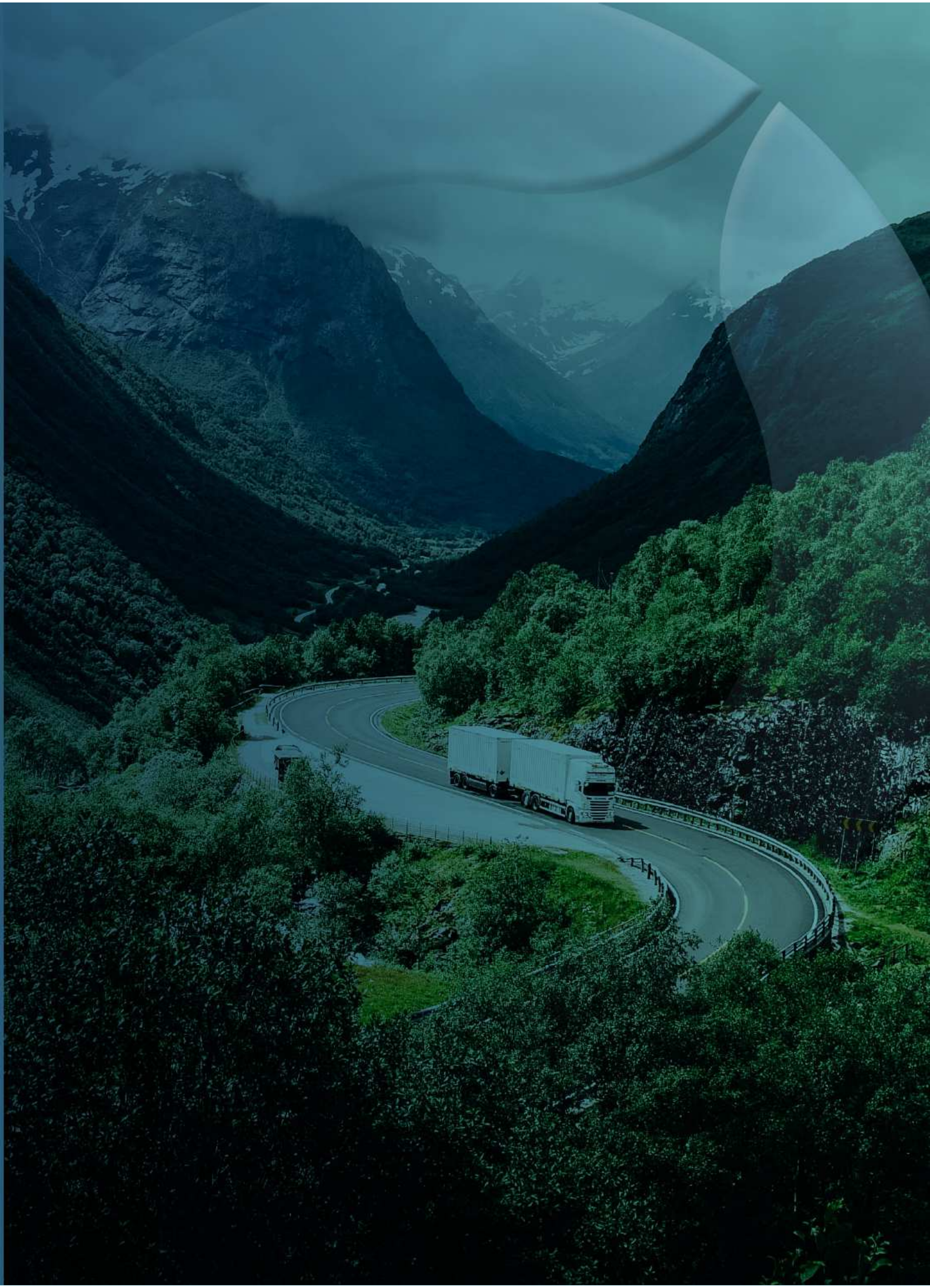
Study report

Fuel Cells Hydrogen Trucks

Heavy-Duty's High Performance Green Solution

December 2020



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FUEL CELLS AND HYDROGEN 2 JOINT UNDERTAKING

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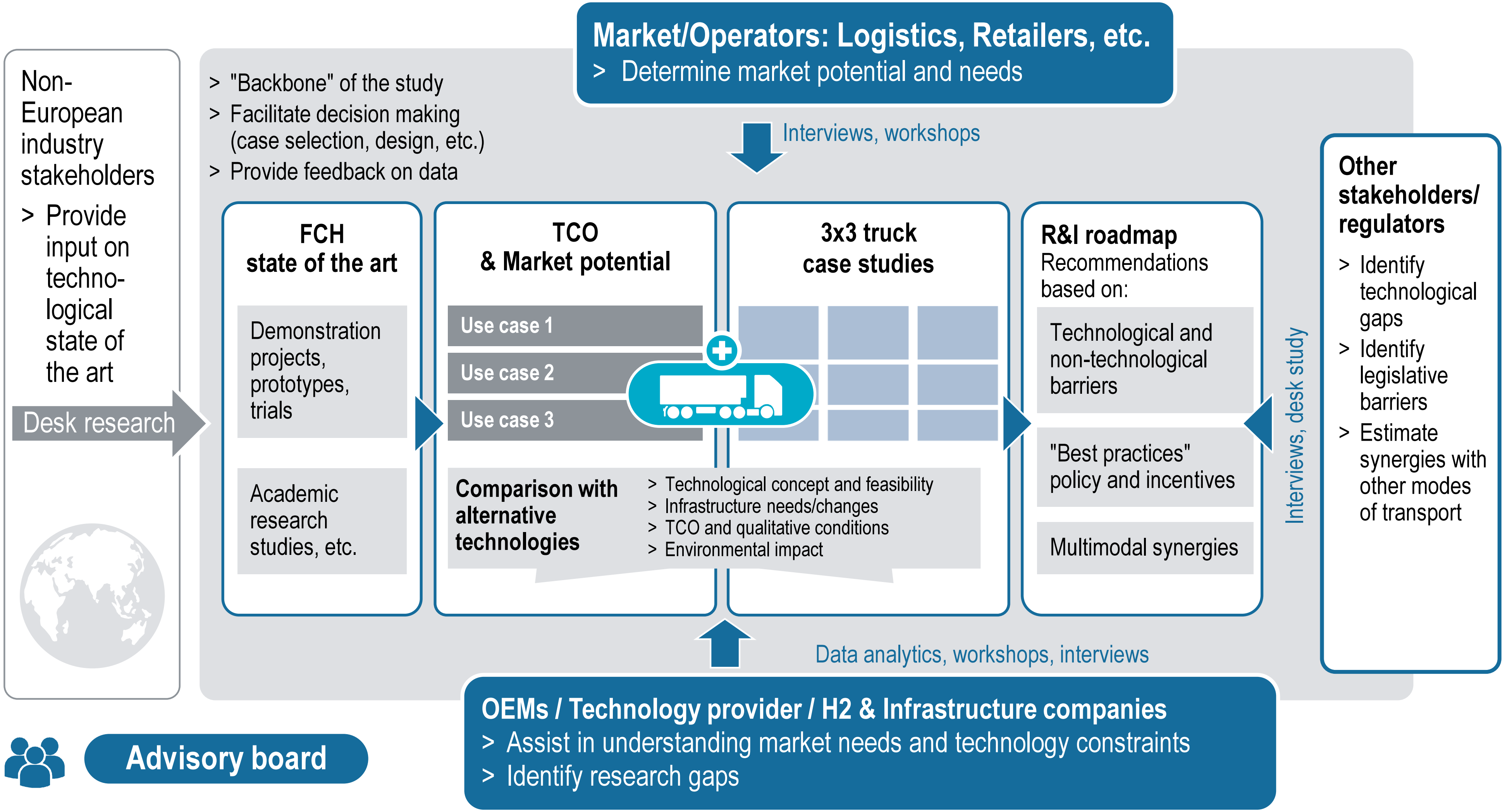
The study considers different dimensions and stakeholders insights from the heavy-duty truck and fuel cell and hydrogen tech. industry

Study set-up in a nutshell



Non-European industry stakeholders
> Provide input on techno-logical state of the art

Desk research

- > "Backbone" of the study
- > Facilitate decision making (case selection, design, etc.)
- > Provide feedback on data

Market/Operators: Logistics, Retailers, etc.
> Determine market potential and needs

Interviews, workshops

FCH state of the art

Demonstration projects, prototypes, trials

Academic research studies, etc.

TCO & Market potential

Use case 1

Use case 2

Use case 3

3x3 truck case studies

Comparison with alternative technologies
- > Technological concept and feasibility
- > Infrastructure needs/changes
- > TCO and qualitative conditions
- > Environmental impact

R&I roadmap
Recommendations based on:

Technological and non-technological barriers

"Best practices" policy and incentives

Multimodal synergies

Interviews, desk study

Other stakeholders/ regulators
- > Identify technological gaps
- > Identify legislative barriers
- > Estimate synergies with other modes of transport

Data analytics, workshops, interviews

OEMs / Technology provider / H2 & Infrastructure companies
- > Assist in understanding market needs and technology constraints
- > Identify research gaps

Advisory board

Source: Roland Berger

This study assesses the state of the art of technology and investigates existing initiatives…

Executive Summary (1/6)

1 **Literature review**

The scientific literature focuses mostly on **developments in North America, followed by Europe**. A strong increase in publications shows **growing interest in FCH technology and applications for HD trucks**. Commercialisation and total cost on ownership analysis are often the focus of research.

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2 **Trial and demonstration projects**

Increasingly, the **number of European FCH heavy-duty trucks trial and demonstration projects is growing**, levelling up with US efforts (esp. forerunner California). As European projects are set up for local European conditions, it is specifically the **success factors of non-European projects** that provide further impulses for development uptake. It is shown that it is often a **combination of partners involved in the project set-up**, the possibility to rely on **public support schemes**, and the **existence of hydrogen ecosystems** from other applications that facilitate demonstration projects.

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3 **State of the art technology**

State of the art technology provides an **aggregated overview of alternative powertrain technologies** of the HD road transportation sector that are available today – namely FCH, battery-electric (BET), lower-carbon fuels, e-fuels and catenary. Based on a review of technical data points, **FCH heavy-duty trucks** could offer a **zero-emission alternative with high operational flexibility** allowing for long-haul rides, while featuring a relatively short refuelling time. [*continued on next page*]

Source: Roland Berger

…as well as conducts a policy analysis in the most relevant markets with focus on the European Union

Executive Summary (2/6)

3

State of the art technology [*continued]*

[…] While **weight and cost of batteries limit range and payload of BET**, **limited reduction potential** of emissions, pollutants and particles is a bottleneck for **lower-carbon fuel trucks**. For e-fuels, the **emission reduction potential depends on sustainable sources for both H_2 and CO_2**, while pollutants /particles of ICEs are not addressed. Non-hybrid catenary trucks are comparable to BET concerning emission reduction without the time of recharging, yet are highly dependent on the catenary system. Overall, **zero-emission powertrains** have **yet to reach full commercial readiness**.

4

Policy analysis

Policy approaches on low emission HD trucks are **different across key markets**, yet become **increasingly stricter in all geographies**. While in North America, HD Trucks increasingly are in focus of **general emission reduction** (e.g. upcoming US Cleaner Trucks Initiative), in Asia, China offers a strong **government incentive schemes** for low emission vehicles, incl. HD trucks. In Europe, the European Union (EU) follows a high-profile agenda on **decarbonisation** (e.g. EU Green Deal).

As policy makers and the general public push for lower carbon solutions, **FCH increasingly move into the focus of transport policy.** In the EU, the Green Deal is a **driving force for low emission vehicles, fuels, and related infrastructure**. If the currently fragmented European approach becomes more cohesive across Member States, FCH HD trucks can **further benefit from support schemes** that support the **uptake of hydrogen applications** and specifically drive **ZLEV[1] development.**

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1) Zero and low emission vehicles

Source: Roland Berger

In a total cost of ownership and market potential analysis, fuel cell and hydrogen trucks are compared with other technologies

Executive Summary (3/6)

5

Business cases and total cost of ownership model

The **total cost of ownership (TCO) modelling** of trucks with conventional and alternative powertrains shows that **fuel cell technology has a significant cost down potential at scale** (not based on prototype cost). This applies to the **three use cases** developed for the analysis, **related to different operation patterns and truck types**. While the results reveal a **cost premium of up to 22% for fuel cell trucks** over diesel trucks in 2023, the analysis indicates a clear trend towards cost competitiveness for all H_2 storage technologies until 2030. In comparison with battery electric trucks, FCH trucks show **lower TCO results across the years for the long- and medium-haul use cases**. In the third use case on **regional logistics, battery electric trucks have a cost advantage** compared to FCH technology. **Cost of powertrain (CAPEX)** and **energy/fuel costs (OPEX)** are identified as the **main cost drivers**. Moreover, **road toll is a potential key lever** to enable business cases already in the short-term.

6

Market model

The results of the market model show **clear potential for FCH and battery technologies** and an **increasing sales share until 2030,** if the market uptake is supported today. After a slower uptake of the technology until 2027, the model indicates a **FCEV market increase to an overall sales share of 17% in 2030** (specific market segments increase up to 32%). The high potential of FCH trucks within the whole market reflects also a necessary **trajectory for reaching the CO_2 emission reduction targets** for 2050, which could be achieved with this market development. However, the analysis shows that this will only hold true **if the modelled growth rate for zero-emission technology is sustained.** Currently, the **market is still in a very early phase** and needs to be developed now to allow for the market potential to materialise. Cost competitiveness and market uptake can only be achieved through a **push to market and the set-up of required infrastructure.**

Source: Roland Berger

Case studies based on real-life operations are developed together with the industry to investigate potential business opportunities

Executive Summary (4/6)

7

Case study approach

In **nine specific case studies**, the **economic and operational benefits of fuel cell and hydrogen technology** within the broader transport environment are demonstrated. The case studies were **selected along the three defined use cases** across the heavy-duty market segments. Hence, three case studies each were developed to illustrate the potential of FCH technology in the market segments of **long-haul, medium-haul & regional distribution**. All nine case studies were developed in **close collaboration with members of the study's Advisory Board** from the transport and logistics industry to build on **expert insights and real-life data**. They provided data on a **specific route they operate to explore potential opportunities** of FCH technology in these operations and business cases. For the case studies, a **balanced geographical spread across Europe** was ensured to allow for a differentiated view on the application potential of FCH technology in different national contexts. The countries in which a case study was developed are: Austria, Czech Republic, France, Germany, Italy, Slovakia, Spain, Sweden, United Kingdom.

8

Specific case studies

The case studies can serve as **tangible business opportunity blueprints for the industry**, while also giving a **first glance on current limitations, but also opportunities in the near term as real life FCH truck products and a mature hydrogen supply chain are still to materialise**. They demonstrate the wide **spectrum of deployment** and show that real-life operations can take diverse forms with specific opportunities and constraints. The case studies illustrate **cross-border and cross-country logistics, high-mileage, multi-shift operations as well as fixed-schedule, low-mileage regional distribution** within a specific perimeter.

9

Results and learnings

FCH technology constitutes a good fit for a wide range of heavy-duty utilisation patterns. For example, in some of the case studies investigated, a similar or better TCO result for battery electric trucks was found. When conducting further stakeholder interviews, **however, it became clear that the trucks** used on the related routes **should be able to allow for flexibility in operations in order to provide a long-term added value** to the truck operators' fleets. This **flexibility (e.g. the necessary power of the fuel cell system, the tank volume and payload considerations) can often be better ensured by FCH trucks**.

Source: Roland Berger

(Non-) technological barriers and synergies are identified that currently affect the industry development and market uptake

Executive Summary (5/6)

10 **Barriers**

Identified **technological and non-technological barriers illustrate the current state of play** regarding **technology development and framework conditions for FCH heavy-duty trucks** in Europe. Of the identified 22 barriers, **none is considered a show-stopper for commercialisation**. However, a prioritisation of the barriers shows that **several roadblocks should be addressed in order to enable a large-scale roll-out** of FCH trucks in the upcoming years. **Technological barriers** have been identified **along the FCH truck value chain**, from truck design to infrastructure availability, refuelling technology to service & maintenance offerings. **Non-technological barriers** relating to **economic, political, legal and social framework conditions** illustrate that a lack of financing and funding support to mitigate TCO considerations and business risks in the market entry phase is a high need for action, as well as establishing planning security for demand and supply side stakeholders.

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11 **Synergies**

A key factor for the successful commercialisation of FCH technologies in the heavy-duty truck industry is **exploiting potential synergies of FCH applications with other industries and modes of transport**, such as buses, taxis, trains, forklifts and maritime applications. The main synergies identified relate to collaborations and industrialisation effects to achieve **lower production costs**, **higher infrastructure utilisation**, and **optimising production, use and transport of hydrogen**. It is illustrated how **multimodal synergies along the entire hydrogen value chain create spill-over effects** for the roll-out of FCH trucks.

