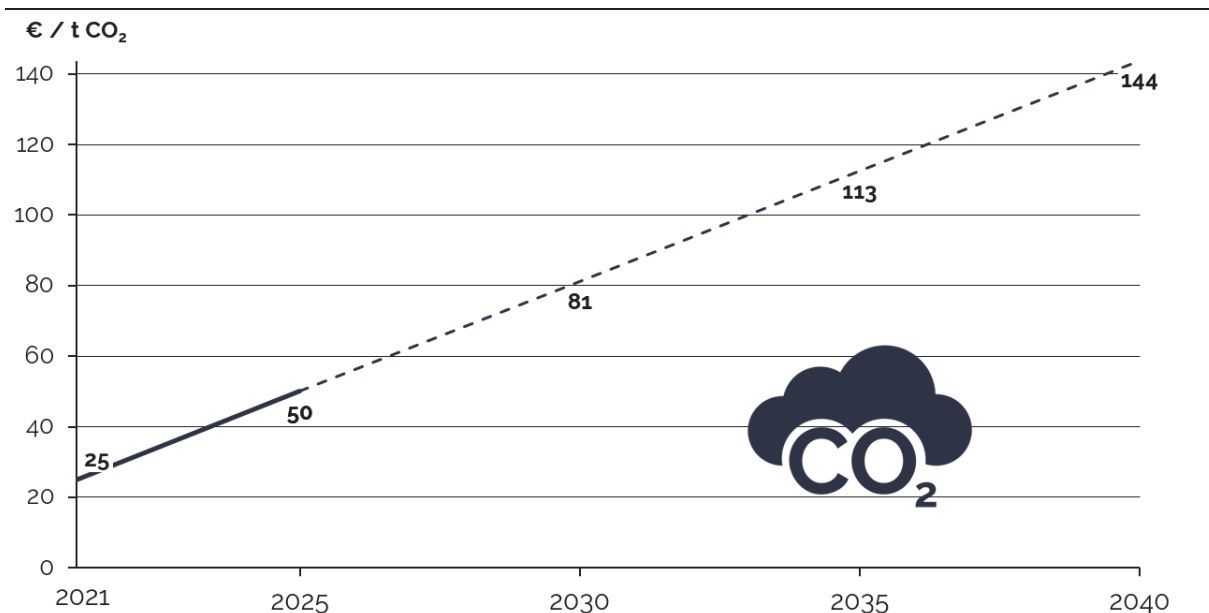


Figure 7: CO<sub>2</sub> Fuel Pricing Scenarios

<sup>6</sup> Bundesregierung: Grundlage für CO<sub>2</sub> Preis steht. 2020

<sup>7</sup> Brennstoffemissionshandelsgesetz | Rutschmann: CO<sub>2</sub>-Preis auf Erdgas, Heizöl und Sprit – das solltest Du wissen. 2021

## 2.4 H<sub>2</sub> price development 2021 – 2040

Two factors will influence the evolution of hydrogen prices in the future – likely improvements in the efficiency of hydrogen production and changes in hydrogen demand in an increasingly decarbonized global economy. The Paris climate agreement sets the following targets for Germany: <sup>8</sup>

- The reduction of greenhouse gas emissions by 55% by 2030 and by 80% to 95% by 2050 compared to 1990 levels
- Extensive greenhouse gas neutrality in all sectors (except agriculture) by the middle of the century.

Hydrogen has an important part to play in helping Germany achieve these ambitious goals, providing a realistic alternative in all kinds of applications where direct use of electricity is either technically impossible or economically not reasonable.

### 2.4.1 Global hydrogen demand & supply

The global demand for hydrogen can be roughly divided into the following main categories:

- Crude oil processing and production of fuels and lubricants
- The production of ammonia, methanol, chlorine and other chemicals
- Steel production by the DRI (direct reduced iron) production method
- As a substitute for natural gas in energy-intensive processes, such as the production of glass
- High temperature steam generation used in a variety of industrial applications.

Hydrogen is currently produced almost exclusively from fossil sources (natural gas and coal) and therefore its production generates greenhouse gas emissions.<sup>9</sup>

The global production volume in 2019 was:

- ~69 Mt H<sub>2</sub>. The two classic production technologies that currently dominate the global H<sub>2</sub> production are
  - Steam methane reforming (SMR) and
  - Autothermal reforming (ATR)
- ~48 MT H<sub>2</sub> is produced as a by-product in other processes (e.g. in the production of chlorine alkali by electrolysis).

**80%-95%**

...is the reduction of CO<sub>2</sub> to be achieved by the year 2050 compared to 1990 levels according to the Paris climate agreement

<sup>8</sup> Federal Ministry for the Environment, Nature Conservation and Nuclear Safety: Climate Action Plan 2050 – Principles and goals of the German government's climate policy. Berlin: Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB) 2016

<sup>9</sup> IEA: The Future of Hydrogen, Seizing today's opportunities. Final Report. 2019



Figure 8 below shows hydrogen demand and supply worldwide.<sup>10</sup>

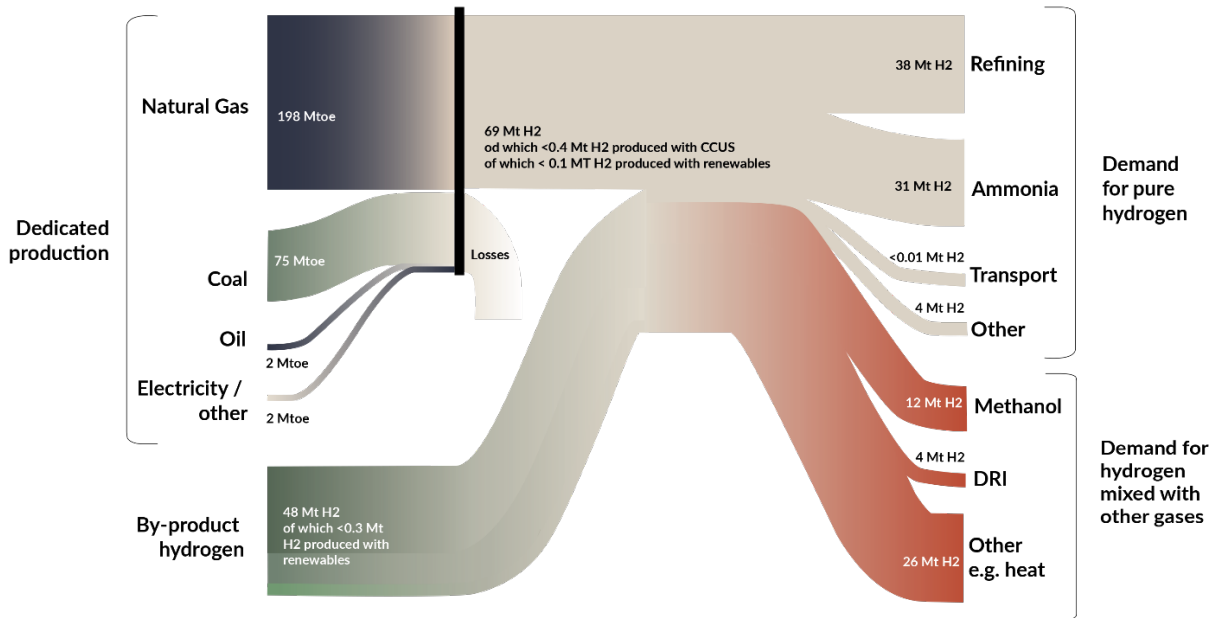


Figure 8: Hydrogen Demand and Supply Worldwide

**\$53**

...is the cost per t CO<sub>2</sub> to capture and climatically neutralize the resulting CO<sub>2</sub> from hydrogen production using the classic steam reforming processes for carbon capture storage (CCS)

On a global scale, apart from chlorine production, electrolysis has played a negligible role in hydrogen production to date. To meet the reduced CO<sub>2</sub> emission targets would require, in any case, that the electrolysis processes be undertaken using electricity generated from sustainable sources.

The production of hydrogen through the two steam reforming processes (SMR, ATR) generates a large amount of greenhouse gas emissions (~ 10.6 t CO<sub>2</sub> / t H<sub>2</sub>).<sup>11</sup> But with a subsequent capture process of the CO<sub>2</sub> for storage (CCS) or use (CCU) following the H<sub>2</sub> generation, about 90% of the resulting CO<sub>2</sub> emissions could be contained. The ATR process is even more suitable for capturing the resulting CO<sub>2</sub> than the SMR process because the process gas contains CO<sub>2</sub> in a more concentrated form. The costs to capture CO<sub>2</sub> are currently ~\$53 per t CO<sub>2</sub>.<sup>12</sup> With regard to achieving climate neutrality in the production of hydrogen, the success of the steam

<sup>10</sup> IEA: The Future of Hydrogen, Seizing today's opportunities. Final Report. 2019

<sup>11</sup> Sternberg, Jens, & Bardow: Life cycle assessment of CO<sub>2</sub>-based C1-chemicals. Green Chemistry. 2017

<sup>12</sup> Helbling, Ragwitz, Fleiter, Groos, Härle, Held, Wietschel: Eine Wasserstoff-Roadmap. 2019

reforming processes in combination with post-cycle CO<sub>2</sub> capture depends on the permanently safe storage of CO<sub>2</sub>, and/or the sustainable use of CO<sub>2</sub>. However, even in a best-case scenario, approximately 1 t CO<sub>2</sub> is still generated for the production of 1 t H<sub>2</sub>. In the context of decarbonisation of industry and transport, therefore, the production of 'grey' hydrogen is only suitable as a transfer technology.

#### 2.4.2 Future demand for H<sub>2</sub>

Despite these drawbacks in its own production, hydrogen is set to play an increasingly important role in achieving a 95% reduction in greenhouse gas emissions in many sectors. Currently it is little used directly or for further processing as an energy carrier. But this is changing rapidly and in addition to the current uses of hydrogen, especially by the chemical industry and in oil refineries, in future the gas will play a key role in the decarbonisation process of the global economy.<sup>13</sup>

- Steel: Hydrogen currently plays a minor role in steel production where the standard processes are the CO<sub>2</sub>-intensive producing blast furnace and electric steel processes. But steel is already being produced by the DRI (direct reduced iron) process, which uses hydrogen, and in future an increasing proportion of steel will be produced this way.
- Ammonia production: In addition to its current usage in the chemical industry, hydrogen will in future be used increasingly as a storable energy carrier in power plants and engines, and in the recovery of chemically bound hydrogen.
- Production of synthetic fuels (Power to X): In this production process water and CO<sub>2</sub> are converted to C<sub>x</sub>H<sub>x</sub> using renewable energy.
- Power generation (e.g. stationary fuel cells).
- Transport: Operation of hydrogen combustion engines or use of fuel cells.
- Heating of buildings.