Source: Roland Berger

Recommendations for future activities are formulated that tackle these barriers and provide further insights for policy makers

Executive Summary (6/6)

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Recommendations for Research and Innovation

Four tailored R&I projects, with an estimated **total budget of EUR 470 million**, are suggested to support overcoming the identified barriers in the short- and medium-term. These projects refer to the **technology development and optimisation for standardised refuelling processes**, the **development of further truck and powertrain prototypes** with higher levels of standardisation of fuel cell system integration, further large scale (~500 trucks) **multi-national demonstration of FCH heavy-duty truck fleets** and specific **technology development for high energy efficiency HRS for trucks**. These **R&I projects could accelerate the successful roll-out of FCH heavy-duty trucks** and provide a strong fundament for standard setting and regulatory frameworks. In that regard, further **political focus areas for tailored programmes are proposed** to **provide funding for truck and component production facilities**, **target the entire truck life cycle** and offer **market entry support to infrastructure providers** (CAPEX and OPEX schemes). Furthermore, **concrete policy recommendations** are formulated to the **European Union, national governments and municipalities** in order to **accelerate FCH HD truck commercialisation**.

Source: Roland Berger

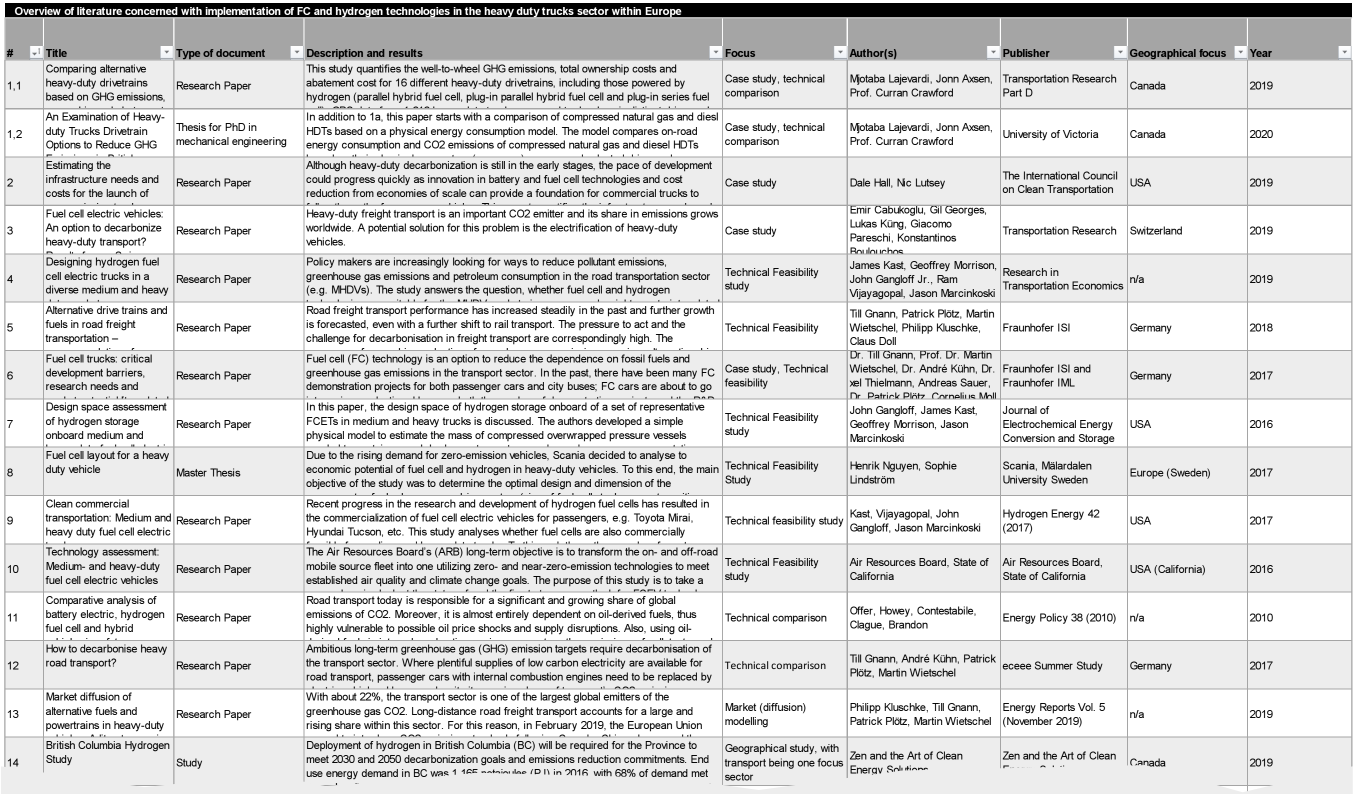
B. State of the art and existing initiatives

B.1 Literature review

We identified 60 relevant scientific publications on FCH and related powertrain technologies for heavy-duty trucks

Literature review

Overview of relevant literature (2015-2020)



Overview of literature concerned with implementation of FC and hydrogen technologies in the heavy duty trucks sector within Europe

#	Title	Type of document	Description and results	Focus	Author(s)	Publisher	Geographical focus	Year
1,1	Comparing alternative heavy-duty drivetrains based on GHG emissions,	Research Paper	This study quantifies the well-to-wheel GHG emissions, total ownership costs and abatement cost for 16 different heavy-duty drivetrains, including those powered by hydrogen (parallel hybrid fuel cell, plug-in parallel hybrid fuel cell and plug-in series fuel	Case study, technical comparison	Mjotaba Lajevardi, Jonn Axsen, Prof. Curran Crawford	Transportation Research Part D	Canada	2019
1,2	An Examination of Heavy-duty Trucks Drivetrain Options to Reduce GHG	Thesis for PhD in mechanical engineering	In addition to 1a, this paper starts with a comparison of compressed natural gas and diesl HDTs based on a physical energy consumption model. The model compares on-road energy consumption and CO2 emissions of compressed natural gas and diesel HDTs	Case study, technical comparison	Mjotaba Lajevardi, Jonn Axsen, Prof. Curran Crawford	University of Victoria	Canada	2020
2	Estimating the infrastructure needs and costs for the launch of	Research Paper	Although heavy-duty decarbonization is still in the early stages, the pace of development could progress quickly as innovation in battery and fuel cell technologies and cost reduction from economies of scale can provide a foundation for commercial trucks to	Case study	Dale Hall, Nic Lutsey	The International Council on Clean Transportation	USA	2019
3	Fuel cell electric vehicles: An option to decarbonize heavy-duty transport?	Research Paper	Heavy-duty freight transport is an important CO2 emitter and its share in emissions grows worldwide. A potential solution for this problem is the electrification of heavy-duty vehicles.	Case study	Emir Cabukoglu, Gil Georges, Lukas Küng, Giacomo Pareschi, Konstantinos Boulouchos	Transportation Research	Switzerland	2019
4	Designing hydrogen fuel cell electric trucks in a diverse medium and heavy	Research Paper	Policy makers are increasingly looking for ways to reduce pollutant emissions, greenhouse gas emissions and petroleum consumption in the road transportation sector (e.g. MHDVs). The study answers the question, whether fuel cell and hydrogen	Technical Feasibility study	James Kast, Geoffrey Morrison, John Gangloff Jr., Ram Vijayagopal, Jason Marcinkoski	Research in Transportation Economics	n/a	2019
5	Alternative drive trains and fuels in road freight transportation –	Research Paper	Road freight transport performance has increased steadily in the past and further growth is forecasted, even with a further shift to rail transport. The pressure to act and the challenge for decarbonisation in freight transport are correspondingly high. The	Technical Feasibility	Till Gnann, Patrick Plötz, Martin Wietschel, Philipp Kluschke, Claus Doll	Fraunhofer ISI	Germany	2018
6	Fuel cell trucks: critical development barriers, research needs and	Research Paper	Fuel cell (FC) technology is an option to reduce the dependence on fossil fuels and greenhouse gas emissions in the transport sector. In the past, there have been many FC demonstration projects for both passenger cars and city buses; FC cars are about to go	Case study, Technical feasibility	Dr. Till Gnann, Prof. Dr. Martin Wietschel, Dr. André Kühn, Dr. xel Thielmann, Andreas Sauer, Dr. Patrick Plötz, Cornelius Moll	Fraunhofer ISI and Fraunhofer IML	Germany	2017
7	Design space assessment of hydrogen storage onboard medium and	Research Paper	In this paper, the design space of hydrogen storage onboard of a set of representative FCETs in medium and heavy trucks is discussed. The authors developed a simple physical model to estimate the mass of compressed overwrapped pressure vessels	Technical Feasibility study	John Gangloff, James Kast, Geoffrey Morrison, Jason Marcinkoski	Journal of Electrochemical Energy Conversion and Storage	USA	2016
8	Fuel cell layout for a heavy duty vehicle	Master Thesis	Due to the rising demand for zero-emission vehicles, Scania decided to analyse to economic potential of fuel cell and hydrogen in heavy-duty vehicles. To this end, the main objective of the study was to determine the optimal design and dimension of the	Technical Feasibility Study	Henrik Nguyen, Sophie Lindström	Scania, Mälardalen University Sweden	Europe (Sweden)	2017
9	Clean commercial transportation: Medium and heavy duty fuel cell electric	Research Paper	Recent progress in the research and development of hydrogen fuel cells has resulted in the commercialization of fuel cell electric vehicles for passengers, e.g. Toyota Mirai, Hyundai Tucson, etc. This study analyses whether fuel cells are also commercially	Technical feasibility study	Kast, Vijayagopal, John Gangloff, Jason Marcinkoski	Hydrogen Energy 42 (2017)	USA	2017
10	Technology assessment: Medium- and heavy-duty fuel cell electric vehicles	Research Paper	The Air Resources Board's (ARB) long-term objective is to transform the on- and off-road mobile source fleet into one utilizing zero- and near-zero-emission technologies to meet established air quality and climate change goals. The purpose of this study is to take a	Technical Feasibility study	Air Resources Board, State of California	Air Resources Board, State of California	USA (California)	2016
11	Comparative analysis of battery electric, hydrogen fuel cell and hybrid	Research Paper	Road transport today is responsible for a significant and growing share of global emissions of CO2. Moreover, it is almost entirely dependent on oil-derived fuels, thus highly vulnerable to possible oil price shocks and supply disruptions. Also, using oil-	Technical comparison	Offer, Howey, Contestabile, Clague, Brandon	Energy Policy 38 (2010)	n/a	2010
12	How to decarbonise heavy road transport?	Research Paper	Ambitious long-term greenhouse gas (GHG) emission targets require decarbonisation of the transport sector. Where plentiful supplies of low carbon electricity are available for road transport, passenger cars with internal combustion engines need to be replaced by	Technical comparison	Till Gnann, André Kühn, Patrick Plötz, Martin Wietschel	eceee Summer Study	Germany	2017
13	Market diffusion of alternative fuels and powertrains in heavy-duty	Research Paper	With about 22%, the transport sector is one of the largest global emitters of the greenhouse gas CO2. Long-distance road freight transport accounts for a large and rising share within this sector. For this reason, in February 2019, the European Union	Market (diffusion) modelling	Philipp Kluschke, Till Gnann, Patrick Plötz, Martin Wietschel	Energy Reports Vol. 5 (November 2019)	n/a	2019
14	British Columbia Hydrogen Study	Study	Deployment of hydrogen in British Columbia (BC) will be required for the Province to meet 2030 and 2050 decarbonization goals and emissions reduction commitments. End use energy demand in BC was 1 165 petajoules (PJ) in 2016, with 68% of demand met	Geographical study, with transport being one focus sector	Zen and the Art of Clean Energy Solutions	Zen and the Art of Clean	Canada	2019

Σ 60 publications reviewed

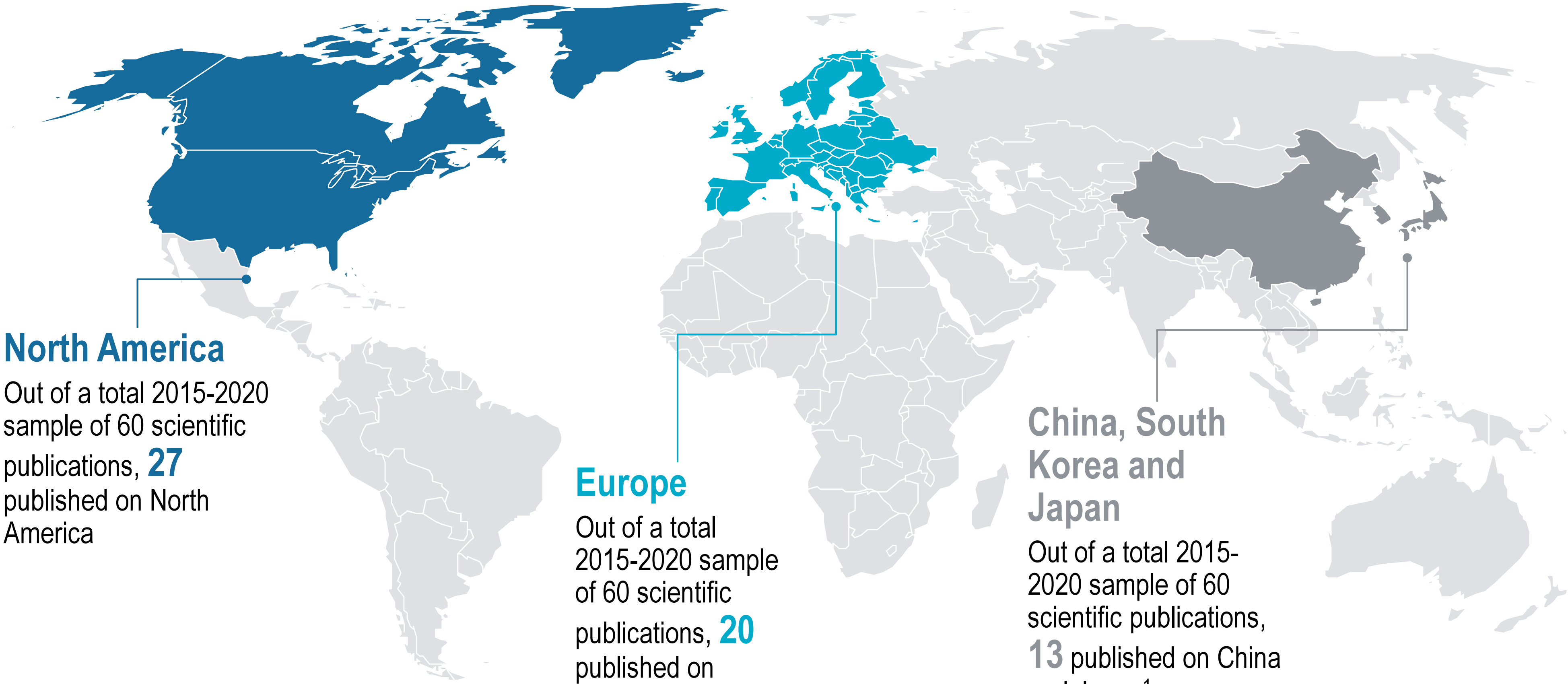
Number of scientific publications **has increased continuously** from 2015 through 2020

Scientific publications are mainly published in and with **focus** on **North America** and **Europe**

Source: Roland Berger

The review of literature shows that the focus of scientific publications is on developments in North America and Europe

Geography of hydrogen fuel cell HDT publications



North America

Out of a total 2015-2020 sample of 60 scientific publications, **27** published on North America

Europe

Out of a total 2015-2020 sample of 60 scientific publications, **20** published on Europe