Thus, hydrogen is indispensable to achieving the climate protection goals of a largely climate-neutral industry and transport sector by 2050. However, this is only possible if the production of the gas is done in a way that does not itself generate CO<sub>2</sub>. The electrolysis processes that can be considered for this purpose at the present time have reached different levels of maturity in terms of technical readiness and economic scaled production. At the same time, the demand scenarios for hydrogen in Europe and Germany up to 2050

90%

...is the amount of CO<sub>2</sub> generated during hydrogen production in current steam reforming processes that can be captured & stored (CCS) or utilized (CCU)

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<sup>13</sup> IEA, 2019

are widely divergent, depending on the target level of CO<sub>2</sub> reduction assumed (e.g. reduction of CO<sub>2</sub> by 2050: a) 85%, b) 90%, c) 95%).

Against this, there are also wide variations in the projections on which options industry and transport will take regarding their future main energy sources.

The following chart, adapted from Hebling et al. (2019), shows two different plausible bandwidths for hydrogen demand and electrolysis capacity for Germany from 2030 to 2050.<sup>14</sup>

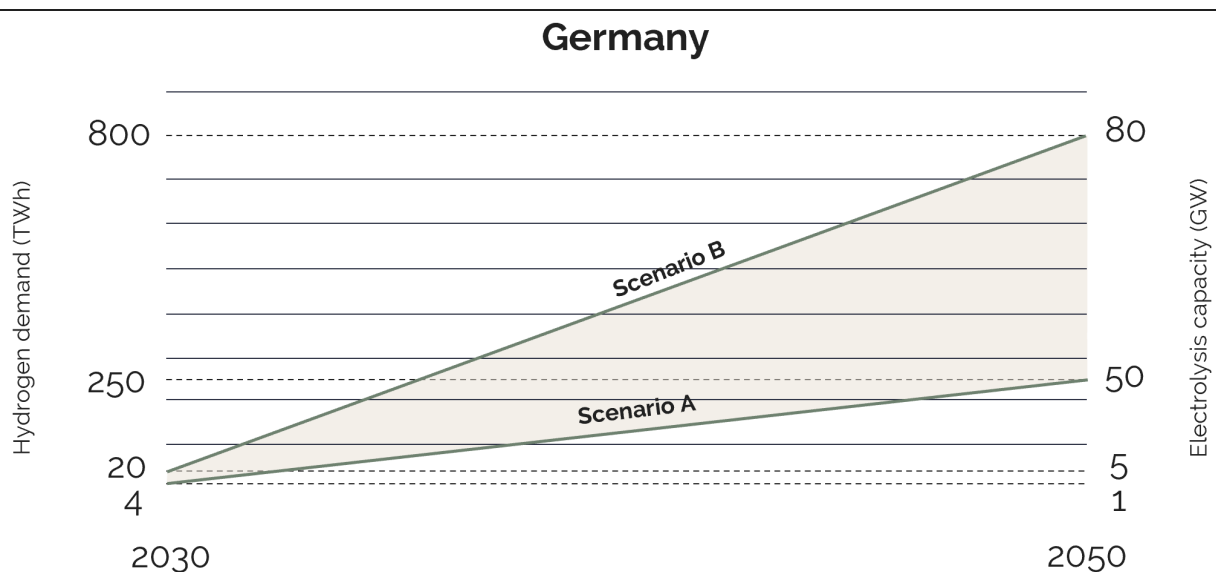


Figure 9: Plausible Bandwidths for Hydrogen Demand and Electrolysis Capacity for Germany (2030 – 2050)

**Scenario A:** Full-electrification scenario, with hydrogen demand growing from 4 tWh in 2030 to 250 tWh in 2050, corresponding to a CAGR of 23%.

**Scenario B:** Large share of material energy carriers – hydrogen, synthetic methane (PtCH<sub>4</sub>), synthetic fuels (PtL) – with the hydrogen demand growing from 20 tWh in 2030 to 800 tWh in 2050, corresponding to a CAGR of 20%.

Based on these different scenarios and their combinations, the following range for future hydrogen demand emerges.

<sup>14</sup> Hebling, Ragwitz, Fleiter, Groos, Härle, Held, Wietschel: Eine Wasserstoff-Roadmap. 2019, p. 11

## Future production technologies of hydrogen

Regardless of which scenario for the medium- and longer-term demand for H<sub>2</sub> is assumed, it is clear that the demand can at best be met in a transitional way by using 'grey' hydrogen from steam reforming processes in combination with capture and storage or utilization of the CO<sub>2</sub> (see above). But the energy transition envisaged in the EU's 2050 targets can only be achieved through the use of electrolysis production processes. Currently, there are three main electrolysis processes available:<sup>15</sup>

- 1) Alkaline water electrolysis with liquid potash lye
- 2) PEM electrolysis (Proton Exchange Membrane)
- 3) High-temperature/steam electrolysis (using a solid oxide electrolyte made of ceramic material and operated at approx. 800°C).

**20%-23%**

...is the expected CAGR of hydrogen demand growth between 2030 and 2050 in the A and B scenarios

Type of electrolysis	Characteristics	Development needs	Technological readiness level
Alkaline water electrolysis with liquid potash lye	<ul style="list-style-type: none"> <li>process already in use since the end of the 19th century</li> <li>demonstrates good efficiency and long service life in continuous stationary operation</li> <li>suitable for coupling with fluctuating current supply and for load management in networks with changing load profiles</li> </ul>	increase in current & thus power density while maintaining high efficiency, long life and manufacturing cost.	All in all, a mature process with a technological readiness level (TRL) 9
PEM electrolysis (Proton Exchange Membrane)	<ul style="list-style-type: none"> <li>has been used successfully in niche applications for about two decades</li> <li>especially suited for coupling with renewable energy sources (due compact design, high dynamics during rapid load changes)</li> </ul>	<ul style="list-style-type: none"> <li>higher power densities (alternative membrane materials Reduction of precious metal requirements (Iridium, platinum))</li> <li>suitable recycling concepts</li> <li>increase of service life</li> <li>development and qualification of large-scale PEM stacks in the MW class</li> </ul>	Currently technological readiness level (TRL) 6-8
High-temperature/steam electrolysis (SOEC = Solid Oxide Electrolysis Cell)	<ul style="list-style-type: none"> <li>broad field test experience is not yet available</li> <li>very good electrical efficiency if waste heat is available on site at 200 °C or higher.</li> </ul>	<ul style="list-style-type: none"> <li>increase of long-term stability</li> <li>increase of cycle stability</li> <li>cost-effective cell manufacturing</li> <li>dev. of high-power stacks</li> <li>suitable &amp; dynamically operable thermal management systems</li> </ul>	Currently technological readiness level (TRL) 4-6

Figure 10: Types of Electrolysis Processes

Based on the expected adjustment processes of the global industry with regard to the targeted climate neutrality by 2050, a massive increase in hydrogen production is necessary, irrespective of the specific demand scenarios. While 'grey' hydrogen, therefore, will meet the requirements for a limited transition period, a massive ramping up in the production of 'green' hydrogen will be required to meet the longer-term objectives.

This increase in demand, however, will also drive production costs down. Producer prices for 'green' hydrogen are expected to fall

<sup>15</sup> Helbling, Ragwitz, Fleiter, Groos, Härle, Held, Wietschel: Eine Wasserstoff-Roadmap. 2019

sharply between now and 2050, as the following graph from a recent Bloomberg analysis (03/2020) shows.<sup>16</sup>

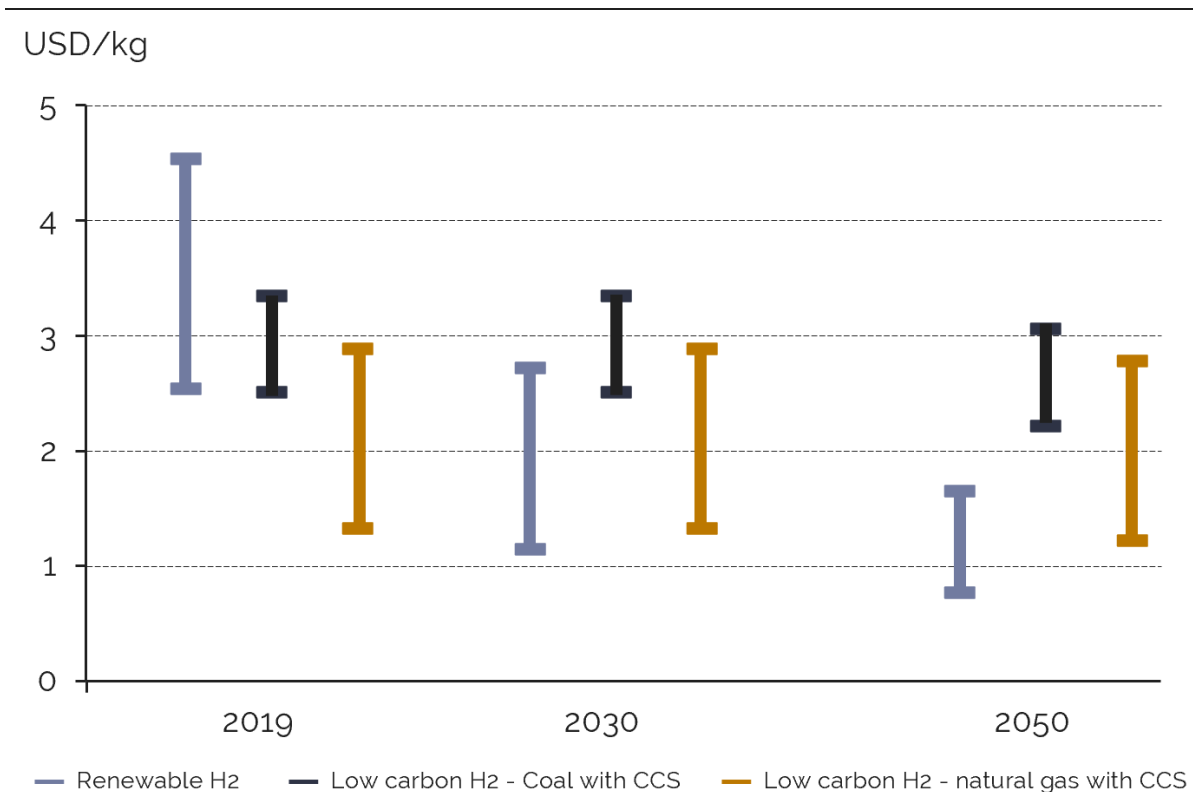


Figure 11: Production Cost Development for Conventional vs. Renewable H2 Production Technology

**\$0.80-  
1.6/kg**

...is the expected  
production cost of  
renewable  
hydrogen in 2050  
according to  
Bloomberg

This analysis suggests that with the expected scaling up of production the cost of renewable hydrogen worldwide could fall from a current level of \$2.50-4.6/kg in 2019 to \$1.10-2.7/kg in 2030 and as low as \$0.80-1.6/kg in 2050. This would put 'green' hydrogen in a comparatively much lower price range than hydrogen produced using natural gas with CCS (\$1.23-2.79/kg) or using coal with CCS (\$2.22-\$3.05/kg).

On the basis of this analysis we developed the following scenarios for the global pricing of 'green' hydrogen. They are based on the expert assumptions of AVL / Strategy Engineers modelled on studies by Öko Institut, McKinsey and Bloomberg.

All three assume a significant drop in the current price level (2021) of ~€9/kg H<sub>2</sub>. However, there are significant differences with regard to the forecast rate of price decline over the next 20 years.

<sup>16</sup> BloombergNEF: Hydrogen Economy Outlook: Will Hydrogen Be the Molecule to Power a Clean Economy?. 2020

Depending on the scenario, the price drop assumed between now and 2030 ranges from 45% to >70%.

1. **H<sub>2</sub>-pessimistic scenario**, modelled on Öko Institut, predicts the least price erosion, with an assumed price level of €7.70/kg in 2025 and €6.25/kg in 2030.<sup>17</sup>
2. **H<sub>2</sub>-realistic scenario**, modelled on Bloomberg, expects a sharp fall in prices until 2025 down to €7.00/kg and then expects a more moderate price decline showing €5.07/kg in 2030.<sup>18</sup>
3. **H<sub>2</sub>-optimistic scenario**, modelled on McKinsey, predicts the sharpest drop in prices between now and 2025 to €5.00/kg, followed by a more gradual decrease in price to €3.37/kg by 2030.<sup>19</sup>

€3.37–

€6.25

...per kg H<sub>2</sub> is the range of the present price scenarios for hydrogen in 2030

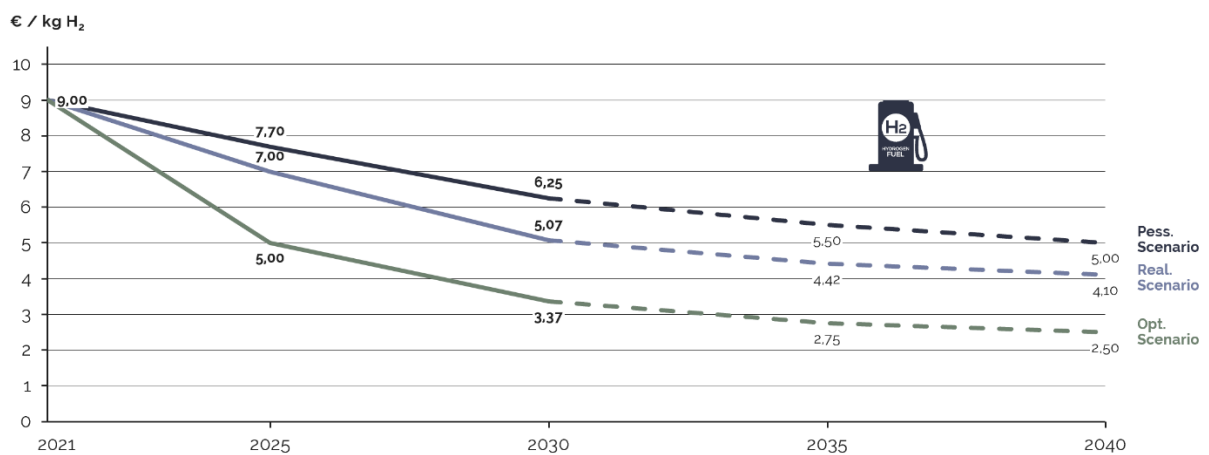


Figure 12: H<sub>2</sub> Price Development 2021 – 2040 (Values after 2030 extrapolated)

<sup>17</sup> Kühnel, Hacker, & Görz, 2018

<sup>18</sup> BloombergNEF, 2020

<sup>19</sup> Rother: Wasserstoff-Fraktion gibt sich noch nicht geschlagen. 2020

The future price of hydrogen, therefore, will be affected by a number of variables, including the extent of and pace at which different industrial sectors increase their use of hydrogen in their processes and for energy transfer. In our analysis we have assumed that hydrogen will not be taxed in the period under consideration in order to encourage an accelerated conversion to a hydrogen economy as a necessary prerequisite for achieving the climate targets. However, it can be assumed that there will come a time, for purely fiscal reasons, when the state will introduce H<sub>2</sub> taxation to replace the declining tax revenues from sales of fossil fuels. Thus, the further one looks into the future, the more likely it appears that the price of hydrogen will be subject to political influence.

## 2.5 Toll charges in Germany

A mileage-based truck toll introduced on German autobahns on January 1, 2005, has been extended subsequently. The toll obligation was extended to around 2,300 km of four-lane federal highways in two stages on August 1, 2012, and July 1, 2015, while in October 2015 the toll threshold was lowered from 12 to 7.5 tonnes of gross vehicle weight.

Finally, in a third stage, on July 1, 2018, tolls for trucks were introduced on all ~40,000 km of federal highways, with uniform toll rates applying on federal highways and federal roads.

For the purposes of this analysis, the toll rates – and specifically the variation in rates based on differences in pollutant emissions – are of immense importance.

The differentiation of the toll rates by pollutant emissions per drive type and by vehicle emission class, in accordance with the Federal Highway Toll Act, allow transport companies to optimize their operating costs through their choice of vehicles based on their truck usage profiles.

- The Federal Highway Toll Act provides a staggered toll reduction for electric and natural gas vehicles to support the market ramp-up of these vehicles. For example, vehicles powered by natural gas will be completely exempt from truck tolls for the period from 2019 to 2023.
- From January 1, 2024, a reduced toll rate will be applied that is 1.1 € cents/km lower than for a comparable Euro 6 diesel vehicle. This reduced rate also applies to vehicles powered by compressed natural gas (CNG) and liquefied natural gas (LNG).
- Electrically powered vehicles will initially be completely exempt from truck tolls for an unlimited period. These include pure battery electric vehicles, externally chargeable hybrid electric vehicles and fuel cell vehicles.



The exemption from tolls for hybrid, electric and hydrogen vehicles on federal highways will significantly reduce the ongoing operating costs of alternative drive technologies for long-distance trucking compared to conventional diesel drives. Compared to a current Euro 6 heavy-duty truck in the >18-tonne class, alternative drive systems currently save 18.7 € cents/km in toll charges. This means that a Euro 6 long-distance heavy-duty truck doing 140,000 km a year, 90% on federal roads subject to tolls, will pay €26,180 annually in tolls while an exempt vehicle will pay none.

The following table shows the currently valid toll rates for the highest weight (and axle) class.<sup>20</sup> In our TCO calculations in this study we have only used the lowest value, of 18.7 € cents/km, because new trucks in 2021 will be offered exclusively in the latest Euro 6 emission class. Nevertheless, the staggered increase in toll rates depending on the emission standard is an important consideration for fleet operators wishing to optimise their ongoing operating costs and will influence their future investment decisions.

**18.7 €  
ct/km**

...is the amount alternative drive systems save in toll charges compared to a current Euro 6 heavy-duty truck in the 18-tonne class on German highways

Toll calculation (valid for highest axle and weight class: > 18t & >= 4 axles) (in € / km)	Toll rate share for external cost air pollution	Toll rate share for external cost noise pollution	Toll rate share for infrastructure	Total toll charges
Euro 6	0,011 €	0,002 €	0,174 €	0,187 €
Euro 5 / EEV	0,022 €	0,002 €	0,174 €	0,198 €
Euro 4 / Euro 3 mit PMK 2	0,032 €	0,002 €	0,174 €	0,208 €
Euro 3 / Euro 2 mit PMK 1	0,064 €	0,002 €	0,174 €	0,240 €
Euro 2	0,074 €	0,002 €	0,174 €	0,250 €
Euro 1, keine SSK	0,085 €	0,002 €	0,174 €	0,261 €

Figure 13: Toll classes depending on pollutant emissions

## 2.6 Outcomes of TCO comparison

The TCO comparison was calculated according to the assumptions above for three different scenarios, which differ in the extent to which they support the transformation to hydrogen-based propulsion systems. (H<sub>2</sub>-pessimistic/realistic/optimistic scenarios). Furthermore, the TCO calculation was also performed for three different 10-year investment periods, commencing in 2021, 2025 and 2030, respectively. As a result we present a total of nine scenarios.

<sup>20</sup> Agentur für Gesundheit und Ernährungssicherheit: Gebührentabelle der Lkw-Maut in Deutschland. 2019

### 2.6.1 Assumptions used:

- All prices are at 2021 consumer purchasing power.
- The basic vehicle (excluding powertrain, fuel and exhaust system) is identical for all four vehicles and constant in all scenarios.
- The components of the alternative drive systems are each subject to specific SE assumptions for price degression due to further development of the technologies and improvements resulting from economies of scale.
- No CO<sub>2</sub> investment penalties are charged in 2021 but do apply in 2025, and with stricter limit values and penalties in 2030.
- The variable costs (OPEX) follow the described scenarios of oil, CO<sub>2</sub> and H<sub>2</sub> price changes.
- Diesel price changes are in line with the crude oil price and reflect the German fiscal approach.
- The price of electricity is constant over the analysis periods considered.
- To travel comparable distances to FCEV trucks, BEV trucks require large, heavy batteries, significantly reducing the vehicle payload and thus the amortisation of the investment. This constraint was not factored into the scenarios presented here.

## 2.6.2 Main results of the TCO comparison:

### 2021 investment

- OPEX is by far the most relevant influencing factor, outweighing investment costs in all the scenarios and investment periods considered.
- Future hydrogen pricing has a greater influence on TCO than the oil price scenarios or CO<sub>2</sub> fuel pricing.
- Alternative drives are already, in 2021, economically competitive over an investment period of 10 years compared to a classic diesel drive.
- Although the FCEV drive in the pessimistic H<sub>2</sub> scenario is still more expensive than the comparable diesel drive in the 10-year TCO-comparison, it is only by 3%. Main reason for this slight TCO disadvantage of FCEV drive is the high cost of hydrogen in 2021 with a price of 9.06 €/kg H<sub>2</sub>.
- However, already in the H<sub>2</sub> realistic & the more so in the H<sub>2</sub>-optimistic scenario the fuel cell truck has a lower TCO than a comparable diesel drive...
- ... and is the most economical scenario among all four drive technologies.