China, South Korea and Japan

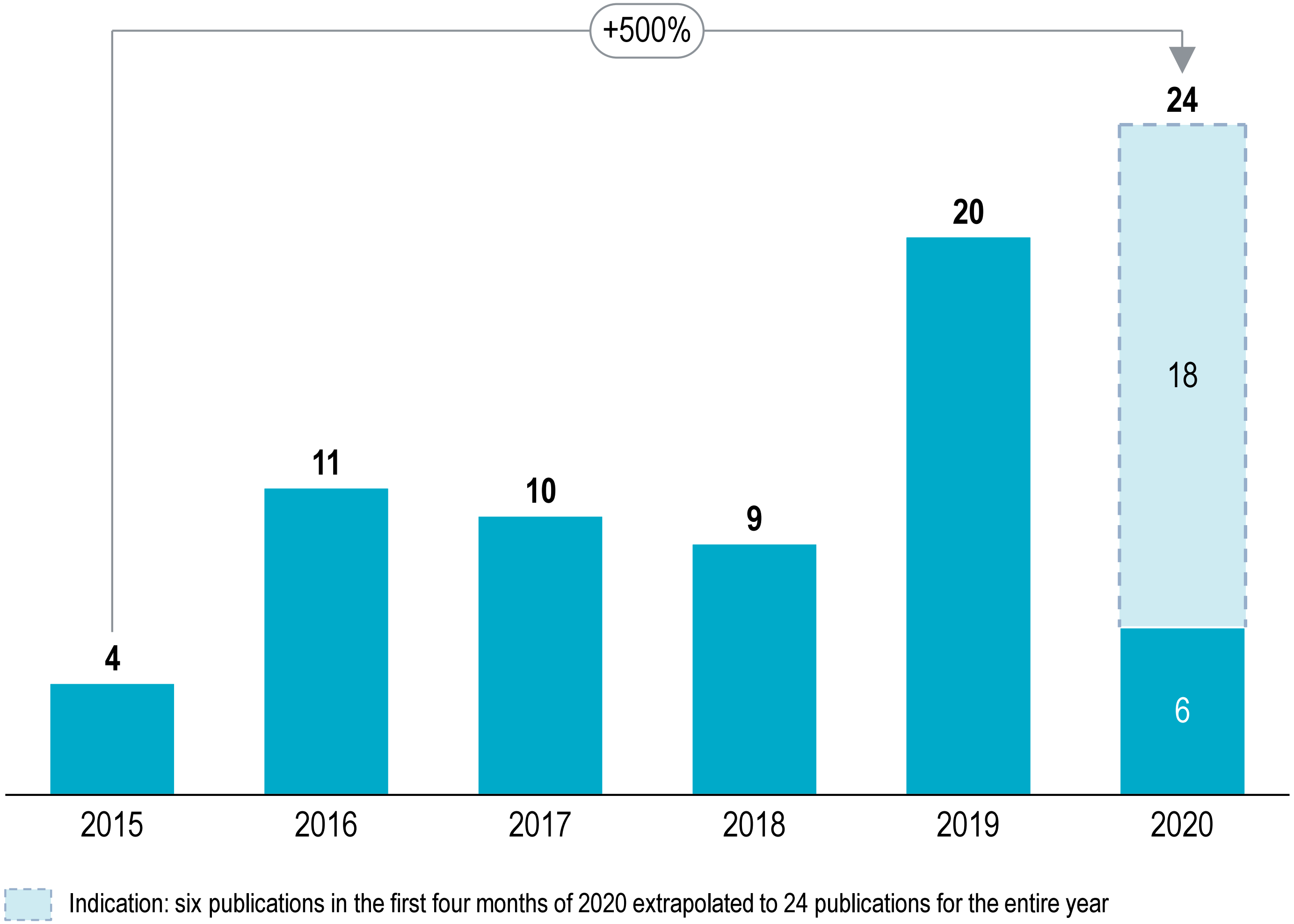
Out of a total 2015-2020 sample of 60 scientific publications, **13** published on China and Japan[1]

[1] No relevant scientific literature was identified for South Korea

Source: Desk research; Roland Berger

The strong increase in scientific publications illustrates the growing interest in FCH technology and applications for heavy-duty trucks

Hydrogen fuel cell HDT publications



- For the time span of 2015-2020 a **sample of 60 relevant scientific publications** was identified
- The review of this literature reveals a clear trend of **increasing interest in FCH technology and applications** for HD trucks
- The main areas of interest are **specific case studies** regarding FCH applications, **technical feasibility studies,** and studies of **technology comparison**
- International comparisons are drawn with **specific regard for national policy landscapes**

Source: Desk research; Roland Berger

We have identified 60 relevant scientific publications on FCH and related powertrain technologies for heavy-duty trucks

Reviewed HDT publications (1/4)

#	Publication title	Authors	Publication type	Geographical focus	Publication year
1	A model-based approach to battery selection for truck onboard fuel cell-based APU in an anti-idling application	Pregelj et al.	Research Paper	Europe	2015
2	Evolution of heavy-duty vehicle fuel efficiency policies in major markets	Kodjak et al.	Research Paper	Worldwide	2015
3	Development trend of solid oxide fuel cell and possibility of carbon dioxide emission reduction	Tohru Kato	Report	Japan	2015
4	Research progress of models for direct methanol fuel cell and system	Wang et al.	Research Paper	n/a	2015
5	Design space assessment of hydrogen storage onboard medium and heavy-duty fuel cell electric trucks	Gangloff et al.	Research Paper	USA	2016
6	Technology assessment: Medium- and heavy-duty fuel cell electric vehicles	Air Resources Board, Cal.	Research Paper	USA (California)	2016
7	Medium- & heavy-duty fuel cell electric truck action plan for California	California Fuel Cell Partnership	Policy paper	USA	2016
8	Air quality impacts of fuel cell electric hydrogen vehicles with high levels of renewable power generation	Mac Kinnon et al.	Research Paper	USA	2016
9	Demonstration of the first European SOFC APU on a heavy duty truck	Rechberger et al.	Research Paper	Sweden	2016
10	Driving an Industry: Medium and Heavy Duty Fuel Cell Electric Truck Component Sizing	Marcinkoski et al.	Research Paper	USA	2016
11	Estimating the fuel efficiency technology potential of heavy-duty trucks in major markets around the world	Delgado et al.	Research Paper	Worldwide	2016
12	A battery-fuel cell hybrid auxiliary power unit for trucks: Analysis of direct and indirect hybrid configurations	Samsun et al.	Research Paper	n/a	2016
13	Empirical membrane lifetime model for heavy duty fuel cell systems	Macauley et al.	Research Paper	Canada	2016
14	Research for solid oxide fuel cells for automotive applications	Ken Terayama	Research Paper	Japan	2016
15	Analysis of key technology patents for fuel cell vehicles	China Automotive Technology and Research Center Co., Ltd	Study	Worldwide	2016

Source: Desk research; Roland Berger

We have identified 60 relevant scientific publications on FCH and related powertrain technologies for heavy-duty trucks

Reviewed HDT publications (2/4)

#	Publication title	Authors	Publication type	Geographical focus	Publication year
16	Fuel cell trucks: critical development barriers, research needs and market potential [translated from German]	Gnann et al.	Research Paper	Germany	2017
17	Fuel cell layout for a heavy duty vehicle	Nguyen, H.; Lindström, S.	Master Thesis	Europe (Sweden)	2017
18	Clean commercial transportation: Medium and heavy duty fuel cell electric trucks	Kast et al.	Research Paper	USA	2017
19	How to decarbonise heavy road transport?	Gnann et al.	Research Paper	Germany	2017
20	The Future of Trucks - Implications for energy and the environment	Majoe et al.	Study	France	2017
21	Geospatial, Temporal and Economic Analysis of Alternative Fuel Infrastructure	Fan et al.	Research Paper	USA	2017
22	Analysis of fuel economy and GHG emission reduction measures from Heavy Duty Vehicles in other countries and of options for the EU	Ricardo Energy & Environment	Study	Europe	2017
23	Truck Choice Modeling: Understanding California's Transition to Zero-Emission Vehicle Trucks Taking into Account Truck Technologies, Costs, and Fleet Decision Behavior	Miller et al.	Report	USA	2017
24	Transitioning to zero-emission heavy-duty freight vehicles	Moultak et al.	White Paper	Europe, USA	2017
25	Fuel cell development status and trends	Liu et al.	Study	China, Japan, USA	2017
26	Alternative drive trains and fuels in road freight transportation – recommendations for action in Germany	Gnann et al.	Research Paper	Germany	2018
27[1]	Energy Consumption and Life Cycle Costs of Overhead Catenary Heavy-Duty Trucks for Long-Haul Transportation	Mareev, I.; Sauer, D.	Research Paper	Germany	2018
28[1]	Battery Dimensioning and Life Cycle Costs Analysis for a Heavy-Duty Truck Considering the Requirements of Long-Haul Transportation	Mareev et al.	Research Paper	Germany	2018
29	Vehicle Technologies and Fuel Cell Technologies	Argonne National Laboratory	Report	USA	2018
30	The Fuel Cell Industry Review 2018	E4tech	Report	USA	2018

1) Literature on relevant alternative powertrain technology with a link to FCH.

Source: Desk research; Roland Berger

We have identified 60 relevant scientific publications on FCH and related powertrain technologies for heavy-duty trucks

Reviewed HDT publications (3/4)

#	Publication title	Authors	Publication type	Geographical focus	Publication year
31[1]	Analysis of long haul battery electric trucks in EU	Earl et al.	Research Paper	Europe	2018
32	Comparative analysis of the cost of fuel cell and pure electric vehicle in different application scenarios	Jing Gao	Research Paper	China, Japan, USA	2018
33	Comparative analysis of fuel cell vehicle powertrain configurations	Yuan et al.	Research Paper	China, Japan	2018
34	Development of Shanghai Automotive Hydrogen Energy Industry and Demonstration of Fuel Cell Vehicles	Rong et al.	Study	China	2018
35	Comparing alternative heavy-duty drivetrains based on GHG emissions, ownership and abatement cost	Lajevardi et al.	Research Paper	Canada	2019
36	Estimating the infrastructure needs and costs for the launch of zero-emission trucks	Dale Hall, Nic Lutsey	Research Paper	USA	2019
37	Fuel cell electric vehicles: An option to decarbonize heavy-duty transport? Results from a Swiss case-study	Cabukoglu et al.	Research Paper	Switzerland	2019
38	Designing hydrogen fuel cell electric trucks in a diverse medium and heavy duty market	Kast et al.	Research Paper	n/a	2019
39	Market diffusion of alternative fuels and powertrains in heavy-duty vehicles: A literature review	Kluschke et al.	Research Paper	n/a	2019
40	British Columbia Hydrogen Study	Zen; Art of Clean Energy Solutions	Study	Canada	2019
41	Hydrogen Fuel Cell Vehicles; Current Status and Future Prospect	Manoharan et al.	Research Paper	USA	2019
42	Optimization of Component Sizing for a Fuel Cell-Powered Truck to Minimize Ownership Cost	Sim et al.	Research Paper	n/a	2019
43	Overview of hydrogen and fuel cells developments in China	Bente Verheul	Study	China	2019
44	Hydrogen Roadmap Europe - A sustainable pathway for the European energy transition	FCH 2 JU	Policy Roadmap	Europe	2019
45[1]	Fuel Switch to LNG in Heavy Truck Traffic	Research Paper	Smajla et al.	Europe	2019

1) Literature on relevant alternative powertrain technology with a link to FCH.

Source: Desk research; Roland Berger

We have identified 60 relevant scientific publications on FCH and related powertrain technologies for heavy-duty trucks

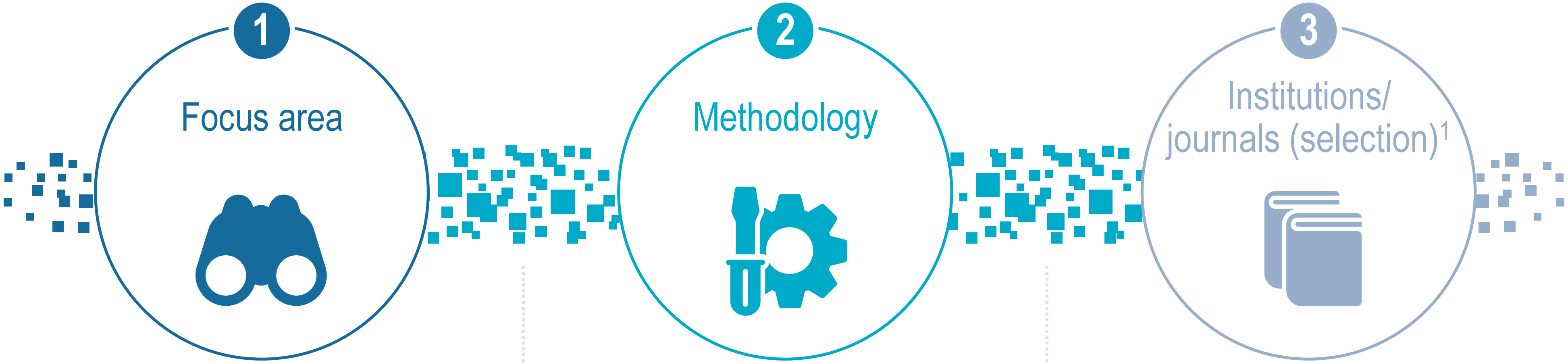
Reviewed HDT publications (4/4)

#	Publication title	Authors	Publication type	Geographical focus	Publication year
46	Evaluating national hydrogen refueling infrastructure requirement and economic competitiveness of fuel cell electric long-haul trucks	Nawei et al.	Research Paper	USA	2019
47	Techno-economic Study of Hydrogen as a Heavy-duty Truck Fuel	Janis Danebergs	Master Thesis	Norway	2019
48	Fuel cells for heavy duty trucks 2030+?	Karlström et al.	Report	Sweden	2019
49	China's vehicle fuel cell technology research and development progress	Song et al.	Study	China	2019
50	Research on Cooling System of Heavy Duty Truck with Hydraulic Retarder	Guo et al.	Research Paper	n/a	2019
51	Analysis of Technology Circuit and Related System of Fuel Cell Heavy Truck	Xiaochun et al.	Research Paper	n/a	2019
52	Technology Research Progress on the Fuel Cell of Commercial Vehicles	Yanan et al.	Research Paper	China	2019
53	Research on Fuel Cell Vehicle Policy System of China in Post-Subsidy Era	Jia et al.	Research Paper	China	2019
54	The hydrogen option for energy: a strategic advantage for Quebec	Roy, J.; Demers, M.	Study	Canada (Québec)	2019
55	An Examination of Heavy-duty Trucks Drivetrain Options to Reduce GHG Emissions in British Columbia	Lajevardi et al.	PhD Thesis	Canada	2020
56	The impact of disruptive powertrain technologies on energy consumption and carbon dioxide emissions from heavy-duty vehicles	Smallbone et al.	Research Paper	China, UK	2020
57	Technology, Sustainability, and Marketing of Battery Electric and Hydrogen Fuel Cell Medium-Duty and Heavy-Duty Trucks and Buses in 2020-2040	Burke, A.; Kumr Sinha, A.	Research Paper	USA	2020
58	Zero-Emission Medium- and Heavy-duty Truck Technology, Markets, and Policy Assessments for California	Burke, A.; Miller, M.	Research Paper	USA (California)	2020
59	Path to hydrogen competitiveness A cost perspective	Hydrogen Council	Report	n/a	2020
60	Fueling the Future of Mobility	Mace et al.	White Paper	Europe, China, USA	2020

Source: Desk research; Roland Berger

A qualitative comparison of the literature shows key focus areas, frequently used methodologies and active institutions and journals

Qualitative insights into literature review



1 Focus area

2 Methodology

3 Institutions/ journals (selection)[1]

FCH commercialisation

Life cycle costs

Infrastructure needs

Air quality

Fuel efficiency

Low emission powertrain configurations

Energy consumption

Policy landscapes

Development barriers

TCO modelling

Policy analysis

Scenario building

Market modelling

(National) Case study

Technical comparison

Optimisation modelling

Literature review

California Fuel Cell Partnership

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International Council on Clean Transportation

International Journal of Hydrogen Energy[2]

Energy Conversion and Management[2]

1) A selection of more frequent institutions and journals is shown here as the reviewed articles come from different sources 2) Peer-reviewed journal

Source: Desk research; Roland Berger

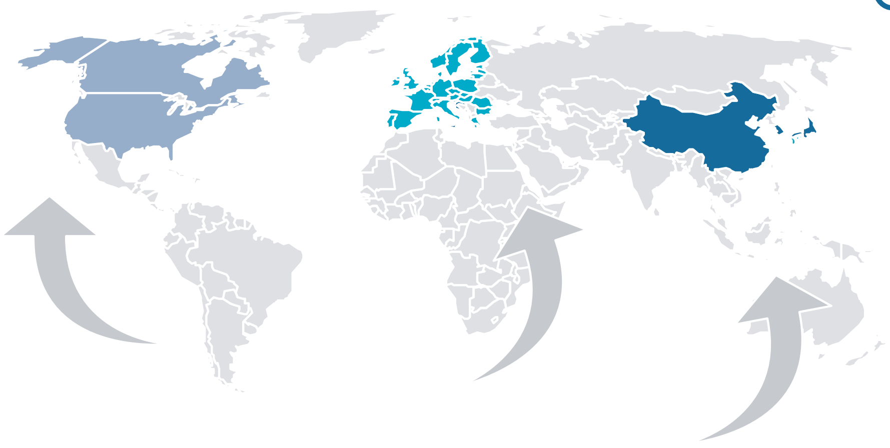
B.2 Trial and demonstration projects

A clear ambition for increased deployment of commercial fuel cell vehicles and better H_2 infrastructure can be observed

Status and publicly stated plans for FCEV and H_2 infrastructure

as of June 2020

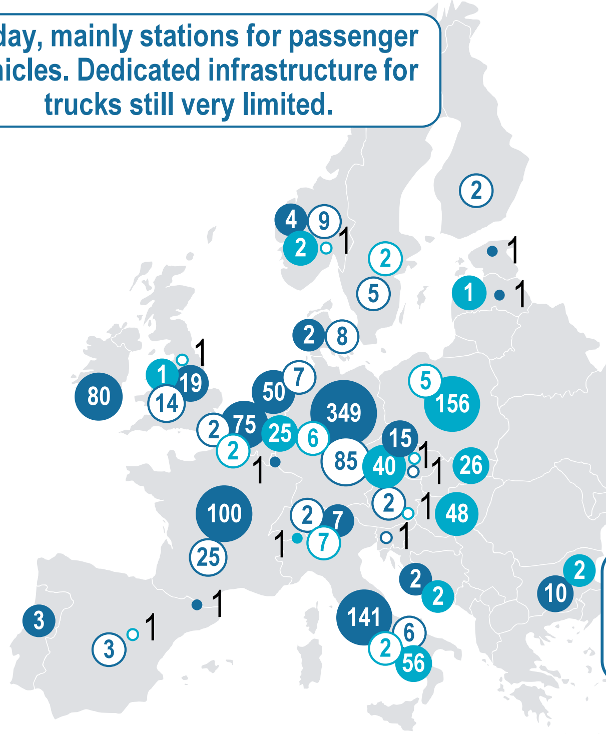
Deployment of FCH technology by continent



	North America	Europe	Asia
Status quo	9	14	2
Plans	>800	>1,650	n/a
Vision for FCEV[1]	~500,000	~45,000	~80,000

Hydrogen refuelling stations (HRS) in Europe

Today, mainly stations for passenger vehicles. Dedicated infrastructure for trucks still very limited.