~€9/kg  
H<sub>2</sub>

...is the approximate market price for 1 kg of H<sub>2</sub> at the point of delivery in 2021

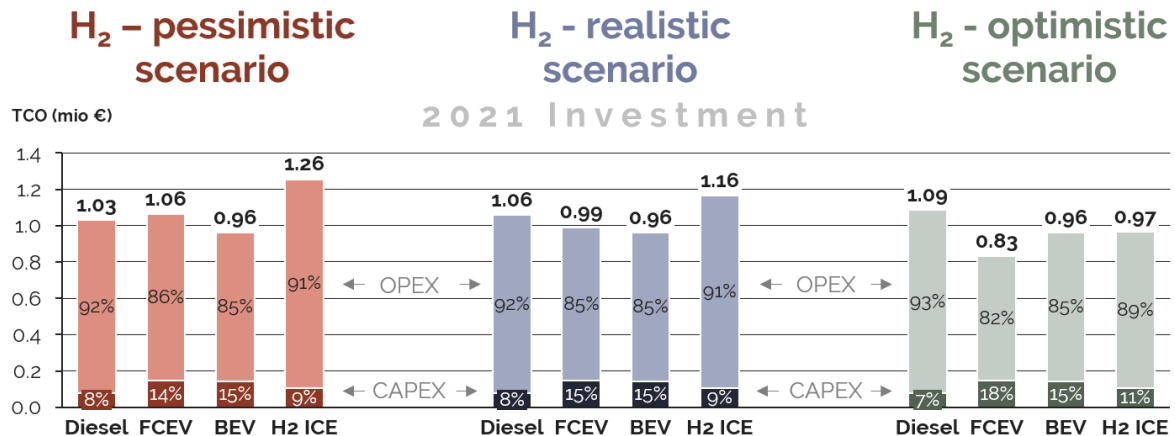


Figure 14: Investment in 2021: TCO (10 Years Op. Time): Powertrain Comparison including CO<sub>2</sub> Pricing

**57  
g/tkm**

...is the average  
CO<sub>2</sub> emission of  
long-haul heavy-  
duty trucks in  
Europe

## 2025 investment

The three scenarios assume, all other things being equal, that there is no change in the level of CO<sub>2</sub> emissions in 2025 compared to 2021; i.e. that the average EU reference value of 57 g/tkm in 2021 will exceed the 15% lower limit by 8.5g in 2025.

In the investment year 2025, all three scenarios are in favour of alternative drives, above all the fuel cell.

The strong decrease in OPEX for the two hydrogen propulsion systems is attributable to the hydrogen price decline assumptions (of varying amounts in each scenario), calculated as a price average over the respective investment periods in the TCO analysis.

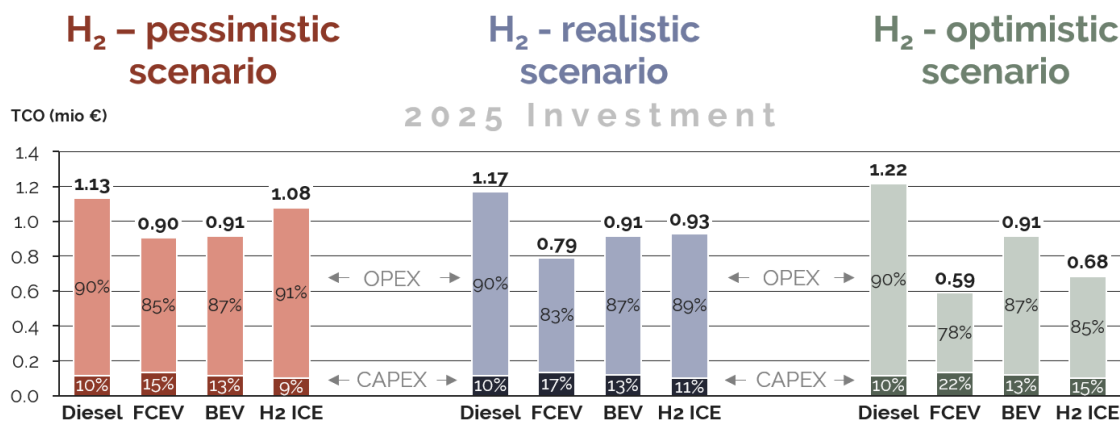


Figure 15: Investment in 2025: TCO (10 Years Operation Time): Powertrain Comparison including CO<sub>2</sub> Pricing

## 2030 investment

Hydrogen propulsion systems achieve their greatest price advantage in the investment year 2030. Even in the H<sub>2</sub>-pessimistic scenario the fuel cell propulsion system has TCO costs that are only about 60% of the classic diesel propulsion system.

Battery vehicles have a higher TCO value than the hydrogen propulsion systems. This is partly because the electricity price in the calculation model is not subject to any price degression over the period under consideration. However, the more significant reason is that in the case of BEV drives the battery system has to be replaced twice during the investment period. Even though battery prices are expected to fall by approximately 50% between 2021 and 2040, the battery system is still likely to remain a significant cost factor well into the future.

# 50%

...is the expected price decline of battery systems between 2021 and 2040

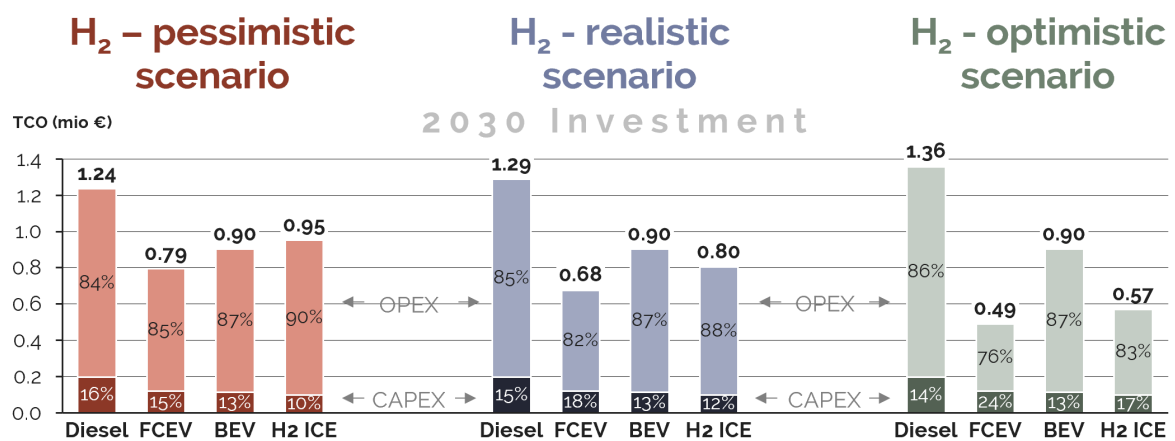


Figure 16: Investment in 2030: TCO (10 Years Operation Time) Powertrain

## Sensitivity analysis:

Potential investors may reasonably question the extent to which price fluctuations in the respective CAPEX and OPEX elements of the investment calculation affect the TCO for each scenario. We undertook a sensitivity analysis to determine this.

## Sensitivity analysis procedure:

The starting point for the sensitivity analysis was the H2-realistic scenario in the investment year 2021. The influence of price fluctuations of +/- 10 % of the respective OPEX and CAPEX cost items on the TCO was examined.

## Outcome of the sensitivity analysis:

- The importance of the influence of the OPEX and CAPEX items on the TCO can be seen in the sensitivity graph (Figure 17). Price fluctuations in operational cost items (hydrogen fuel and maintenance) have a considerably higher influence on the TCO than those of the components of an FCEV drive. **OPEX significantly exceeds CAPEX.**
- The leverage ratio between the largest cost items in CAPEX (fuel cell) & OPEX (hydrogen) is ~1:21.
- In respect of fluctuations in cost items, **OPEX contributes 10x more** to an increase in TCO than CAPEX. Only 11% are attributable to investment costs but **89% are attributable to operating costs** (hydrogen and maintenance).

The sensitivity analysis therefore supports one of the core findings of the study: That operating costs, and fuel costs in particular, have by far the greatest influence on TCO. Thus, for a fuel cell drive system the bandwidths of the price assumptions for the main components have only a minor influence on the TCO per kilometre.

The two most expensive CAPEX components of a fuel cell powered vehicle are the fuel cell system (including pumps, sensors, heat exchangers, seals, compressors, recirculation fans, charge air coolers and/or humidifiers) and the hydrogen tank, which is made of a high-pressure resistant composite material and, depending on the configuration, operates at a pressure of between 350 and 700 bar.

Price fluctuations of these two CAPEX components have only a minor impact on the TCO. Thus, in the case of a price fluctuation of +/- 10% for the fuel cell, the TCO of the truck is only changed by 0.74% (The same applies to the hydrogen tank: Only 0.73% effect on the truck-TCO).

On the other hand, price fluctuations of 20% for hydrogen account for a 15 % fluctuation range in the TCO.

~1:21

...is the ratio of the largest CAPEX position (fuel cell) to the largest OPEX position (hydrogen)

The future development of the hydrogen prices is one of the greatest uncertainties in the TCO analysis of the different propulsion systems. This is because they may well be subject to considerable fiscal influences in the future. Currently, hydrogen is not taxed, although it can be expected that with a progressive decarbonisation of the transport sector and a corresponding discontinuation of mineral oil tax revenues, an appropriate substitute for revenue generation will be sought.

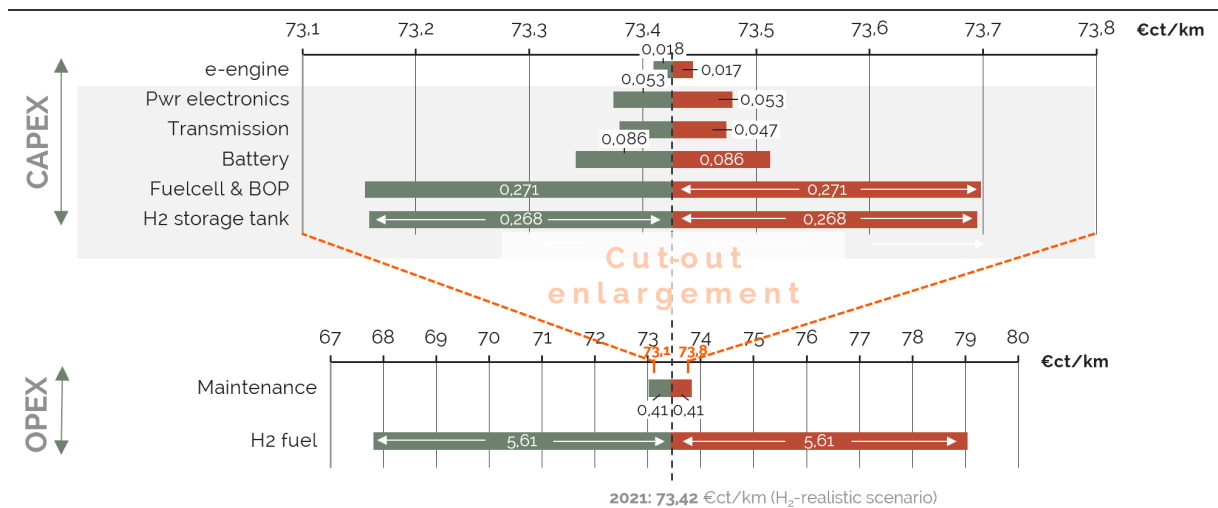


Figure 17: Sensitivity Analysis of CAPEX- & Maintenance- & Fuel- Cost in regards to TCO per km for FCEV heavy-duty long-haul trucks; (Investment in 2021, H<sub>2</sub>-realistic-scenario)



The results of the TCO analysis can be summarised as follows:

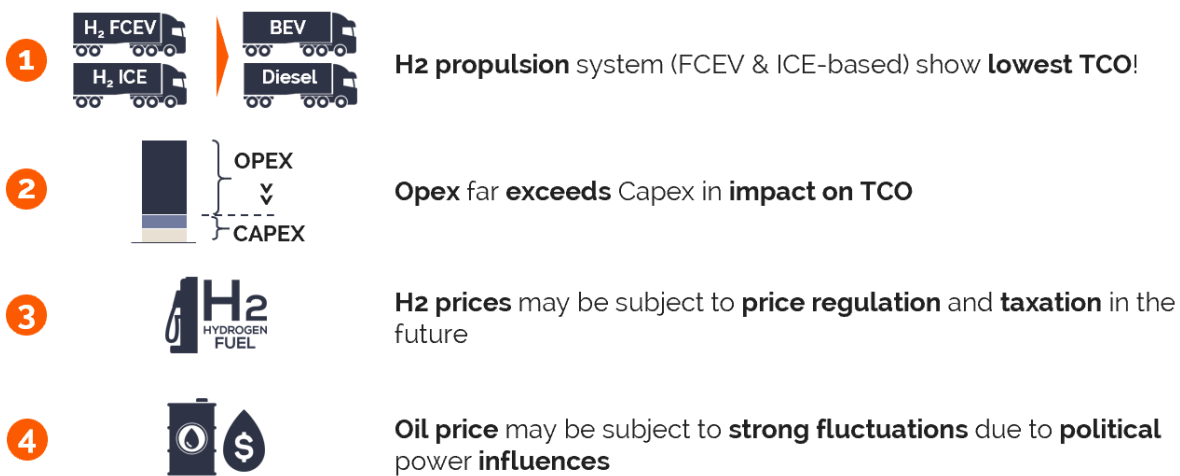


Figure 18: Key takeaways TCO comparison propulsion systems: FCEV vs. H2 ICE vs. Diesel ICE vs. BEV

**>35%**

...is the TCO advantage of fuel cell propulsion compared to Diesel propulsion in 2030 – even in the H<sub>2</sub>-pessimistic scenario

The TCO comparison over an investment period of 10 years shows that both hydrogen-based propulsion systems – fuel cell and combustion engine – are economically the most favourable drive systems compared to diesel combustion engine and battery electric drive. The primary reason for this is the expected rapid decline in the price of hydrogen. Against this, possible price regulations and the taxation of hydrogen are often cited as risks. However, our study shows that the TCO advantage of the fuel cell drive compared to conventional diesel technology is likely to endure, even with future price regulation and taxation. The TCO advantage of FCEV propulsion over diesel propulsion at the time of investment in 2030 is greater than 60% in the H<sub>2</sub>-optimistic scenario and still a robust >35% even in the H<sub>2</sub>-pessimistic scenario. Thus, the TCO leadership of FCEVs over conventional propulsion should be maintained, even if H<sub>2</sub> taxes are imposed.

Our analysis shows that over an investment period of 10 years variable costs are by far most the important influencing factor in the TCO, far outweighing investment costs. For an investment made in 2021, for example, the proportion that CAPEX represents in the total TCO is between 8% and 18% across all scenarios and drive systems. Implicitly, OPEX has a five to 10 times greater impact than CAPEX on the TCO.

Oil prices have historically been subject to large fluctuations, strongly influenced by economic cycles, the activities of international cartels and a variety of geopolitical factors.

In this study we have tried to reflect possible differences in oil prices across the three scenarios. It is quite possible, maybe even probable,

that we will experience an oil price peak in the context of decarbonisation, followed by significant price degression. But even this will not lead to diesel drives being able to beat alternative drive systems in terms of price in the future.

We are convinced that due to their poor payload ratio (a factor which was not explicitly taken into account in this study), BEV trucks will not prevail on long-distance routes in the future. They will almost certainly continue to be particularly suitable for frequent stop/start goods delivery within urban settings. However, for the purpose of long-distance transport, which is the focus of this study, hydrogen technology, both in combustion engines and especially in fuel cell-powered trucks, delivers the lowest TCO of all the main existing and potential drive technologies.

### 3. Potential pilot application for long-haul heavy-duty transport: Break-even analysis of infrastructure alternatives



To make a meaningful contribution towards the transition to the alternative environmentally friendly drive systems envisaged in the EU's Green Deal it is useful to provide concrete examples of economically viable applications.

As shown in the previous chapter, FCEV-based drive systems have already gained competitive advantages over conventional diesel-based drive systems in heavy-duty long-distance road transport. However, the practical application of such a hydrogen-based system depends not only on the economic efficiency of the vehicles but also, to a large extent, on the technical and economic feasibility of the necessary fuelling infrastructure.

## 900 km

...is the approximate range of a FCEV HD long-haul truck, based on 75 kg H<sub>2</sub> tanks

### 3.1 Reference route & necessary infrastructure

As acknowledged earlier in this report, the widespread refuelling infrastructure needed to support hydrogen-powered vehicles is not yet in place.

To benefit from the advantages of future FCEV-based long-haul traffic this infrastructure needs to be established. We were interested in exploring the economics of its creation today for a small-scale pilot.

The following is a practical example of what would be involved in creating the ecosystem needed to support a hydrogen-based heavy-duty long-haul transportation system between Malmö and Stockholm, Sweden. In this example we identify the interacting elements of this ecosystem and practical options for how it could be configured to assess the profitability of different approaches to a hydrogen refuelling infrastructure.

In the following we analyse two different configurations of a hydrogen filling station, depicted in Figure 19 below.

1. Hydrogen filling station with regular deliveries of hydrogen.
2. Hydrogen filling station with an on-site hydrogen electrolyser.

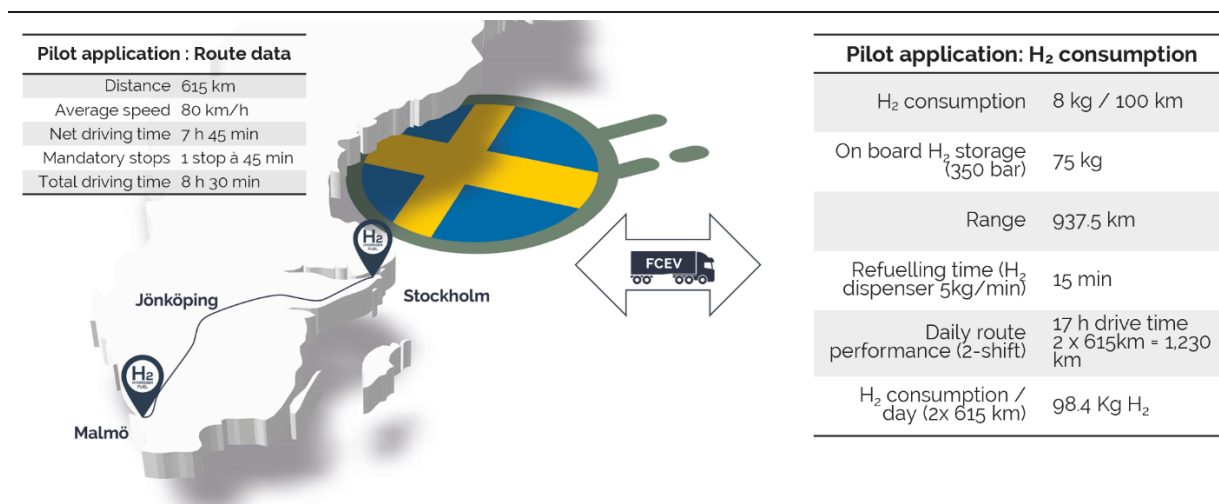


Figure 19: Basic Data Hydrogen Heavy-Duty Long-Haul Reference Route

The reference route, Stockholm to Malmö, is 615 km. Including a mandatory driver stop of 45 minutes, it can be completed by trucks in approximately 8 hours and 15 minutes. The configuration of the FCEV truck used in this study (a 350-bar hydrogen tank and an H<sub>2</sub> capacity of 75 kg) can cover at least 250 km more than this on a single fill, so will only need to be refuelled at the starting point of each one-way journey. It would only be necessary, therefore, to

install one H<sub>2</sub> filling station in each city. Assuming that a truck undertakes two legs of that journey each day, in two shifts, it would consume around 100 kg of hydrogen per day. A small test fleet of 10 trucks would therefore consume around 1,000 kg of hydrogen. The two filling stations, one in Stockholm and the other in Malmö, would either have to be resupplied with hydrogen every two days or produce the corresponding quantity on site. It is realistic, however, to assume that these filling stations will also be freely available to other vehicles, including private cars, so in the following break-even analysis we assume a daily demand of around 1,000 kg H<sub>2</sub> for each filling station.

In this analysis we look at the comparative costs in terms of on-site and off-site hydrogen production options.

### 3.1.1 Hydrogen refuelling station with hydrogen supply

An H<sub>2</sub> filling station is basically a very simple operation. Hydrogen is delivered by truck as a pressurised gaseous medium. The filling station has a corresponding hydrogen tank in which the gas is stored at a pressure of around 1000 bar to ensure a sufficient pressure gradient for the refuelling process, even for tanks in trucks with a pressure level of 700 bar.

The 1000 bar is achieved and maintained by compressors, which require an energy input of 4 kWh/kg.<sup>21</sup> Assuming daily consumption of about 1,000 kg and an electricity price of €0.10/kWh gives daily energy costs of €400. Assuming amortisation of the investment over 10 years, we calculate an average price for renewable energy costs of €0.07/kWh over the period from 2021-30, or an average daily energy cost of €280.

This configuration of the hydrogen filling station is dependent on regular hydrogen procurement at current market prices and requires corresponding logistics by means of special hydrogen trailers.