● X	Number of stations planned until 2025 for passenger cars
○ X	Number of stations operating 2020 for passenger cars
● X	Number of stations planned for fuel cell trucks and buses
○ X	Number of stations operating 2020 for fuel cell trucks and buses

~1,000 stations planned until 2030

The overall development of HRS in Europe shows ambition for the uptake of refuelling infrastructure suitable for trucks

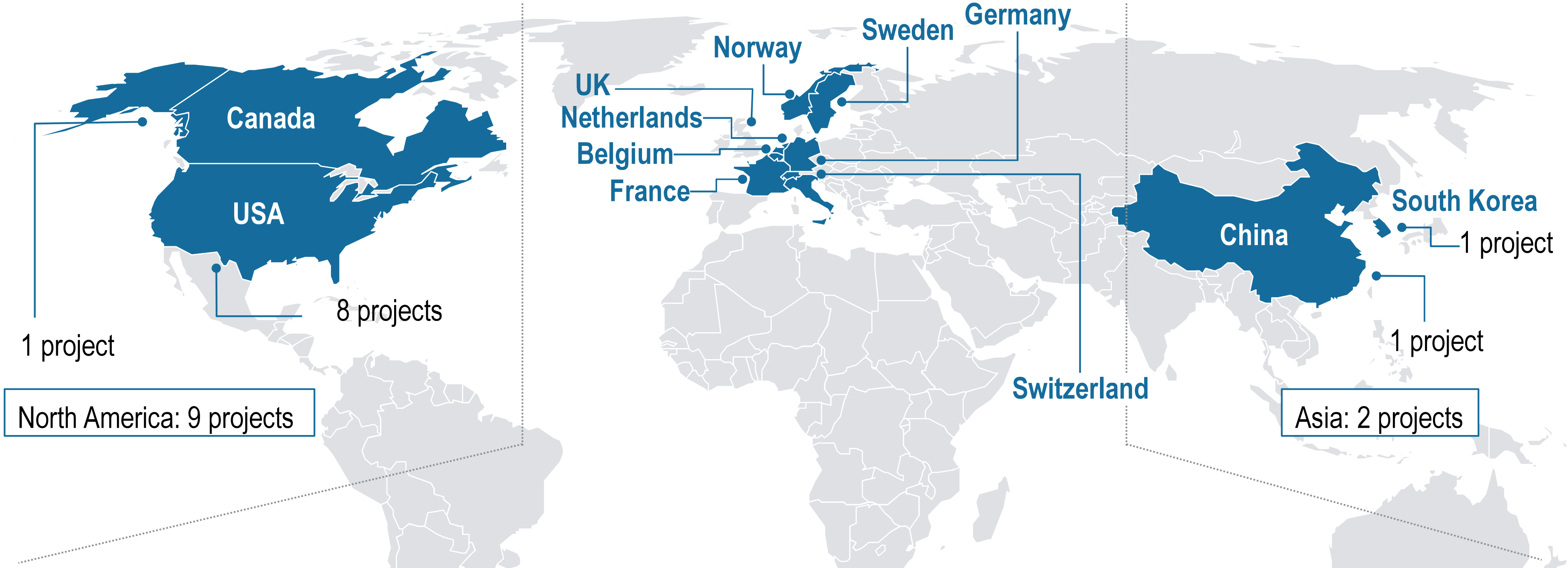
heavy-duty trucks (>15 t) [#]

1) Fuel cell electric vehicles; Sum of governments' and companies' publicly stated ambition worldwide (Mid-to-long-term 2025+) incl. all types of trucks (light-, medium-, heavy-duty) and buses as plans and visions often do not differentiate the specific types of commercial vehicles

Source: Public reports and databases, Desk Research, Roland Berger

Increasingly, Europe shows a specific focus on FCH heavy-duty trucks trial and demonstration projects, levelling up with US efforts

Geography of key fuel cell hydrogen HDT trial and demonstration projects[1]



Europe: Overall, 12 relevant projects have been identified – many projects are conducted cross-nationally[2]

Belgium	France	Germany	Netherlands	Norway	Sweden	Switzerland	UK
5 projects (5)	5 projects (3)	5 projects (3)	6 projects (5)	1 project	1 project	4 projects (1)	1 project (1)

[1] Finalised, ongoing and planned HDT trial and demonstration projects since 2015 until today [2] The number in ( ) signals the number of cross-national projects

Source: Desk research; Roland Berger

European projects often include multi-national stakeholders with a strong participation of wholesale and retail companies…

Selected fuel cell hydrogen HDT trial and demonstration projects (1/3)

Project	Country	Duration	Operator / logistics user	Application	OEM/ System integrator	FC provider
1 H2-Share	🇧🇪 🇫🇷 🇩🇪 🇳🇱	2017 – 2021	BREYTNER, Colruyt Group	🚚	VDL (DAF)	Ballard
2 H2Haul	🇧🇪 🇫🇷 🇩🇪 🇨🇭	2019 – 2024	BMW Group logistics, Coop, Colruyt Group, Carrefour (Chabas, Perrenot), Air Liquide	Rigid and tractor	IVECO, FPT Industrial, VDL	ElringKlinger, PowerCell
3 Waterstofregio 2.0	🇧🇪	2016 – n/a	Colruyt Group	🚛	VDL (DAF)	Ballard
4 ASKO distribution logistics trucks	🇳🇴	2017 - 2024	ASKO	🚚	Scania / Hydrogenics	Hydrogenics
5 Hyundai Hydrogen Mobility[1] Business venture	🇨🇭	Start in 2020	Hyundai Hydrogen Mobility	🚚	Hyundai	Hyundai

🚚 Rigid 4x2 truck 🚛 Tractor 4x2 truck 🚚 Rigid 6x4 truck 🚛 Tractor 6x4 truck

[1] The Hyundai Hydrogen Mobility project refers to a commercial roll-out of trucks. It is not a trial and demonstration in a strict sense.

Source: Desk research; Roland Berger

Note: Information in the trial and demonstration dossier relies on company information and publicly available sources. Some information is missing as indicated.

…while North American projects build on broad public support from regional governments, e.g. FCH frontrunner California

Selected fuel cell hydrogen HDT trial and demonstration projects (2/3)

Project	Country	Duration	Operator / logistics user	Application	System integrator	FC provider
6 Esoro hydrogen truck for Coop	🇨🇭	2017 – n/a	Coop	🚚	Esoro (MAN)	SwissHydrogen, PowerCell
7 Alberta Zero-Emissions Truck Electrification Collaboration (AZETEC)	🇨🇦	2019 – 2022	Bison Transport, Trimac Transportation	🚛	Freightliner / Daimler	Ballard
8 Zero and Near-Zero Emissions Freight Facilities Project (ZANZEFF)	🇺🇸	2019 – n/a	Toyota Logistics Services, UPS, TTSI[1], Southern Counties Express	🚛	Toyota, Kenworth	Toyota
9 GTI Fast-Track Fuel Cell Truck	🇺🇸	2018 – 2020	TTSI, Daylight Transport LLC	🚛	Transpower (Navistar), Peterbilt	Hydrogenics, Loop Energy
10 Anheuser Busch Zero-Emission Beer Delivery	🇺🇸	Start in 2018	Anheuser Busch	🚛	Nikola	Bosch

🚚 Rigid 4x2 truck 🚛 Tractor 4x2 truck 🚚 Rigid 6x4 truck 🚛 Tractor 6x4 truck

[1] Total Transportation Services Inc.

Source: Desk research; Roland Berger

In Europe there are also several ongoing demonstration projects in the area of FCH waste collection and garbage trucks

Selected fuel cell hydrogen HDT trial and demonstration projects (3/3)

Project	Country	Duration	Operator / logistics user	Application	System integrator	FC provider
11 Refuse Vehicle Innovation and Validation in Europe (REVIVE)	🇳🇱 🇮🇹 🇧🇪 🇸🇪	2018 – 2021	SUEZ, SEAB SPA, ASM Merano Stadtwerke, Renova	n/a	DAF	Proton Motor Fuel Cell
12 Hydrogen Waste Collection Vehicles in North West Europe (HECTOR)	🇧🇪 🇫🇷 🇳🇱 🇬🇧 🇩🇪	2019 – 2023	Aberdeen, Groningen, Touraine Vallee de l'Indre	n/a	n/a	n/a

Additional information on FCH applications for waste collection and garbage trucks

> FCH technology is particularly suited for this application as FCH technology can also well cater for the additional power needs of garbage trucks (e.g. hydraulics for lifting and compressing garbage)
> Due to back-to-base schedule, operation of fleet of vehicles is possible as trucks can be fuelled by one HRS
> Year-round (daily) operations results in high utilisation of both trucks and infrastructure
> Potential noise reduction during start-stop operations and idleing

Rigid 4x2 truck
Tractor 4x2 truck
Rigid 6x4 truck
Tractor 6x4 truck

Source: Desk research; Roland Berger

H2-Share is a cooperation between 16 partners that aim to create a 'transnational living lab' across four European countries

Deep-dive: H2-Share (1/2)

1

General information

Image: H2-Share

Country / countries	Belgium, France, Germany, Netherlands
Start / end year	2017 - 2021
System integrator	VDL (DAF)
FC provider	Ballard
Truck operator / logistics user	BREYTNER, Colruyt Group
Other partners	AutomotiveNL, BREYTNER, Colruyt Group, Cure, DPDHL, E-mobil, Hydrogen Europe, Dutch ministry of Infrastructure, TNO, VDL ETS, WaterstofNet, Wystrach; City of Helmond; VIL

Project description

The demonstration project tests hydrogen solutions for heavy-duty transport aimed at the reduction of emissions in North West Europe. It deploys a heavy-duty (27 t) truck with fuel cell electric drive for zero emission last mile delivery.

Wystrach has developed a mobile hydrogen refuelling station to allow for refuelling operation in six different regions: Rotterdam region (NL), Einhoven (NL), Breda (NL), Stuttgart (GER), Brussels region (BE), Rochefort-sur-Nenon (FR).

The demonstration project is planned to take place in each region for the duration of three months.

Project budget / funding

The project is supported with EUR 1.69 million via the Interreg North-West Europe programme.

Source: H2-Share; WaterstofNet; Desk research; Roland Berger

H2-Share is a cooperation between 16 partners that aim to create a 'transnational living lab' across four European countries

Deep-dive: H2-Share (2/2)

1

Detailed truck information

Number of trucks	[#]	1
Truck type		Rigid 6x2
Cabin type		Day cabin
GVWR / GCWR[1]	[tonnes]	27 / n/a
Range per year	[km]	n/a
Powertrain power	[hp]	n/a
Battery capacity	[kWh]	82
Tank location		Back of cabin
H_2 tank pressure	[bar]	350
Tank size	[kg]	30
Range per tank	[km]	400
refuelling speed	[kg/min]	n/a
Fuel cell power	[kW]	60

Detailed refuelling infrastructure information

Type		Mobile infrastructure
Ownership		Private ownership
Supply		Trailer (gaseous)
H_2 source		n/a
Required space	[sqm]	141
Storage type		Mobile (gaseous)
Storage size	[kg]	n/a
H_2 tank pressure	[bar]	350
Fuelling speed	[min]	15
Capacity	[kg/day]	120

Additional information

- Demonstration started in April 2020
- The Wystrach mobile hydrogen refuelling station consists of two units / containers which function as hydrogen storage (tank container) and refuelling station (refueller container)
- While the tank container has to be transported to be refilled, the refueller container can fill up to three trucks / buses coming from an internal storage
- The refuelling station is 'stand alone', transportable and controlled via a smart system with no personnel necessary

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1) GVWR = Gross vehicle weight rating, GCWR = Gross combined weight rating

Source: H2-Share; WaterstofNet; Desk research; Roland Berger

H2Haul is an EU-funded cross-national project that sets out to deploy 16 zero-emission fuel cell trucks over the course of 5 years

Deep-dive: H2Haul (1/2)

2

General information


Image: H2Haul

Country / countries	Belgium, France, Germany, Switzerland
Start / end year	2019 - 2024
System integrator	IVECO, FPT Industrial, VDL
FC provider	ElringKlinger, Bosch, PowerCell
Truck operator / logistics user	BMW Group logistics, Coop, Colruyt Group, Carrefour (Chabas and Perrenot), Air Liquide
Other partners	Air Liquide, Eoly, H2 Energy, Hydrogen Europe, IRU Projects, thinkstep, WaterstofNet, Element Energy Limited

Project description

H2Haul (Hydrogen Fuel Cell Trucks for Heavy Duty Zero Emissions Logistics) tests 16 heavy duty hydrogen fuel cell trucks in commercial operations in Europe (Belgium, France, Germany and Switzerland). The project began in 2019 and will run for five years.

For the project, two European manufacturers design, build, and test three types of FCH HD trucks, incl. rigid and articulated vehicles up to 44 tonnes. The fuel cell systems will be produced in Europe by two different suppliers.

Project budget / funding

The project is supported with EUR 12 million by the Fuel Cell and Hydrogen Second Joint Undertaking (FCH 2 JU).

Source: H2Haul, WaterstofNet; Desk research; Roland Berger

H2Haul is an EU-funded cross-national project that sets out to deploy 16 zero-emission fuel cell trucks over the course of 5 years

Deep-dive: H2Haul (2/2)

2

Detailed truck information

Number of trucks	[#]	16
Truck type		Rigid / tractor[2]
Cabin type		Day cabin
GVWR / GCWR[1]	[tonnes]	n/a / 26 - 44[2]
Range per year	[km]	40,000-240,000[2]
Powertrain power	[hp]	n/a
Battery capacity	[kWh]	n/a
Tank location		n/a
H_2 tank pressure	[bar]	n/a
Tank size	[kg]	n/a
Range per tank	[km]	n/a
refuelling speed	[kg/min]	n/a
Fuel cell power	[kW]	n/a

Detailed refuelling infrastructure information

Type		Fixed infrastructure
Ownership		Private
Supply		Gaseous
H_2 source		*see add. information*
Required space	[sqm]	n/a
Storage type		Fixed (gaseous)
Storage size	[kg]	n/a
H_2 tank pressure	[bar]	700(3)
Fuelling speed	[kg/min]	n/a
Capacity	[kg/day]	120

Additional information

- Currently, the project is in the design phase for the different truck types
- Hydrogen refuelling stations will be installed to provide hydrogen supply to the trucks
- H_2 providers are DATS24 (Belgium), Air Liquide (France), and H2 Energy (Switzerland)
- In Belgium and Switzerland, the supply with Green H_2 will be provided

1) GVWR = Gross vehicle weight rating, GCWR = Gross combined weight rating 2) Depending on the specific truck type (3 truck types planned) 3) Air Liquide refuelling station

Source: H2Haul, WaterstofNet; Desk research; Roland Berger

A 44 ton heavy-duty truck is developed and demonstrated by the initiative Hydrogen region 2.0 in the Flanders region, Belgium

Deep-dive: Waterstofregio 2.0 (1/2)

3

General information

Country / countries	Belgium
Start / end year	2016 - n/a
System integrator	VDL (DAF)
FC provider	Ballard
Truck operator / logistics user	Colruyt Group
Other partners	WaterstofNet

Project description

Hydrogen region 2.0 is a project-based collaboration between Flanders and the Netherlands. Among the ongoing and planned projects, the partners develop and demonstrate the first large (44 ton) hydrogen truck by VDL.

The collaboration also focuses on improving and showing various applications and the development of several filling stations. It is coordinated by WaterstofNet and supported by companies / organisations in the field of hydrogen infrastructure and zero-emission applications.

Project budget / funding

The EUR 13.9 million project is supported with EUR 5.9 million by the Interreg Vlaanderen-Nederland programme.