**4**  
**kWh/kg**

...is the energy needed each day to compress gaseous hydrogen in the refuelling station's storage tanks to 1000 bar

<sup>21</sup> Reuter, Faltenbacher, & Schuller: New Bus Fuel Refuelling for European Hydrogen Bus Depots - Guidance Document on Large Scale Hydrogen Bus Refuelling. 2017

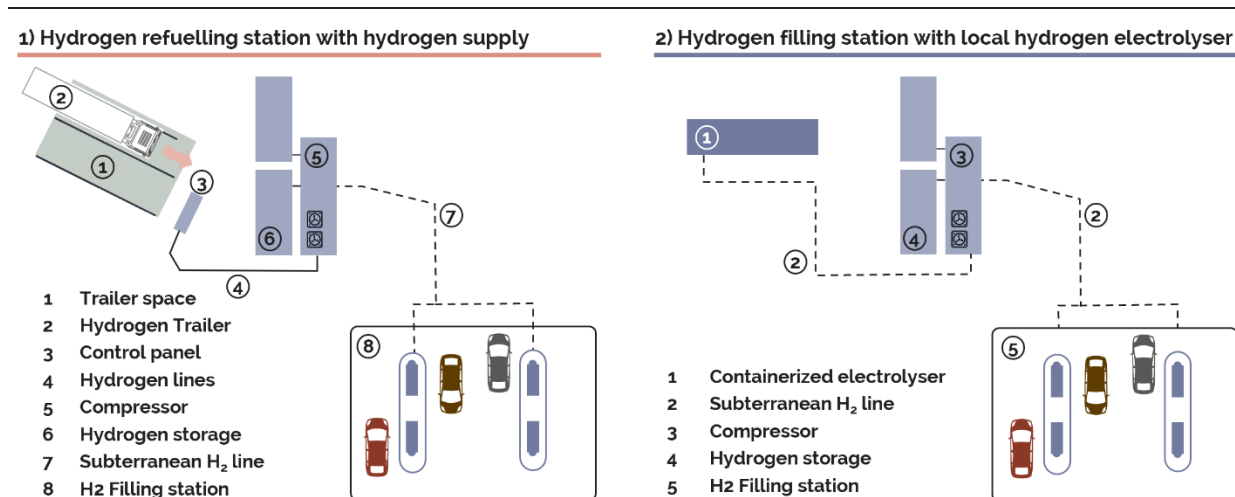


Figure 20: Configurations of H<sub>2</sub> Refuelling Stations

## 1000 bar

...is the required pressure level for the refuelling stations H<sub>2</sub> high-pressure storage to maintain a sufficient pressure gradient for the refuelling of truck pressure tanks

At the refuelling station the hydrogen trailer is parked in a dedicated secure trailer space and the hydrogen, operated by the control panel, is pumped to the compressor. This boosts the hydrogen to the required working pressure of 1000 bar.<sup>22</sup>

### 3.1.2 Hydrogen filling station with local hydrogen electrolyser

Alternatively, using hydrogen produced on-site could potentially reduce supply costs. In this configuration, the filling station would be able to produce its own hydrogen in the required quantity by a suitable electrolyser. To achieve complete CO<sub>2</sub> neutrality the energy supply would have to come entirely from renewable sources.<sup>23</sup>

The energy required to produce 1 kg of hydrogen by using hydrogen electrolysis is 53 kWh/kg.<sup>24</sup> At a current industrial electricity price of about €0.10/kWh, the cost to produce 1 kg of hydrogen would be approximately €5.30. For the purposes of this calculation we have assumed an average price of €0.07/kWh, giving an average hydrogen production price of €3.71/kg over the entire investment period of 2021–2030. There are further costs of approximately €0.30/kg for compression, storage and dispensing. Finally, maintenance costs and capital costs must also be included in the OPEX, which are approximately €1.10. Taking all these costs into account, total production costs would be ~€ 5.10/kg H<sub>2</sub>. Using the same average sales price of hydrogen as in the 2021-30 H<sub>2</sub>-realistic

<sup>22</sup> NOW GmbH: Einführung von Wasserstoffbussen im ÖPNV - Fahrzeuge, Infrastruktur und betriebliche Aspekte. 2019

<sup>23</sup> NOW GmbH: Einführung von Wasserstoffbussen im ÖPNV - Fahrzeuge, Infrastruktur und betriebliche Aspekte. 2019

<sup>24</sup> Fraunhofer ISE Industrialisierung der Wasserelektrolyse in Deutschland: Chancen und Herausforderungen für nachhaltigen Wasserstoff für Verkehr, Strom und Wärme. 2018



scenario employed elsewhere in this report (€7.02/kg) results in a margin of approx. €1.90, which serves to amortise the investment costs for the hydrogen filling station.

### 3.1.3 Comparison of both concepts

Both concepts require technical equipment for the storage and compression of H<sub>2</sub> and have comparable cost positions in this respect. However, they differ in terms of their cost positions for the supply of hydrogen.

Stations supplied with hydrogen by tanker will receive those supplies from a relatively large electrolysis plant with higher scaled processes and correspondingly lower production costs. Therefore, the cost of hydrogen produced in this way will be lower than that of hydrogen produced in a smaller on-site plant. However, the additional transport cost of the hydrogen also has to be taken into account. This will be influenced by the distance between the central electrolysis plant and the filling station and the means of transport used, as indicated in Figure 21, Hydrogen Economy Outlook, published by Bloomberg in March 2020.<sup>25</sup>

€2/kg  
H<sub>2</sub>

...is the average transport cost from hydrogen production to the refuelling station

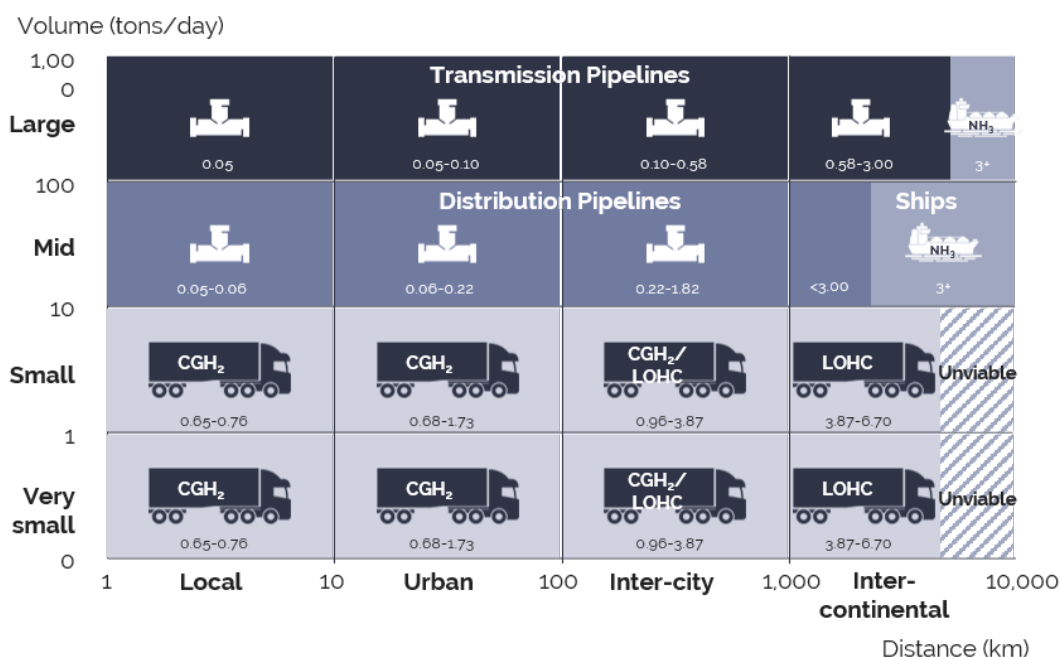


Figure 21: H<sub>2</sub> transport costs based on distance and volume, \$/kg, 2019

The average realistic distance in Germany or Sweden between an H<sub>2</sub> filling station and a central electrolysis plant (most likely located on a seacoast to avail of renewable electricity from offshore wind

<sup>25</sup> BloombergNEF: Hydrogen Economy Outlook - Key messages. 2020. p. 4

farms) is probably in the region of 300 to 500 km. According to the Bloomberg analysis, transporting relatively small quantities of H<sub>2</sub> over this distance by truck could cost anywhere between \$0.96 and \$3.87/kg H<sub>2</sub>. In our study, therefore, we have assumed an average transport cost of €2/kg H<sub>2</sub>. Based on these considerations, the OPEX of an H<sub>2</sub> filling station without an electrolyser is higher than the OPEX of a plant with its own electrolyser. The following comparative break-even calculations consider these differences in the cost structures for both configurations and the corresponding specific payback times on investment.

### 3.2 Investment calculation and break-even analysis

The investment costs of both alternatives differ significantly, as the following Figure 22 shows. Investment Alternative 1, in which the hydrogen is delivered by truck, requires investment of less than a quarter of the costs of Alternative 2 (with on-site electrolyser). On the other hand, Alternative 2's variable costs are lower than those of Alternative 1, as the subsequent analysis shows.

The main components of a hydrogen filling station are the hydrogen tank, the compressor delivering pressure of 1000 bar, and at least one dispenser, as shown in our example. Excavation work and hydrogen pipelines on the filling station site are not taken into account in the calculations.

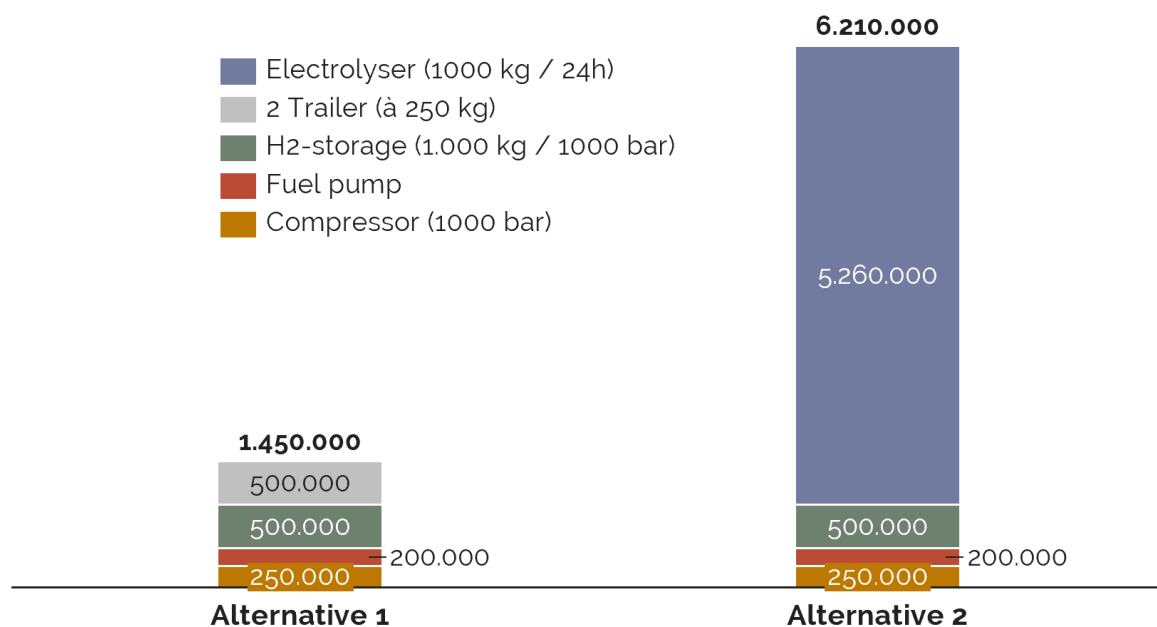


Figure 22: Investment cost comparison

In the case of investment alternative 1, it is common practice for the filling station operator to purchase the necessary hydrogen trailers and make them available to the corresponding supplying logistics company.