Source: WaterstofNet; Desk research; Roland Berger

A 44 ton heavy-duty truck is developed and demonstrated by the initiative Hydrogen region 2.0 in the Flanders region, Belgium

Deep-dive: Waterstofregio 2.0 (2/2)

3

Detailed truck information

Number of trucks	[#]	1
Truck type		Tractor 4x2
Cabin type		Sleeper cabin
GVWR / GCWR[1]	[tonnes]	n/a / 44
Range per year	[km]	n/a
Powertrain power	[hp]	n/a
Battery capacity	[kWh]	85
Tank location		n/a
H_2 tank pressure	[bar]	350
Tank size	[kg]	30
Range per tank	[km]	350
refuelling speed	[kg/min]	n/a
Fuel cell power	[kW]	60

Detailed refuelling infrastructure information

Type		Fixed infrastructure
Ownership		Private
Supply		Gaseous
H_2 source		n/a
Required space	[sqm]	n/a
Storage type		Fixed (gaseous)
Storage size	[kg]	n/a
H_2 tank pressure	[bar]	350
Fuelling speed	[kg/min]	n/a
Capacity	[kg/day]	n/a

Additional information

> The truck and trailer recently passed the homologation phase, the operational demonstration is being planned

> H_2 supply is organised via the Colruyt Group refuelling station in Belgium

---

1) GVWR = Gross vehicle weight rating, GCWR = Gross combined weight rating

Source: WaterstofNet; Desk research; Roland Berger

Norwegian retailer ASKO deploys 4 FCH heavy-duty trucks supported by industry partners and government in a first pilot

Deep-dive: ASKO distribution logistics trucks (1/2)

4

General information

Image: ASKO

Country / countries	Norway
Start / end year	2017 - 2024
System integrator	Scania, Hydrogenics
FC provider	Hydrogenics
Truck operator / logistics user	ASKO
Other partners	Hexagon, NEL Hydrogen

Project description

The ASKO demonstration project includes four fuel cell powered electric Scania trucks for Norway's largest grocery wholesaler. The 27 tonnes Scania trucks are powered by four fuel cell systems and four hydrogen tank systems from Hydrogenics. They are deployed for ASKO's distribution network in the Trondheim area.

The demonstration project is focused on resource efficiency, low emissions and sustainable development for the wholesaler.

Project budget / funding

The project is supported with NOK 19.6 million (EUR ~1,8 million) by the Norwegian clean energy agency Enova SF.

Source: ASKO; Cummins; Scania; Desk research; Roland Berger

Norwegian retailer ASKO deploys 4 FCH heavy-duty trucks supported by industry partners and government in a first pilot

Deep-dive: ASKO distribution logistics trucks (2/2)

4

Detailed truck information

Number of trucks	[#]	4
Truck type		Rigid 6x2
Cabin type		Day cabin
GVWR / GCWR[1]	[tonnes]	27 / n/a
Range per year	[km]	45,000-60,000
Powertrain power	[hp]	290
Battery capacity	[kWh]	56
Tank location		Back of cabin
H_2 tank pressure	[bar]	350
Tank size	[kg]	33
Range per tank	[km]	400 - 500
refuelling speed	[kg/min]	n/a
Fuel cell power	[kW]	90

Detailed refuelling infrastructure information

Type		Fixed infrastructure
Ownership		Private
Supply		Gaseous
H_2 source		n/a
Required space	[sqm]	n/a
Storage type		Fixed (gaseous)
Storage size	[kg]	n/a
H_2 tank pressure	[bar]	350
Fuelling speed	[kg/min]	n/a
Capacity	[kg/day]	300

Additional information

- The demonstration started in 2019
- The H2 supply is provided by NEL Hydrogen using electrolysers with electricity from photovoltaics
- The refuelling station also operates further FCH applications, e.g. forklifts
- ASKO takes on a very proactive role being involved in the supply chain and material selection process

1) GVWR = Gross vehicle weight rating, GCWR = Gross combined weight rating

Source: ASKO; Cummins; Scania; Desk research; Roland Berger

An industry partnership between Hyundai Motor Company and H2Energy will provide 1,600 FCH trucks for a pay-per-use model

Deep-dive: Hyundai Hydrogen Mobility (1/2)

Business venture 5

General information


Image: Hyundai Motor Europe

Country / countries	Switzerland
Start year	2020
System integrator	Hyundai
FC provider	Hyundai
Truck operator / logistics user	Swiss customers
Other partners	H2Energy, Association pro H2 Mobility Switzerland, Hydrospider, Alpiq, Linde

Project description

Hyundai Hydrogen Mobility, a partnership between Hyundai Motor Company and H2Energy, are planning to bring 1,600 Xcient fuel cell trucks and the respective H_2 infrastructure to the Swiss market.

The first seven trucks have been delivered to the clients in October 2020. 50 trucks are to be delivered until the end of 2020.

The trucks are offered to companies in the form of a pay-per-use model. A flat rate per kilometre will be charged based on the driving profile, the usage of the vehicle, and the annual mileage. The fee per km includes the complete operation of the truck, including hydrogen refuelling.

Project budget / funding

The fuel cell trucks are exempt from the Swiss heavy vehicle environmental duties (LSVA).

Source: Hyundai; Hyundai Hydrogen Mobility; Desk research; Roland Berger

An industry partnership between Hyundai Motor Company and H2Energy will provide 1,600 FCH trucks for a pay-per-use model

Deep-dive: Hyundai Hydrogen Mobility (2/2)

5

Detailed truck information

Number of trucks	[#]	1,600
Truck type		Rigid 4x2
Cabin type		Day cabin
GVWR / GCWR[1]	[tonnes]	19 / 36
Range per year	[km]	n/a
Powertrain power	[hp]	471
Battery capacity	[kWh]	73.2
Tank location		Back of cabin
H_2 tank pressure	[bar]	350
Tank size	[kg]	32
Range per tank	[km]	400
refuelling speed	[min]	8-20
Fuel cell power	[kW]	190

Detailed refuelling infrastructure information

Type		Fixed infrastructure
Ownership		Private
Supply		Gaseous
H_2 source		Green H_2
Required space	[sqm]	n/a
Storage type		Fixed (gaseous)
Storage size	[kg]	n/a
H_2 tank pressure	[bar]	350
Fuelling speed	[kg/min]	n/a
Capacity	[kg/day]	n/a

Additional information

> The fuel cell trucks will either have a dry or refrigerated body

> H_2 supply will be provided by Hydrospider, a Joint Venture of Alpiq, H2 Energy and Linde

1) GVWR = Gross vehicle weight rating, GCWR = Gross combined weight rating

Source: Hyundai Hydrogen Mobility; Desk research; Roland Berger

Esoro developed a 34-tonnes logistics truck to match Coop's fleet specifications and logistics management requirements

Deep-dive: Esoro hydrogen truck for Coop (1/2)

6

General information


Image: Coop

Country / countries	Switzerland
Start year	2016
System integrator	ESORO (MAN)
FC provider	SwissHydrogen, PowerCell
Truck operator / logistics user	Coop
Other partners	H2Energy, Emoss

Project description

Specifically for the purpose of matching regular Coop logistics, ESORO developed a fuel cell truck in the 34-tonnes category. The truck has the necessary load capacity to be fully integrated into the Coop logistics management process.

The deployed truck has a refrigerated body and a refrigerated trailer. Additionally, cooling systems and hydraulic lifts are included.

Project budget / funding

n/a

Source: ESORO; Coop; H2 Energy; WaterstofNet; Desk research; Roland Berger

Esoro developed a 34-tonnes logistics truck to match Coop's fleet specifications and logistics management requirements

Deep-dive: Esoro hydrogen truck for Coop (2/2)

6

Detailed truck information

Number of trucks	[#]	1
Truck type		Rigid 4x2
Cabin type		Day cabin
GVWR / GCWR[1]	[tonnes]	18 / 34
Range per year	[km]	n/a
Powertrain power	[hp]	n/a
Battery capacity	[kWh]	120
Tank location		Back of cabin
H_2 tank pressure	[bar]	350
Tank size	[kg]	34,5
Range per tank	[km]	375-400
refuelling speed	[kg/min]	3-4
Fuel cell power	[kW]	100

Detailed refuelling infrastructure information

Type		n/a
Ownership		Private
Supply		Gaseous
H_2 source		n/a
Required space	[sqm]	n/a
Storage type		Gaseous
Storage size	[kg]	n/a
H_2 tank pressure	[bar]	350
Fuelling speed	[kg/min]	n/a
Capacity	[kg/day]	n/a

Additional information

> The rigid truck is combined with a trailer

> The demonstration project is currently not in operation

> The hydrogen used by the hydrogen refuelling station linked to the trucks is being produced by H2 Energy through a PEM electrolyser which sources the electricity from a run of the river plant in Aarau

---

1) GVWR = Gross vehicle weight rating, GCWR = Gross combined weight rating

Source: ESORO; Coop; H2 Energy; WaterstofNet; Desk research; Roland Berger

The AZETEC logistics industry project in Canada is a joint collaboration set out to test two FCH trucks on a fixed route

Deep-dive: Alberta Zero-Emissions Truck Electrification Collaboration (AZETEC) (1/2) [7]

General information

picture rights permission missing

Country / countries	Canada
Start / end year	2019 - 2022
System integrator	Freightliner / Daimler
FC provider	Ballard
Truck operator / logistics user	Bison Transport (logistics), Trimac Transp. (logistics)
Other partners	Zen Clean Energy Solutions, Dana Inc., Nordresa, Alberta Motor Transportation Ass.

Project description

AZETEC is an industry led project to design and manufacture two heavy-duty FCH hybrid trucks that move freight between Edmonton and Calgary from 2021 to mid 2022. By the end of the project the trucks will have travelled more than 500,000 km and carried about 20 million ton-km of freight. The refuelling infrastructure for the project will be generated by Praxair Services, Canada Inc. leveraging existing Oil & Gas infrastructure and transported under a 'drop and swap' model that will move fuel between the Praxair facility and a centralized depot in Edmonton.

Project budget / funding

The CAD 15 million project is supported with CAD 7.3 million by Emissions Reduction Alberta (ERA) through the BEST Challenge programme.

Source: Ballard; Desk research; Roland Berger

The AZETEC logistics industry project in Canada is a joint collaboration set out to test two FCH trucks on a fixed route

Deep-dive: Alberta Zero-Emissions Truck Electrification Collaboration (AZETEC) (2/2) 7

Detailed truck information

Number of trucks	[#]	2
Truck type		Tractor 6x4
Cabin type		Day cabin
GVWR / GCWR[1]	[tonnes]	24 / 63.5
Range per year	[km]	n/a
Powertrain power	[hp]	n/a
Battery capacity	[kWh]	n/a
Tank location		n/a
H_2 tank pressure	[bar]	350
Tank size	[kg]	100
Range per tank	[km]	700
refuelling speed	[kg/min]	n/a
Fuel cell power	[kW]	210

Detailed refuelling infrastructure information

Type		Fixed infrastructure
Ownership		Private
Supply		Pipeline (gaseous)
H_2 source		n/a
Required space	[sqm]	n/a
Storage type		Fixed (gaseous)
Storage size	[kg]	n/a
H_2 tank pressure	[bar]	350
Fuelling speed	[kg/min]	n/a
Capacity	[kg/day]	n/a

Additional information

> Expected demonstration from July 2021 until December 2022

> It is estimated that about 50 trucks, using about five tonnes of hydrogen a day, would be required to make fuel distribution cost-efficient

---

1) GVWR = Gross vehicle weight rating, GCWR = Gross combined weight rating

Source: Ballard; Desk research; Roland Berger

The Californian ZANZEFF project sets out to deploy 10 FCH Class 8 trucks in two port freight facilities and expand the H_2 fuelling network

Deep-dive: Zero and Near-Zero Emissions Freight Facilities Project (ZANZEFF) (1/2) 8

General information

picture rights permission missing

Country / countries	USA, California
Start year	2019
System integrator	Toyota, Kenworth
FC provider	Toyota
Truck operator / logistics user	Toyota Logistics Services, UPS, Total Transportation Services Inc., Southern Counties Express
Other partners	Port of Los Angeles, Shell, Air Liquide

Project description

After two previous demonstration projects, the third ZANZEFF fuel cell electric truck demonstration project deploys 10 FCH Class 8 trucks to move cargo from the Ports of Los Angeles and Long Beach throughout the Los Angeles basin. The trucks will offer an estimated range of more than 450 km per fill.

In addition, two new large capacity heavy-duty hydrogen fuelling stations will be developed by Shell. These new stations will expand the existing network to form an integrated, five-station heavy-duty hydrogen fuelling network for the area.

Project budget / funding

The USD 82.5 million ZANZEFF project is supported with USD 41.1 million by the California Air Resources Board (CARB).

Source: Toyota, Desk research; Roland Berger

The Californian ZANZEFF project sets out to deploy 10 FCH Class 8 trucks in two port freight facilities and expand the H_2 fuelling network

Deep-dive: Zero and Near-Zero Emissions Freight Facilities Project (ZANZEFF) (2/2) 8

Detailed truck information

Number of trucks	[#]	10
Truck type		Tractor 6x4
Cabin type		Day cabin
GVWR / GCWR[1]	[tonnes]	n/a
Range per year	[km]	n/a
Powertrain power	[hp]	670
Battery capacity	[kWh]	12
Tank location		Back of cabin
H_2 tank pressure	[bar]	700
Tank size	[kg]	60
Range per tank	[km]	~ 480
refuelling speed	[min]	~3
Fuel cell power	[kW]	n/a

Detailed refuelling infrastructure information

Type		Fixed infrastructure
Ownership		Private
Supply		Gaseous
H_2 source		n/a
Required space	[sqm]	n/a
Storage type		Fixed (gaseous)
Storage size	[kg]	n/a
H_2 tank pressure	[bar]	700
Fuelling speed	[min]	20-25
Capacity	[kg/day]	1,500

Additional information

- The H_2 infrastructure will be provided by Shell, Toyota Logistics Services, and Gardena R&D facilities
- The new large-capacity H_2 refuelling stations in Wilmington and Ontario (California) are planned to be completed in spring 2020

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1) GVWR = Gross vehicle weight rating, GCWR = Gross combined weight rating

Source: Toyota, Desk research; Roland Berger

The GTI-led Fast-Track Fuel Cell Truck project in LA and San Diego operates five Class 8 trucks, focusing on impacts on local air quality

Deep-dive: GTI Fast-Track Fuel Cell Truck (1/2)

9

General information


Image: GTI

Country / countries	USA, California
Start / end year	2018 - 2020
System integrator	Transpower (Navistar), Peterbilt
FC provider	Hydrogenics, Loop Energy
Truck operator / logistics user	Total Transportation Services Inc (TTSI), Daylight Transport LLC
Other partners	GTI, TransPower, Frontier Energy, Center for Sustainable Energy, OneH2

Project description

The GTI-led, multi-partner collaboration demonstration project operates five fuel cell–electric hybrid Class 8 trucks in the Port of Los Angeles and the San Diego region. Existing infrastructure is used for charging and mobile H_2 fuelling infrastructure is provided.

Of the five trucks, three are Navistar chassis with Hydrogenics fuel cells systems and two are Peterbilt gliders with Loop Energy fuel cells systems.

An important project focus lies on the gathering of performance data and analysis from real-world conditions with regard to local air quality.

Project budget / funding

The USD 6.78 million project is supported with USD 5.1 million by California Air Resources Board (CARB).

Source: Hydrogenics; California Climate Investments, Desk research; Roland Berger

The GTI-led Fast-Track Fuel Cell Truck project in LA and San Diego operates five Class 8 trucks, focusing on impacts on local air quality

Deep-dive: GTI Fast-Track Fuel Cell Truck (2/2)

9

Detailed truck information

Number of trucks	[#]	5
Truck type		Tractor 6x4
Cabin type		Day cabin
GVWR / GCWR[1]	[tonnes]	n/a
Range per year	[km]	n/a
Powertrain power	[hp]	n/a
Battery capacity	[kWh]	n/a
Tank location		n/a
H_2 tank pressure	[bar]	350
Tank size	[kg]	19
Range per tank	[km]	n/a
refuelling speed	[kg/min]	n/a
Fuel cell power	[kW]	60

Detailed refuelling infrastructure information

Type		Mobile infrastructure
Ownership		PPP
Supply		Gaseous
H_2 source		n/a
Required space	[sqm]	n/a
Storage type		Mobile (gaseous)
Storage size	[kg]	n/a
H_2 tank pressure	[bar]	350
Fuelling speed	[kg/min]	n/a
Capacity	[kg/day]	n/a

Additional information

> The H_2 infrastructure is in part provided by OneH2; existing charging infrastructure is also used

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1) GVWR = Gross vehicle weight rating, GCWR = Gross combined weight rating

Source: Hydrogenics; California Climate Investments, Desk research; Roland Berger

US brewer Anheuser Busch plans to integrate 800 Nikola hydrogen-electric semi-trucks from 2020 on and convert delivery fleet by 2025

Deep-dive: Anheuser Busch Zero-Emission Beer Delivery (1/2)

10

General information

picture rights permission missing

Country / countries	USA
Start year	2018
System integrator	Nikola
FC provider	Bosch
Truck operator / logistics user	Anheuser Busch
Other partners	NEL Hydrogen

Project description

Anheuser-Busch, a large US brewery company, ordered up to 800 hydrogen-electric powered semi-trucks from Nikola Motor Company. The integration of the zero-emission trucks into Anheuser-Busch's fleet will be starting in 2020.

By 2025, Anheuser Busch plans to convert their entire delivery fleet to renewable power.

The truck order comes after a trial project from 2019 in which the partners completed the first Zero-Emission Beer Delivery in St. Louis.

Project budget / funding

n/a

Source: Anheuser Busch; Nikola; Desk research; Roland Berger

US brewer Anheuser Busch plans to integrate 800 Nikola hydrogen-electric semi-trucks from 2020 on and convert delivery fleet by 2025

Deep-dive: Anheuser Busch Zero-Emission Beer Delivery (2/2)

10

Detailed truck information

Number of trucks	[#]	800
Truck type		Tractor 6x4
Cabin type		Day cabin
GVWR / GCWR[1]	[tonnes]	n/a / 40
Range per year	[km]	n/a
Powertrain power	[hp]	1,000
Battery capacity	[kWh]	250
Tank location		n/a
H_2 tank pressure	[bar]	700
Tank size	[kg]	81
Range per tank	[km]	800-1,200
refuelling speed	[kg/min]	4
Fuel cell power	[kW]	240

Detailed refuelling infrastructure information

Type		Fixed infrastructure
Ownership		Private
Supply		Gaseous
H_2 source		n/a
Required space	[sqm]	n/a
Storage type		Fixed (gaseous)
Storage size	[kg]	n/a
H_2 tank pressure	[bar]	700
Fuelling speed	[min]	20
Capacity	[kg/day]	7,000

Additional information

- The H_2 supply will be provided on site
- The order of 'up to 800 trucks' was placed as the relatively new company Nikola started the trucks' series production from 2019 on

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[1] GVWR = Gross vehicle weight rating, GCWR = Gross combined weight rating

Source: Anheuser Busch; Nikola; Desk research; Roland Berger

REVIVE is an EU-funded multi-national project deploying 15 fuel cell refuse trucks over the course of four years

Deep-dive: REVIVE

11

General information

Image: REVIVE

Country / countries	Belgium, France, Sweden, Italy
Start / end year	2018 - 2021
System integrator	E-trucks Europe / Renova
FC provider	Proton Motor Fuel Cell, PowerCell
Truck operator / logistics user	Suez, SEAB SPA, ASM Merano, Renova, Antwerp, Amsterdam, Breda, Groningen
Other partners	PowerCell, Proton Motor, CEA, Element Energy, Tractebel, WaterstofNet

Project description

The demonstration project tests fuel cell refuse trucks in urban settings. It deploys 15 heavy-duty refuse trucks for zero emission waste collection in urban areas where air quality is a particularly important issue.

The 'Refuse Vehicle Innovation and Validation in Europe' project is planned to take place in eight sites across Europe for a total project duration of four years. The test vehicles will be operated in real-world conditions in Breda, Helmond, Amsterdam and Groningen (NL), Antwerp (BE), Bolzano and Merano (IT) and Gothenburg (SE) by waste operators for at least two years.

Project budget / funding

The project is supported with EUR 5 million by the Fuel Cell and Hydrogen Second Joint Undertaking (FCH JU).

Source: REVIVE; Desk research: Roland Berger

HECTOR is an EU-funded project that deploys seven fuel cell garbage trucks in seven cities across North West Europe

Deep-dive: HECTOR

12

General information


Image: HECTOR

Country / countries	Belgium, France, Netherlands, UK, Germany
Start / end year	2019 - 2023
System integrator	n/a
FC provider	n/a
Truck operator / logistics user	Aberdeen, Groningen, Touraine Vallee de L'Indre, Suez, ARP-GAN, AGR, Wirtschaftsbetriebe Duisburg
Other partners	HAN University of Applied Science

Project description

The 'Hydrogen Waste Collection Vehicles in North West Europe' demonstration project tests fuel cell garbage trucks in various operational settings. Seven FCH waste collection trucks will be operated in urban and rural areas on fixed and flexible schedules while using existing HRS infrastructure.

The project is scheduled from January 2019 until 2023 and is taking place in seven cities in five countries in North West Europe. The project consortium consists of several waste management companies, local authorities, research and data analysis providers and Aberdeen City Council as the lead partner.

Project budget / funding

The project is supported by EUR 5.5 million from the INTERREG North West Europe programme and has a total budget of EUR 9.28 million.

Source: HECTOR, Aberdeen City Council; Desk research: Roland Berger

Further demonstration projects indicate the breadth of FCH HDT applications that take place across Europe and increasingly in Asia

Further FCH HDT trial and demonstration projects

Project	Country	Duration	Operator / logistics user	Application	OEM/ System integrator	FC provider
CNHTC hydrogen truck for port operation	🇨🇳	2017 – n/a	Jinan Port	🚛	China National Heavy Duty Truck Company (CNHTC)	Loop Energy
GOH! Generation of Hydrogen 40 t truck	🇨🇭	2019 – n/a	Migros	🚚	Kamaz	Green GT
CATHy0PÉ 44 t truck	🇫🇷	2017 – 2021	Carrefour	🚚	Kamaz	Green GT
ROAD H2 refrigerated trailer	🇫🇷	2016 – 2019	Malherbe	Trailer only	Chereau	FC Lab, Tronico
Hyundai partnership with Gwangyang Port (infrastruct. and trucks)	🇰🇷	2020 – n/a	Gwangyang Port	🚚	Hyundai	n/a

🚚 Rigid 4x2 truck 🚛 Tractor 4x2 truck 🚚 Rigid 6x4 truck 🚛 Tractor 6x4 truck

Source: Desk research; Roland Berger

The comparison of selected trial and demonstration projects shows different levels of transferability to the European context

Qualitative comparison of projects

Transferability analysis of selected trial and demonstration projects

1	🇧🇪🇫🇷 🇩🇪🇳🇱	H2-Share
2	🇧🇪🇫🇷 🇩🇪🇳🇱	H2Haul
3	🇧🇪	Waterstofregio 2.0
4	🇳🇴	ASKO distribution logistics trucks
5	🇨🇭	Hyundai Hydrogen Mobility
6	🇨🇭	Esoro hydrogen truck for Coop
7	🇨🇦	AZETEC
8	🇺🇸	ZANZEFF
9	🇺🇸	GTI Fast-Track Fuel Cell Truck
10	🇺🇸	Anheuser Busch Zero-Emission Beer Delivery

Understanding of transferability

Transferability refers to the replicability and direct implementation potential of trial and demonstration activities / projects to the European context

Approach

1. Multi-dimensional transferability analysis

Selected projects are assessed using a multi-dimensional framework to draw a relative comparison across projects:

> Regulatory framework
> Use case
> Technical features
> Stakeholders
> Political motivation

2. Qualitative evaluation of specific projects

As activities from other geographies provide different project set-ups and ecosystems, success factors and favourable conditions of non-European projects are analysed that could offer further impulses for the European context

Source: Roland Berger

The transferability of selected key trial and demonstration projects is assessed against five key dimensions in a structured framework

Multi-dimensional transferability analysis framework

Dimensions	Criteria	Examples
Technical features	> Technology	> E.g. power, range, distance, battery capacity
Regulatory framework	> Geography	> E.g. EU, USA
	> Internationalisation	> E.g. cross-national transport
Use case	> Truck segment	> E.g. 18 tonnes, 40 tonnes
	> Route type	> E.g. long distance, distribution
	> Infrastructure conditions	> E.g. high number of hydrogen refuelling stations
Stakeholders	> Involvement of global suppliers and system integrators	> E.g. participation of Ballard, Hydrogenics, etc.
	> Mechanisms of cooperation	> Presence of coalitions, e.g. PPP
Political motivation	> Degree of political support	> E.g. enablement by political actors / institutions
	> Rationale behind investment	> E.g. national environmental programme
	> Availability of government funding	> E.g. funding by Ministry of Transport, etc.

Source: Roland Berger

The transferability assessment clearly shows European projects as highly transferable, North American conditions as different

Assessment of transferability

		Technical features	Regulatory framework	Use case	Stake-holders	Political motivation	**Overall transferab.**
1	H2-Share	●	●	●	●	●	●
2	H2Haul	●	●	●	●	●	●
3	Waterstofregio 2.0	●	●	●	●	●	●
4	ASKO distribution logistics trucks	●	◕	●	◑	◕	◕
5	Hyundai Hydrogen Mobility Business venture	●	◕	◕	◑	◕	◕
6	Esoro hydrogen truck for Coop	●	◕	●	◕	◕	◕
7	AZETEC	◔	◑	◑	◕	●	◑
8	ZANZEFF	●	◑	◑	◕	◕	◕
9	GTI Fast-Track Fuel Cell Truck	◑	◑	◑	◕	●	◕
10	Anheuser Busch Zero-Emission Beer Delivery	◔	◑	◑	◑	◕	◑

● Very similar/easily transferable ◕ Similar/transferable ◑ Different/less transferable ◔ Very different/hardly transferable

Source: Market analysis; Roland Berger

The EU demonstration projects provide a high transferability and level of similarity, with little difference for the Norwegian project

Detailed assessment of transferability (1/3)

	🇧🇪🇫🇷🇩🇪🇳🇱 H2-Share	🇧🇪🇫🇷🇩🇪🇳🇱 H2Haul	🇧🇪 Waterstofregio 2.0	🇳🇴 ASKO distribution logistics trucks
Technical features	●	●	●	●
Regulatory framework	●	●	●	◕
Use case	●	●	●	●
Stakeholders	●	●	●	◑
Political motivation	●	●	●	◕
Overall transferability	●	●	●	◕
Key factors for overall score	> Cross-EU, multi-partner project (industry and public sector) > High transferability in all aspects	> Cross-EU, multi-partner project (industry and public sector) > High transferability in all aspects	> Regional project with partners from industry and political support > Comparable regulatory framework and political motivation	> European context in application and technical features > Industry use case with high engagement from individual party

● Very similar/easily transferable ◕ Similar/transferable ◑ Different/less transferable ◔ Very different/hardly transferable

Source: Market analysis; Roland Berger

Similar technical and legal provisions make Swiss projects transferable, Canadian technology different from European context

Detailed assessment of transferability (2/3)

	🇨🇭 Hyundai Hydrogen Mobility **Business venture**	🇨🇭 Esoro hydrogen truck for Coop	🇨🇦 AZETEC
Technical features	●	●	◔
Regulatory framework	◕	◕	◑
Use case	◕	●	◑
Stakeholders	◑	◕	◕
Political motivation	◕	◕	●
Overall transferability	◕	◕	◑
Key factors for overall score	> Relevance of technology (power, range, etc.) in European country > Comparable legal framework > Unique set up of high involvement of system integrators and operator coalition less transferable	> Relevance of technology and use case for European market > Comparable legal framework > Involvement of system integrators and coalitions transferable	> Little transferability of technology directed to a different market > Limited similarities of regulatory framework and specific use case > Stakeholder coalition and political motivation transferable

● Very similar/easily transferable ◕ Similar/transferable ◑ Different/less transferable ◔ Very different/hardly transferable

Source: Market analysis; Roland Berger

US demonstration projects each benefit from specific, mostly local factors that limit transferability to the European context

Detailed assessment of transferability (3/3)

	ZANZEFF	GTI Fast-Track Fuel Cell Truck	Anheuser Busch Zero-Emission Beer Delivery
Technical features	●	◑	◔
Regulatory framework	◑	◑	◑
Use case	◑	◑	◑
Stakeholders	◕	◕	◑
Political motivation	◕	●	◕
Overall transferability	◕	◕	◑
Key factors for overall score	> Relevance of technology (power, range, etc.) similar to Europe > Comparability of legal framework and use case limited > Polit. motivation very similar, but financial support less transferable	> Limited relevance of technological features, legal framework, and use case for European market > Involvement of system integrators and coalitions transferable	> Limited relevance of technical features, legal framework, and use case for European market > High industry ambition as individual case less transferable > Similar political support

● Very similar/easily transferable ◕ Similar/transferable ◑ Different/less transferable ◔ Very different/hardly transferable

Source: Market analysis; Roland Berger

Despite lower transferability, success factors of non-European projects offer impulses regarding set-up, support & ecosystems

Success factors of non-European projects

Country	Selected project	Overall transferab.	Success factors
🇨🇦	7 Alberta Zero-Emissions Truck Electrification Collaboration (AZETEC)	◑	The project builds on a **multi-partner industry lead** and **substantial public funding**. It will take place on a **fixed route** with a 'drop and swap' **refuelling model** included in the route.
🇺🇸	8 Zero and Near-Zero Emissions Freight Facilities Project (ZANZEFF)	◑	The Californian Los Angeles basin region (incl. the ports of Los Angeles and Long Beach) forms a **local hydrogen ecosystem**. FCH HDT applications can leverage the existing synergies from different modes of applications (**multi-modal approach**), e.g. short-range port operations and forklifts, and infrastructure. Projects build on advantageous regulation and receive significant **political support** and **public funding**.
🇺🇸	9 GTI Fast-Track Fuel Cell Truck	◑	
🇺🇸	10 Anheuser Busch Zero-Emission Beer Delivery	◑	The project (incl. planned fleet replacement) is rooted in the **company strategy and commitment** on zero-emission transport for a **back-to-base distribution use case**. Initiative is strongly driven by US-based start-up Nikola Motors.

Source: Roland Berger

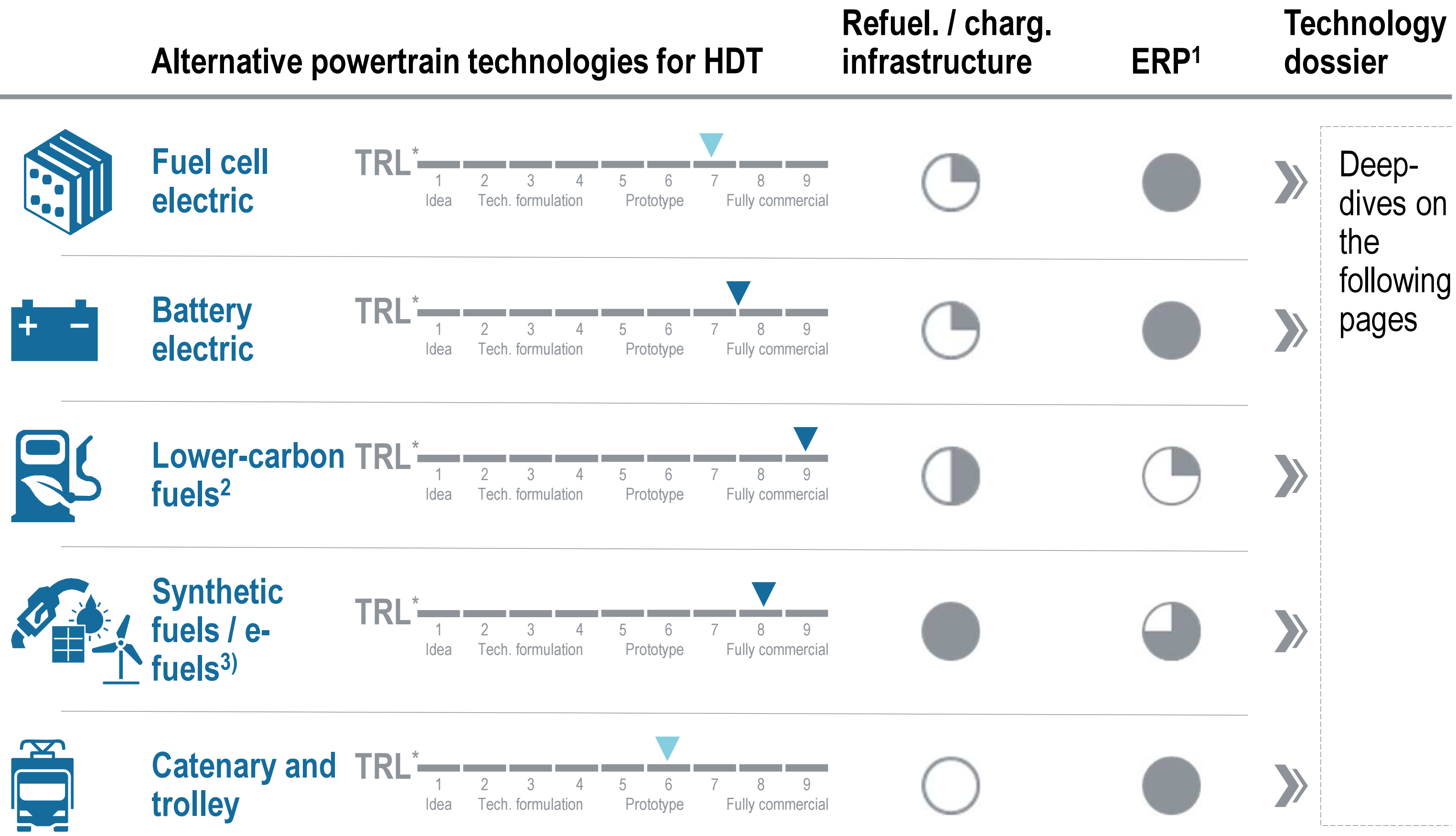
B.3 State of the art technology

The technology dossier shows the state of the art through comparing alternative powertrain technologies and current activities