In the case of Alternative 2, because the hydrogen is produced on-site there is no need for transport and therefore no investment in trailers.

Assuming a sales price of ~€7/kg H<sub>2</sub> for both refuelling station configurations (an average sales price for the period 2021-30, corresponding to the average H<sub>2</sub> sales price in the H<sub>2</sub>-realistic scenario TCO calculation in the previous chapter) and annual sales of 365,000 kg H<sub>2</sub> (an average 1,000 kg H<sub>2</sub> per day), both alternatives generate annual revenue of ~€2.56 million.

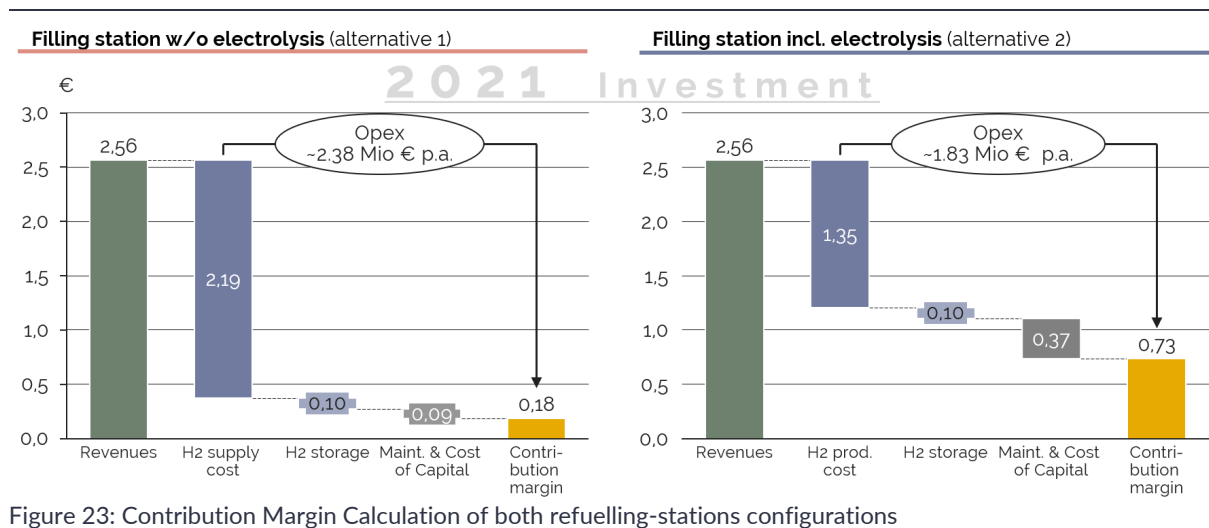


Figure 23: Contribution Margin Calculation of both refuelling-stations configurations

Figure 23 shows the net margin calculations for both filling station configurations based on these sales price and volume assumptions. This highlights the higher supply cost for hydrogen in Alternative 1. When transport costs are added to the relatively cheaper centrally produced gas, the H<sub>2</sub> production costs for the filling station with on-site production are around 40% lower than the respective procurement costs for a station supplied with hydrogen. However, the cost advantage of local production is in turn reduced by the fact that the maintenance costs (~4% of the investment costs p.a.) and the capital costs (2% in interest) are around 4x higher than those of the centrally supplied filling station. Taking these various factors into consideration, local hydrogen production still ends up costing about ~20% less.

The different cost structures of both alternatives, therefore, lead to very different contribution margins. In Alternative 1 (without local

**20%**

...is the advantage of investment in Alternative 2 compared to Alternative 1 in OPEX.

electrolysis), the contribution margin is approximately €180,000 p.a. In Alternative 2 (with on-site electrolysis), the contribution margin is about 3x higher at approximately €700,000.

## ~ 8 years

...is the approximate time it takes to reach breakeven for both alternatives based on an investment made in 2021

*How do the different investment requirements and operating cost structures of the two alternatives affect the break-even calculation?*

In the first instance, we took an investment made in 2021 and assumed that both the initial investment and the contribution margin for Alternative 2 is approximately four times greater than for Alternative 1. In this scenario, both reach breakeven in about the same time span. Alternative 1 requires less than 8 years (7.87), while Alternative 2 requires about half a year longer (8.45). Alternative 2, with its lower operating costs, amortises after 8.65 years compared to Alternative 1.

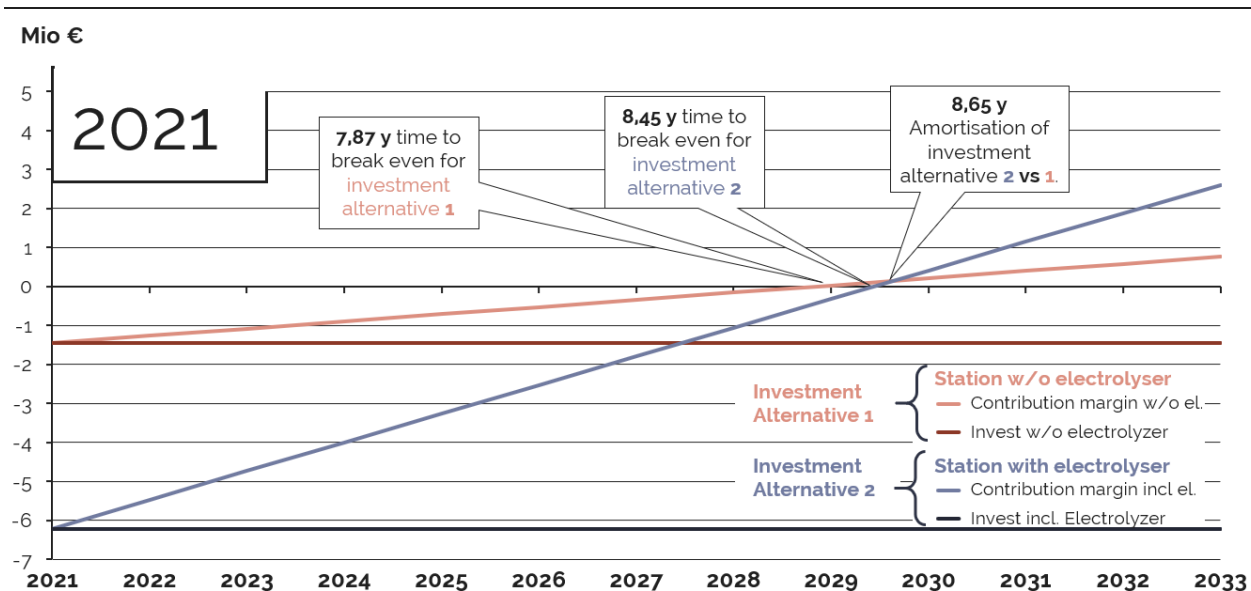


Figure 24: Break-even analysis investment Alternatives 1 and 2 in 2021

What is the return on investment for the two filling station designs in 2025 and 2030?

The investment costs of electrolysis units are falling more sharply than those of any other cost component, so in principle an investment in a filling station with its own hydrogen supply is becoming increasingly attractive. We assume that alkaline electrolysis plants will be >20% cheaper by 2025 than they are now while the price of the remaining filling station components will fall by around 10%.

**20%**

...is the expected price drop for alkaline electrolysis in 2025 compared to 2021

As a result, for an investment made in 2025 the break-even point for both alternatives falls by around one year, to ~6.5 for Alternative 1 and ~7.5 years for Alternative 2, compared to an investment made in 2021.

Due to the stronger price decline of electrolysis technology compared to other components, the payback period of Alternative 2 decreases by more than half a year to 8 years between 2021 and 2025 compared to Alternative 1.

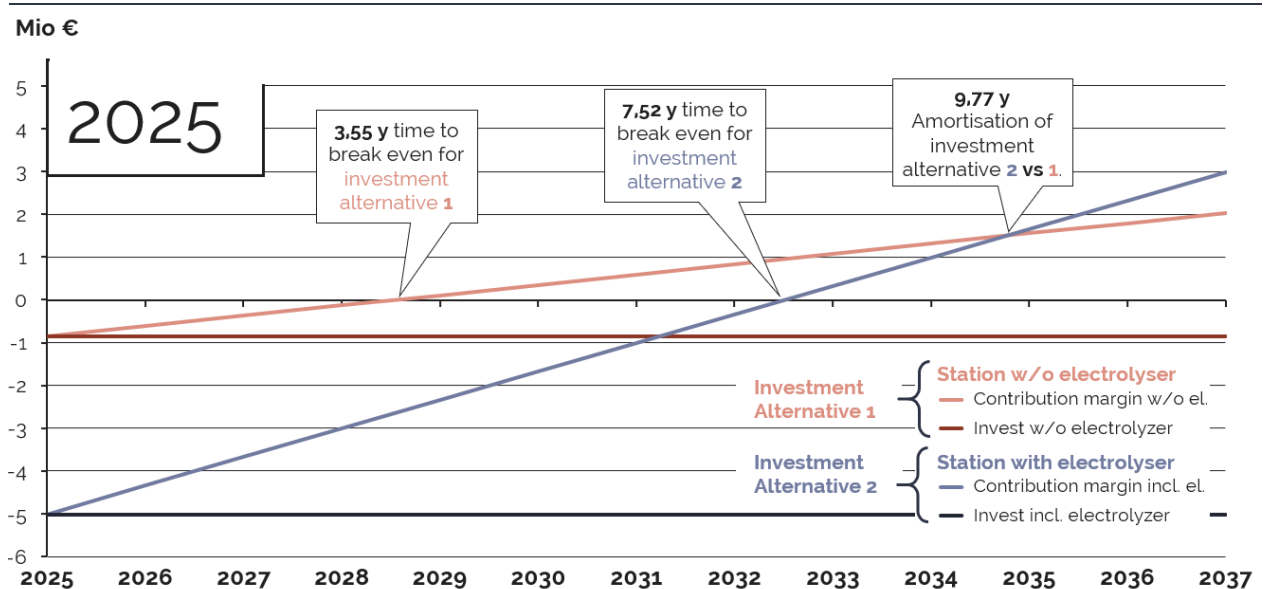
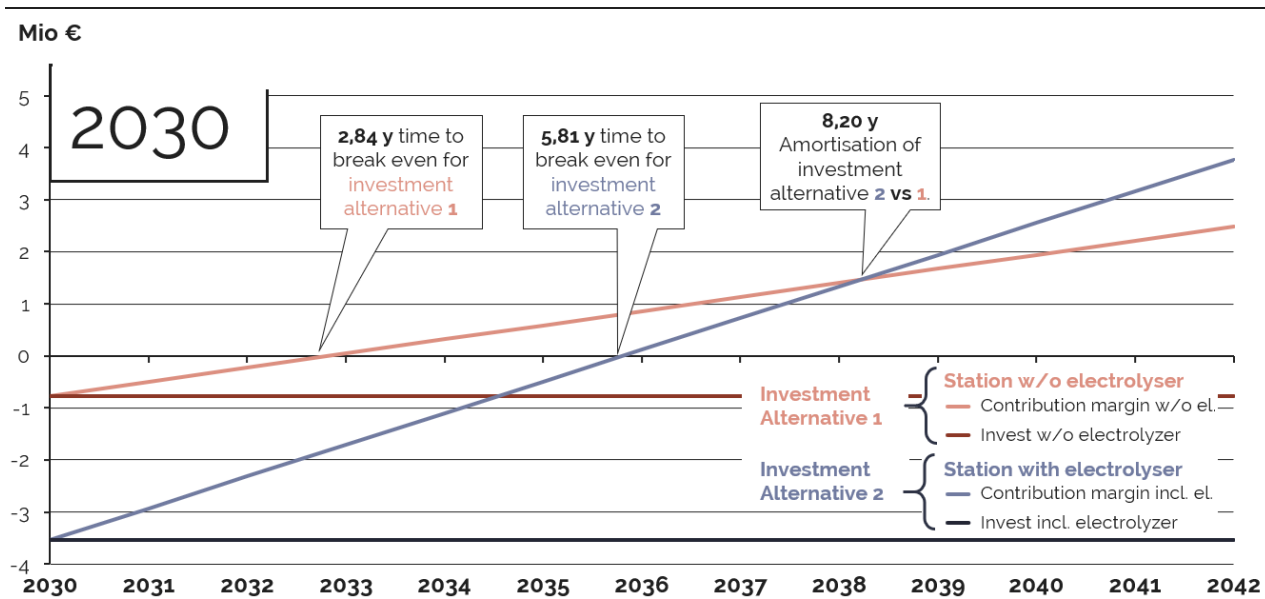


Figure 25: Break even analysis investment Alternatives 1 and 2 in 2025

We expect the price of alkaline electrolysis technology to fall by another 33% between 2025 and 2030, with prices of the other components falling a further 10%. This results in Alternative 2 having a break-even period that is only about six months longer than Alternative 1. The payback period for Alternative 2 compared to Alternative 1 drops to just six years. Thus, in 2030 there will no longer be an economically rational argument for investing in a refuelling station that does not have its own on-site hydrogen production facility.



In summary, we believe that at this point in time investing in hydrogen propulsion technology only makes sense if it is accompanied by parallel investment in the necessary infrastructure. The joint investment in a fleet and the necessary infrastructure will assure operability on the basis of an autonomous fuel supply.

**~6 years**

...is the amortisation period of investment Alternative 1 compared to Alternative 2

At some stage in the future it will no longer be necessary to operate one's own infrastructure. But our break-even analysis shows that such an investment can be operated economically based on normally acceptable payback periods.

As our calculations indicate, the later the investment is made, the shorter the break-even period is likely to be. If a fleet operator builds its own refuelling station infrastructure it should be designed with a capacity reserve from the outset, as in our practical example. This is partly to enable the company to accommodate the growth of its own H<sub>2</sub> fleet, but also to provide access to external customers from the outset and thus generate additional contribution margins.

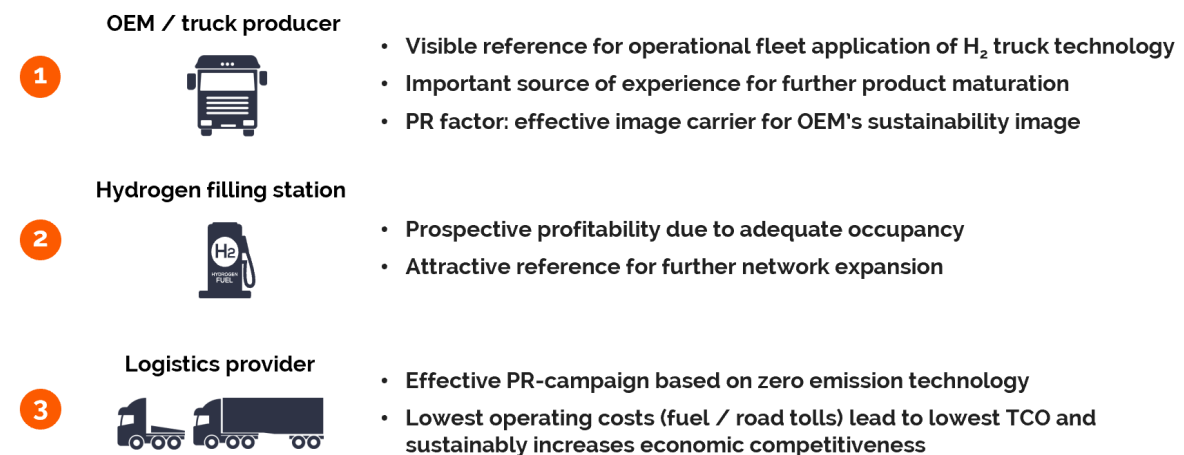


Figure 27: Effects for cooperation partners of hydrogen-based long-distance freight transport

In addition to the economic feasibility of a regenerative and hydrogen-based long-distance truck route, there are a number of other advantages for everyone involved. The manufacturers of FCEV-HD-trucks can gain valuable practical experience at an early stage through operational fleet use and can thus mature their product offerings more quickly. In addition, they will be widely seen as an early player in the market and enjoy the perception of having a first-mover advantage. Service station network operators may take over the construction and operation of H<sub>2</sub> refuelling stations in partnership with fleet operators, providing predictable high utilisation of their refuelling stations as an important prerequisite for their amortisation. Early adopters will lay the foundation for larger networks, covering larger areas, and obtaining high visibility in the marketplace.

Finally, fleet operators that are the first to adopt coherent hydrogen strategies can anticipate a lot of positive PR at little, if any cost. This could boost demand for their services because their customers may also want to promote their zero-emissions footprint. As an added benefit, H<sub>2</sub> drive system operators avoid the highway tolls increasingly imposed by governments on users of traditional fossil fuels. As our TCO analysis clearly shows, H<sub>2</sub> is not merely an attractive option for the future, it can already deliver TCO advantages for enlightened investors.

## 4. Key takeaways

- The last investments in conventional drive technology will be made by 2040 at the very latest in order for them to be amortised before the EU's 2050 CO<sub>2</sub> neutrality target applies.
- Fuel cell technologies for long-distance heavy-duty road transport are already an economically viable investment alternative, with the lowest TCO of the four fuel systems considered in this report.
- Comparative TCO calculations are subject to future uncertainties, especially with regard to regulation, taxation, CO<sub>2</sub> charges and commodity market prices for hydrogen and oil.
- Fuel cell technology is the best of the credible alternative zero-emission approaches available to long-haul heavy-duty transport operators today because it:
  - offers a **longer range** compared to BEV vehicles;
  - has a **higher payload**, due to the much lower weight of the fuel cell compared to that of a high capacity battery;
  - requires a much **easier to install distribution and fuelling infrastructure** compared to the capacity limits in electrical power supply for fast charging applications;
  - takes a much **shorter** refuelling time than electrical power.
- Hydrogen refuelling stations can be set up relatively easily using deliveries of gas by truck from established central suppliers.
- To meet demand for larger quantities of hydrogen, however, it may also be worthwhile to install relatively small-scale on-site hydrogen production where sources of renewable energy are available.
- Such applications will amortize quite quickly on the basis of economies of scale, with investment costs for alkaline hydrogen electrolysis technology expected to fall sharply in the near future.



## List of Abbreviations

ATR	Autothermal Reforming
BEV	Battery Electric Vehicle
CAPEX	Corporate Average Fleet Economy
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CO <sub>2</sub>	Carbon Dioxide
C <sub>x</sub> H <sub>x</sub>	Hydrocarbon
DRI	Direct Reduced Iron
EU	European Union
FCEV	Fuel Cell Electric Vehicle
H <sub>2</sub>	Hydrogen
HDV	Heavy-Duty Vehicle
HV	High-Voltage
ICE	Internal Combustion Energy
IEA	International Energy Agency
kWh	Kilowatt Hour
MCC	Mercator Research Institute on Global Commons and Climate Change
OPEX	Operational Expenditure
PEM	Proton Exchange Membrane
PIK	Potsdam Institute for Climate Impact Research
SE	Strategy Engineers
SMR	Steam Methane Reforming
TCO	Total Cost of Ownership
tkm	Tonne-kilometres

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## The Authors



### Arndt v. Gregory

Manager, Strategy Engineers

As an expert in alternative drive concepts, Arndt v. Gregory is entrusted with the topics surrounding the decarbonisation of the transport sector. Recent topics: Battery concept comparisons incl. all solid state, climatic vehicle testing, automotive diagnostics in CASE era.

E-Mail: avg@strategyengineers.com



### Dr Albert Neumann

Managing Director, Strategy Engineers

As founder of Strategy Engineers – Albert Neumann has from the outset been committed to accompanying and shaping transformations in the automotive industry - a subject more topical than ever & at the heart of the content of our study.

E-Mail: an@strategyengineers.com



### Peter Gillbrand

Vice President and Managing Director, AVL

AVL is right in the middle of the automotive transformation epicenter and as VP for the Instrumentation and Test Systems segment of AVL in Europe – Peter Gillbrand is directly engaged in this rapidly accelerating transformation.

E-Mail: peter.gillbrand@avl.com



### Martin Rothbart

Senior Product Manager Energy & Sustainability, AVL

Martin Rothbart is working for the Powertrain Systems division of AVL and is responsible for business development for energy, alternative & synthetic fuels, and sustainability, as well as analysis of market potential in the different regions where he supports the global sales efforts.

E-Mail: martin.rothbart@avl.com

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Strategy Engineers GmbH & Co. KG

Phone: +49 89 4161 7235  
E-Mail: [publications@strategyengineers.com](mailto:publications@strategyengineers.com)  
Website: [www.strategyengineers.com](http://www.strategyengineers.com)

Munich: Seidlstraße 18, 80335 Munich, Germany  
Shanghai: Aurora Plaza, 27<sup>th</sup> floor, Fucheng Road 99, Pudong Shanghai 200120, China  
Plymouth: 47519 Halyard Drive, Plymouth, MI 48170, USA

HRA-96163, Munich District Court

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