Prioritisation of technology focus

Outside-in view

- Interest and action on FCH trials and demonstration projects is increasing
- Other alternative powertrain technologies are pushed forward in parallel
- In the state of the art technology dossier, we
  - cluster technologies according to type
  - identify key application cases per cluster to include in the technology dossier
  - focus on high emission reduction potential and TRL 6+ for the TCO analysis



Alternative powertrain technologies for HDT	Refuel. / charg. infrastructure	ERP[1]	Technology dossier
Fuel cell electric	◔	●	» Deep-dives on the following pages
Battery electric	◔	●	»
Lower-carbon fuels[2]	◑	◔	»
Synthetic fuels / e-fuels[3)]	●	◕	»
Catenary and trolley	○	●	»

1) Emission reduction potential: Tank-to-Wheel
3) Sustainable e-fuels from renewable sources
2) Low carbon fuels (e.g. CNG, LNG), liquid biofuels
*) Technology Readiness Level of truck ▼ ≤ 5 ▼ 6-7 ▼ 8-9

Legend: ○ low level ● high level

Source: Roland Berger

Comparing alternative powertrains is complex with inherent uncertainties – We aim for a balanced comparison through case studies

Complexity of alternative powertrains

Not exhaustive

	Factors contributing to complexity			Comments
Technologies	> ICE (+ e-fuels) > BEV > FCEV > Catenary/Trolley			> Adoption of more than one technology likely for different applications, use cases and regions > CO_2 advantage not conclusive to single technology > Furthermore, each technology has its own complexity, e.g. development of high energy density batteries (solid-state) can increase adoption of BEV
Infrastructure	> Each technology will require different infrastructure	> Infrastructure investments pend political decisions > Electricity grid and H_2 fuel supply require large investments and political decisions		> Infrastructure will be a prerequisite for adoption of the specific technology > Fleet projects could lower hurdles for road to market
Regional differences	> Electricity price > Diesel price > Hydrogen price	> Electricity/fuel supply > Clean electricity/fuel supply	> Infrastructure > Regulations > Incentives	> Regional differences will affect both TCO advantage and the operational feasibility for each technology > Objective with electrification (CO_2 reduction vs. local emission reduction) varies between regions
Customer requirements	> Daily driving range > Fuelling/charging time > Budget constraints	> Healthier working environment > Green image	> Noise level > Safety > Flexibility	> Most important requirement differs between applications and regions
TCO advantage	> Vehicle cost > Battery raw material costs > Maintenance cost	> Fuel cost > Electricity cost > Hydrogen cost	> Road tolls > Incentives > Driving range	> TCO advantage for technologies differ between and within segments depending on applications / use cases

Alternative fuels / electrification is surrounded by high complexity – Technology adoption expected to differ between applications and depend on infrastructure, regulations, incentives, customer requirements and TCO for the technology

Source: Press research, Interviews, Roland Berger

The technology portfolio for HD truck powertrains is comprised of conventional / fossil and zero-emission technology concepts

High-level comparison of powertrain technology portfolio for HDT

	Reference		Project focus			
	Fossil powertrains			Zero emission[1]		
	Diesel	**LNG/CNG**	**e-fuels**	**Battery-electric**	**Fuel Cell-electric**	**Catenary / Trolley**
Description	Combustion engine powered by diesel	Combustion engine powered by LNG/CNG	Combustion engine powered by e-diesel	Electric motor powered by chemic. stored energy in a rechargeable battery	Electric motor powered by a fuel cell, combined with a battery	Electric motor powered by DC from overhead lines using a pantograph
Strengths	> Established technology with widespread infrastructure > Long daily driving ranges	> Fuel cost advantage compared to diesel > Lower particulate emissions than diesel	> Use of existing infrastructure > Use of existing HDT combustion engines	> Meet emission restrictions > High powertrain efficiency	> Meet emission restrictions > Possibility for long daily driving ranges > Quick refuelling compared to BET	> Charging while driving, i.e. no stops needed > Smaller batteries and good CO_2 footprint
Potential constraints	> CO_2 and NO_x emissions and related regulation	> Infrastructure availability > Limited emission reduction potential > Relatively low fuel efficiency (~25%)	> Production cost not on competitive level: ~3.5 x diesel price > Remaining local emissions (e.g. NO_x) > CO_2 sourcing	> Cost, size and weight of batteries > Range limitations > Recharging time and space required > Vehicle cost	> Availability of infrastructure > Production cost of H_2 > Vehicle cost	> Availability of infrastructure > Limited flexibility of routes > Early development stage

1) With primary energy derived from renewable sources

▨ Remaining local emissions

Source: Desk research; Roland Berger

The relevant powertrain technologies are considered in the different project segments – Hydrogen application as focus technologies

Analysed relevant powertrain technologies

Powertrain technology	State of the art technology	TCO & market potential	3x3 truck case studies	Recommendations and R&I roadmap
Diesel		✓	✓	
e-diesel	✓	✓	✓	
BET	✓	✓	✓	
CGH_2 (350 bar)	✓	✓	✓	✓
CGH_2 (500 bar)				✓
CGH_2 (700 bar)	✓	✓	✓	✓
LH_2 (-253 °C)	✓	✓	✓	✓
H_2 ICE				✓
Catenary	✓	✓	✓	
LNG/CNG[1]	✓			

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[1] LNG/CNG-powered trucks have been excluded for the detailed analysis due to their limited CO_2 reduction potential and their potential contribution to the EU's decarbonisation targets (e.g. EU Green Deal); furthermore, while also bio-based processes exist to produce renewable methane, the EU biomass potential is limited and methane slip risks prevail

Source: Roland Berger

LNG/CNG are used commercially in some locations, FCH and BE beginning larger demonstration, catenary and e-fuels in small demo

Trial and demonstration activities for HDT

Not exhaustive – includes announcements

Project AZETEC, Canada, 2019-22:
An industry-led, CAD 15 m project to design and manufacture two heavy-duty FCH hybrid trucks that move freight between Edmonton and Calgary

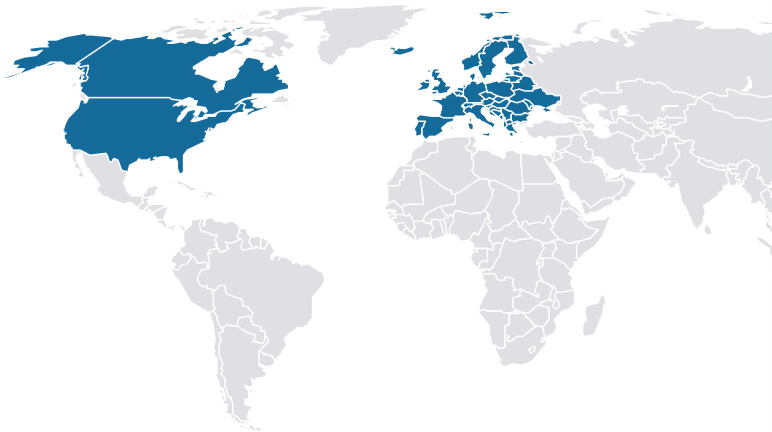
Renova, Sweden, 2019:
Delivery of test series of Volvo garbage truck for a Swedish waste and recycling company

PepsiCo, USA, 2019:
Pre-Order of 100 electric Tesla Semi trucks

Penske Truck, USA, 2019:
Purchase of the first heavy-duty Freightliner eCascadia (class 8) with a range of up to 400 km

Consortium BioLNG EuroNet, Europe, 2019:
Commitment of Scania, Shell, Grupo DISA, OSOMO, and Iveco to provide additional 2,000 LNG trucks on the road

Anheuser Busch, USA, 2019:
Testing of Nikola hydrogen electric trucks for beer delivery. Announcement to order 800 Nikola trucks by 2025 to convert its long-haul fleet to renewable energy



DHL Freight, Germany, 2019:
DHL Freight has deployed a LNG-powered Iveco Stralis long-haul truck

Hyundai Hydrogen mobility, Switzerland, 2019
Provision of 1,600 Xcient fuel cell trucks and H$_2$ infrastructure to logistics and transport industry via leasing

Low Emission Freight and Logistics Trial, UK, 2017:
Logistics company Howard Tenens has taken delivery of 2 26 t rigid dedicated CNG trucks from Scania

H2-Haul, Europe, 2019:
Project to test 16 heavy-duty hydrogen fuel cell trucks in commercial operations within Europe

H2Share, Europe, 2020:
Project to test a heavy-duty hydrogen fuel cell truck with mobile refuelling station in last-mile commercial operations in multiple European countries

REVIVE, Europe, 2018:
Project to test 15 hydrogen fuel cell refuse vehicles in 8 regions across Europe in real-world conditions

e-fuel production plant, Nordic Blue Crude, Norway, 2021:
Capacity: 8,000 t p.a.; Input: 20 MW$_{el}$; E-fuel: e-Diesel; Price: 2 EUR/kg

e-fuel production plant, KIT, Germany, 2019:
Capacity: 45 t p.a.; Input: 10 kW$_{el}$; E-fuel: e-Diesel; Price: 2.3 EUR/kg

HECTOR, Europe, 2019
Test and deployment of seven fuel cell garbage trucks in seven pilot sites across north west Europe

eHighway/Elisa, Germany, 2018:
Testing of 5 trucks on 10 km of A5-highway test route (670 volts of DC power with max. speed of 90 km/h)

e-way, Sweden, 2016:
Testing of 2 hybrid trucks (bio-fuel and additional batteries) on 2 km of E61-highway (max. speed of 90 km/h)

Cat trolley assist system, Sweden, 2018:
Testing of 4 trucks on a 0.7 km track of a mining corporation (337 t payload on 10% grade, saving 90% fuel and engine costs)

e-fuel production plant, Audi, Germany, 2021:
Capacity: 1,500 t p.a.; Input: 6 MW$_{el}$; E-fuel: e-methane; Price: 10 EUR/kg

☐ FCH ☐ Battery electric ☐ LNG/CNG ☐ e-fuel ☐ Catenary

Source: Desk research; Roland Berger

Fuel cell heavy-duty trucks could offer a zero-emission alternative with high operational flexibility

Fuel cell heavy-duty trucks

Brief description: FCH HD trucks use an electric motor powered by a fuel cell, combined with a battery (hybrid powertrain)

Use cases: FCH HD trucks are potentially applicable to long-haul rides, depending on the storage system[1]

High-level assessment:

Costs: Relatively high vehicle costs and production costs of H_2 compared to conventional diesel

Application: Possibility for long daily driving ranges; shorter refuelling times compared to BET

Emission: Potential to meet emission regulation standards

Efficiency: ~16% higher powertrain efficiency than diesel

Infrastructure: Availability of refuelling infrastructure currently limited

FCH heavy-duty truck	[Unit]	State of the art (2015-2020)[2]
Powertrain power	[kW]	208-745
Fuel cell power	[kW]	88-240
Truck type		rigid and tractor 6x4; rigid and tractor 4x2
Torque	[Nm at rpm]	n/a
GCWR	[tonnes]	34-64
Average range per charge	[km]	350-1,250
Refuelling time	[min]	6-40
H_2 consumption	[kg/100 km]	5-9
CO_2 emission	[gCO_2/kWh][3]	0
Tank size	[kg]	32-100
Battery capacity[4]	[kWh]	50-120
H_2 storage	[bar]	350; n/a
Vehicle costs	[EUR]	n/a

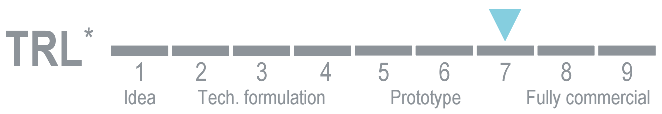
[1] Approx. with CGH_2 at 350 bar: 500 km; 700 bar: 1000 km; with LH_2: 1250 km [2] Only ready-to-road trucks are taken into account [3] Tank-to-Wheel [4] Exception: Nikola Two truck

Source: Desk research, COOP; ASKO; Roland Berger

Several FCH heavy-duty truck prototypes are beginning on-road demonstration – Limited commercial availability of products to date

Fuel cell heavy-duty trucks

Overall technological readiness: Generally at prototype-stage; prototypes are demonstrated in relevant environments, e.g. Esoro FC truck tailored for retailer COOP or ZECT II program, Nikola One FCH truck presented in December 2016; activities by Norwegian grocery retailer ASKO



Demonstration projects / deployment examples (selection only)

Project	Country	Start	Scope	Project volume [EUR]
H2Haul	🇧🇪 🇩🇪 🇫🇷 🇨🇭	2019	H2Haul tests 16 heavy-duty hydrogen fuel cell trucks in commercial operations in Europe (Belgium, France, Germany and Switzerland)	12 m
ASKO	🇳🇴	2017	The ASKO demonstration project includes four fuel cell powered electric 27 t Scania trucks for Norway's largest grocery wholesaler	1.8 m
Hydrogen region 2.0	🇧🇪	2016	Hydrogen region 2.0 is a project-based collaboration between Flanders and the Netherlands. The partners develop and demonstrate the first large (40 ton) hydrogen truck by VDL	13.9 m

Major prototypes (selection only)

Name	OEM	Product features	Country	Since	Cost [EUR]
ZANZEFF-truck	TOYOTA	GCWR[1]: n/a; Battery capacity: 12 kWh; Range per tank: 480 km; Fuel cell power: n/a; Type: tractor 6x4	🇨🇦	2019	n/a
AZETEC-truck	FREIGHTLINER	GCWR[1]: 63.5 t; Battery capacity: n/a kWh; Range per tank: 700 km; Fuel cell power: 210 kW; Type: tractor 6x4	🇺🇸	2019	n/a
Hydrogen region-truck	VDL BUS & COACH	GCWR[1]: 44 t; Battery capacity: 72 kWh; Range per tank: 350 km; Fuel cell power: 72 kW; Type: tractor 4x2	🇧🇪	2016	n/a

*) Technology Readiness Level ▼ ≤ 5 ▼ 6-7 ▼ 8-9

[1] Gross Combined Weight Rating

Source: Desk research, Roland Berger

Battery electric heavy-duty trucks could offer a zero-emission alternative with low-medium range

BE heavy-duty trucks

Brief description: BE HD trucks use an electric motor powered by chemical stored energy in a rechargeable battery

Use cases: BE HD trucks are limited on low-medium range/drayage due to cost, size, and weight of batteries resulting in range limitations

High-level assessment:

Costs: Reduced fuel and maintenance costs, increased battery cost compared to conventional diesel engine

Application: Relatively long recharging time, large size/weight of battery limit payload, battery capacity limits range

Emission: Potential to meet emission regulation standards

Efficiency: ~45% higher powertrain efficiency than diesel

Infrastructure: Availability of charging infrastructure currently limited

BE heavy-duty truck	[Unit]	State of the art (2019)[1]
Powertrain power	[kW]	355-536
Truck type		rigid 6x4; tractor 6x4
Torque	[Nm at rpm]	850 - 2,300 at n/a
GCWR	[tonnes]	26-47
Average range per charge	[km]	120-400
Charging time	[min]	90-390
Energy consumption	[kWh/100 km]	100-140
CO_2 emission	[gCO_2/kWh][2]	0
Battery capacity	[kW]	200-550
Battery size	[tonnes]	2-7
Lifetime battery	[years]	5
Vehicle costs3)	[EUR]	140k-180k

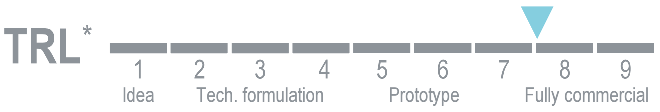
1) Only ready-to-road trucks are taken into account 2) Tank-to-Wheel 3) EUR 150/kWh battery

Source: Desk research, Roland Berger

Several BE heavy-duty trucks are currently being tested – Experience from passenger cars accelerates the development

BE heavy-duty trucks

Overall technological readiness: In general, BE HD trucks are at a pre-series-stage demonstrated in operational environment. However, technological development of BE HD trucks is not fully completed ensuring competitiveness in operational environment; e.g. delivery of Freightliner 'eCascadia'



Demonstration projects / deployment examples (selection only)

Project	Country	Start	Scope	Project volume [EUR]
Penske Truck/ NFI Industries	🇺🇸	2019	American customers Penske Truck Leasing and NFI Industries have acquired the first heavy-duty Freightliner eCascadia trucks (class 8) with a range of up to 400 km; market launch 2021	n/a
PepsiCo	🇺🇸	2019	PepsiCo has reserved 100 of Tesla's new electric Semi trucks; market launch Q4 2020	13.7 m
TGM Sweden	🇸🇪	2019	Delivery of test series as Volvo garbage truck for the waste and recycling company Renova and a distribution truck for the DB Schenker service provider TGM operating in Sweden	n/a

Major prototypes/products (selection only)

Name	OEM	Product features	Country	Since	Cost [EUR]
Semi	TESLA	Battery capacity: 650 kW; Range per tank: 800 km; GCWR[2]: 40 t; Powertrain power: 800 kW	🇺🇸	2021, Q4	150k-180k
eCascadia	FREIGHTLINER	Battery capacity: 50 kW; Range per tank: 400 km; GCWR[2]: 36 t; Powertrain power: 739 kW	🇺🇸	2019	n/a
FE Electric	VOLVO	Battery capacity: 200 kW; Range per tank: 120-200 km; GCWR[2]: 27 t; Powertrain power: 400 kW	🇸🇪	2019	n/a

*) Technology Readiness Level ▼ ≤ 5 ▼ 6-7 ▼ 8-9

1) Specifically adjusted to port requirements
2) Gross Combined Weight Rating

┆ Example of use case I
┆ Example of use case II

Source: Desk research, Roland Berger

Lower-carbon fuels heavy-duty trucks could offer an alternative to diesel trucks, but featuring limited emission reduction potential

Lower-carbon fuels heavy-duty trucks

Brief description: Lower-carbon HD trucks are combustion-engine trucks using LNG/CNG as a fuel

Use cases: Lower-carbon fuels HD trucks are limited to medium-high range due to availability of infrastructure

High-level assessment:

Costs: Fuel cost advantage compared to diesel

Application: Same fields of application as diesel

Emission: Overall limited emission reduction potential compared to diesel

Efficiency: Relatively low fuel efficiency (~25%)

Infrastructure: Availability of refuelling infrastructure limited, esp. for LNG

Lower-carbon fuels heavy-duty truck	[Unit]	**State of the art (2017-2019)[1]**
Powertrain power	[kW]	294 - 338
Truck type		4x2 tractor
Torque	[Nm at rpm]	1,700-2,300 at 1,100-1,400
GCWR	[tonnes]	40
Average range per tank	[km]	1,000-1,600
refuelling speed	[min][2]	9-20
Fuel consumption	[l/100 km]	50-70
CO_2 emission	[gCO_2/km][3)]	688-776 (~3-14% less than diesel)
Storage capacity	[l]	495-1080
1st life	[km]	772,000
Vehicle costs	[EUR]	130k-145k

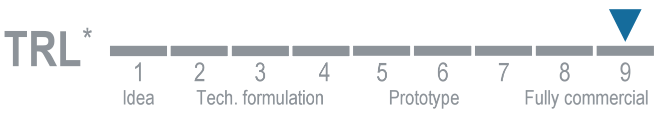
1) Only ready-to-road trucks are taken into account 2) 55 l/min 3) Tank-to-Wheel

Source: Desk research, Roland Berger

Several LNG/CNG heavy-duty trucks have been developed – Re-fuelling infrastructure and remaining emissions as main bottleneck

Lower-carbon fuels heavy-duty trucks

Overall technological readiness: Lower-carbon fuel technology is commercially ready with leading OEMs offering selected models in serial production; widespread market introduction depending on expansion of LNG/CNG refuelling infrastructure and economies of scale / learning-curve effects to lower the premium on the product cost



Demonstration projects / deployment examples (selection only)

Project	Country	Start	Scope	Project volume [EUR]
Consortium BioLNG EuroNet	🇪🇺	2019	Scania, Shell, Grupo DISA, OSOMO and Iveco have committed to provide 2,000 more LNG trucks on the road, LNG fuelling stations and the construction of a BioLNG production plant in the Netherlands	2.9 bn
DHL Freight-LNG	🇩🇪	2019	DHL Freight has deployed a LNG-powered Iveco Stralis long-haul truck. One year test as a daily shuttle between DHL's logistics centre and a BMW Group production plant	n/a
Low Emission Freight and Logistics Trial	🇬🇧	2017	Logistics company Howard Tenens has taken delivery of 2 26 t rigid dedicated CNG trucks from Scania back in 2017, followed by two more 26 t trucks in March 2019	n/a

Major products (selection only)

Name	OEM	Product features	Country	Since	Cost [EUR]
G 410 LNG	SCANIA	Power: 301 kW; Range per tank: 1,100 km; Fuel consumption: 0,68 l/km; Storage capacity: 750 l (LNG) Torque: 2,000 Nm at 1,100 rpm; GCWR[1]: 40 t	🇸🇪	2019	n/a
Stralis NP 460	IVECO	Power: 294 kW; Range per tank: 1,600 km; Fuel consumption: 0,67 l/km; Storage capacity: 746 l (LNG) Torque: 1,700 Nm at n/a rpm; GCWR[1]: 40 t	🇮🇹	2017	n/a
FM 460 LNG	VOLVO	Power: 338 kW; Range per tank: 1,000 km; Fuel consumption: 0,49 l/km; Storage capacity: 495 l (LNG) Torque: 2,300 Nm at n/a rpm; GCWR[1]: 40 t	🇸🇪	2017	n/a

*) Technology Readiness Level ▼ ≤ 5 ▼ 6-7 ▼ 8-9

[1] Gross Combined Weight Rating

▭ Example of use case I

Source: Desk research, Roland Berger

e-fuels heavy-duty trucks could offer a CO_2-neutral alternative with medium-high range due to limited mass supply of e-fuel

Synthetic fuels/e-fuels heavy-duty trucks

Brief description: e-fuel HD trucks are otherwise-conventional multi-ton trucks using e-diesel as thermal energy to fuel an internal combustion engine

Use cases: e-fuels HD trucks are limited to medium-high range due to availability of mass supply

High-level assessment:

Costs: Production cost not on competitive level: ~3.5 x diesel price

Application: Use of e-diesel for currently available trucks without retrofitting

Emission: Remaining local emissions (e.g. NO_x), CO_2 sourcing challenging

Efficiency: Same as for conventional diesel

Infrastructure: Potential use of existing infrastructure of conventional fuel/gas; however, mass supply not existing yet

e-fuels heavy-duty truck	[Unit]	State of the art (2018)[1]
Powertrain power	[kW]	330-338
Truck type		4x2 tractor
Torque	[Nm at rpm]	2,200-2,350 at 1,100
GCWR	[tonnes]	40
Average range per tank[2]	[km]	800 – 1,500
Refuelling speed	[min]	10
Fuel consumption	[l/100 km]	30-31
CO_2 emission[3]	[gCO_2 /km]	CO_2 neutral
Storage capacity	[l]	1,000-1,500
Lifetime	[km]; [years]	9.5-15 m; 9
Vehicle costs	[EUR]	106k-109k

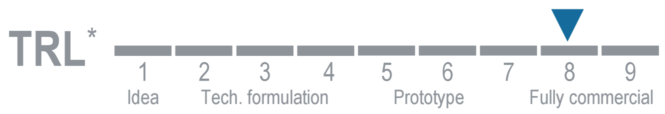
1) Only ready-to-road diesel trucks are taken into account 2) Equivalent to conventional diesel trucks depending on size of tanks 3) Tank-to-Wheel

Source: Desk research, Roland Berger

Several e-fuel projects have shown technological readiness – Fuel price as bottleneck of full commercialisation

Synthetic fuels/e-fuels heavy-duty trucks

Overall technological readiness: Various demonstration projects have shown technological maturity; high fuel costs remain a barrier for widespread adoption, despite principle benefits of CO_2 reduction compared to conventional diesel-engines



e-fuel production projects (selection only)

Project	Country	Start	Scope	Project volume [EUR]
Nordic Blue Crude	🇳🇴	2021	Capacity: 8,000t p.a.; Input: 20 MW_{el}; E-fuel: e-Diesel; Price: 2 EUR/kg	75 m
KIT	🇩🇪	2019	Capacity: 45t p.a., Input: 10 kW_{el}; E-fuel: e-Diesel; Price: 2 EUR/l	20 m
Audi	🇩🇪	2013	Capacity: 1,500t p.a.; Input: 6 MW_{el}; E-fuel: e-methane; Price: 10 EUR/kg	n/a

Major products (selection only)

Name	OEM	Product features	Country	Since	Cost [EUR]
Actros 1845 LS Streamspace	DAIMLER	Power: 330 kW; Range per tank: 400 km; Fuel consumption: 30.5 l/100 km; Storage capacity: 1,300 l; Torque: 2,400 Nm at 1,100 rpm; GCWR[1]: 40 t	🇩🇪	2018	109,000
R 450A4x2NA CR20H	SCANIA	Power: 331 kW; Range per tank: 450 km ; Fuel consumption: 30 l/100 km; Storage capacity: 1,500 l; Torque: 2,350 Nm at 1,150 rpm; GCWR[1]: 40 t	🇸🇪	2018	109,000
FH460 Globetrotter	VOLVO	Power: 338 kW; Range per tank: 460 km; Fuel consumption: 31.3 l/100 km; Storage capacity: 1,470 l; Torque: 2,300 Nm at 1,200 rpm; GCWR[1]: 40 t	🇸🇪	2018	106,000

*) Technology Readiness Level ▼ ≤ 5 ▼ 6-7 ▼ 8-9

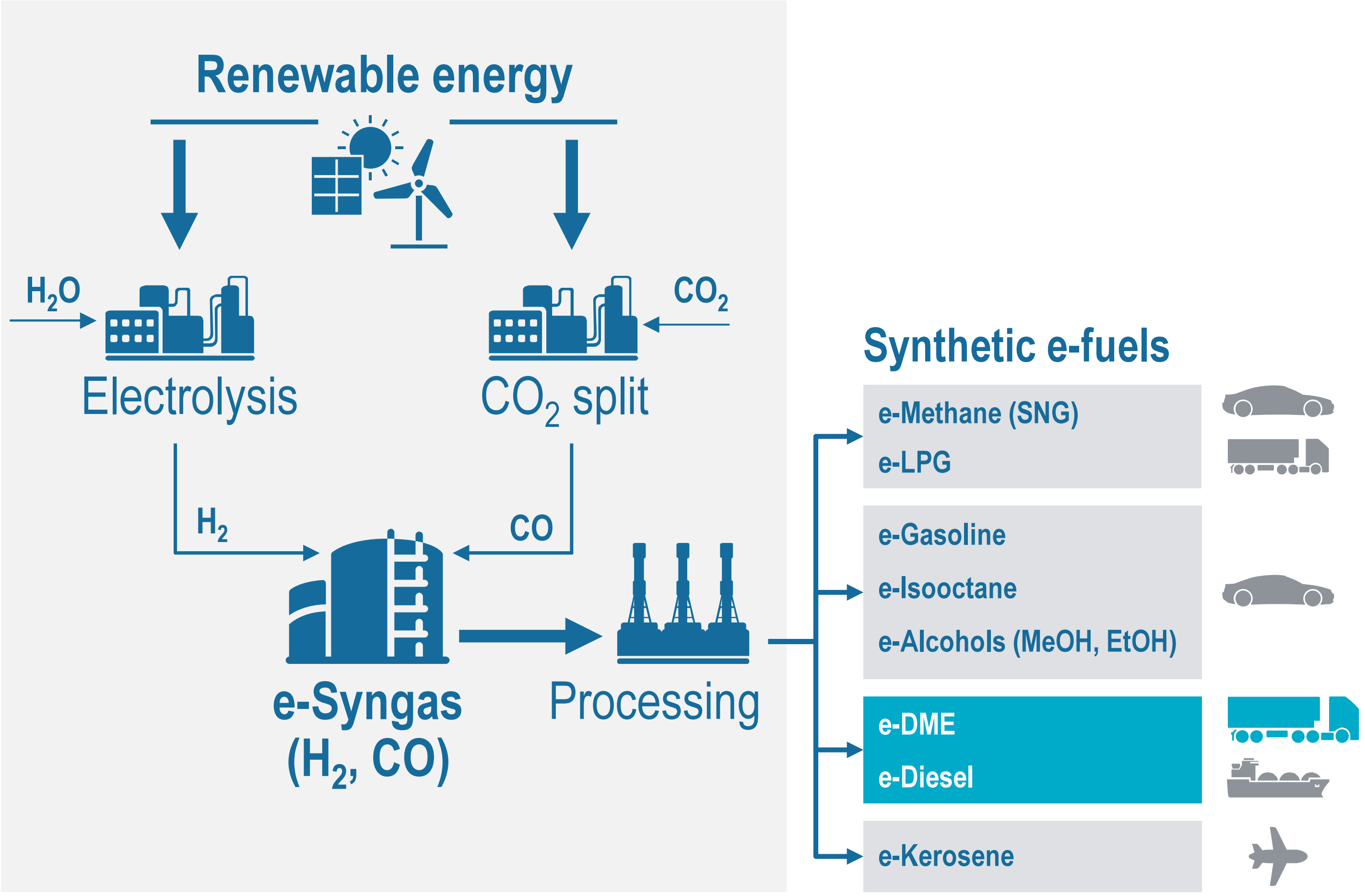
1) Gross Combined Weight Rating

⬚ Example of use case I

Source: Desk research, Roland Berger

Various e-fuels can be produced with known process technology – e-Diesel and e-DME most relevant for heavy-duty trucks

E-fuel production and application possibilities



Renewable energy

H_2O

Electrolysis

CO_2

CO_2 split

H_2

CO

e-Syngas (H_2, CO)

Processing

Synthetic e-fuels

- e-Methane (SNG)
- e-LPG
- e-Gasoline
- e-Isooctane
- e-Alcohols (MeOH, EtOH)
- e-DME
- e-Diesel
- e-Kerosene

Technological maturity of Power-to-Liquid (PtL) process steps has already reached **commercial readiness** but integrated value chains so far **only in first pilot plants**

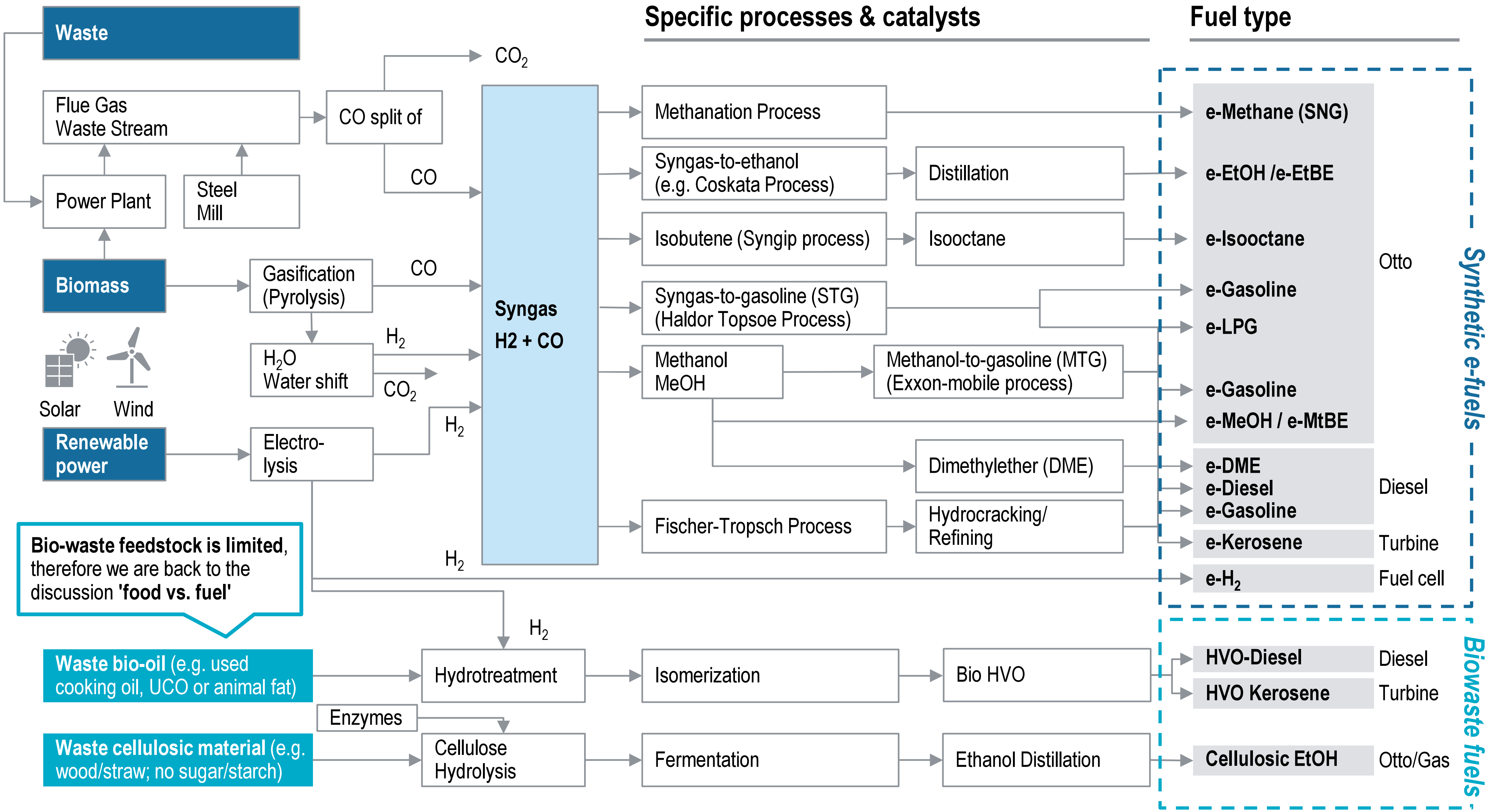
Two e-fuels could be used with existing engine technology: e-DME **and e-Diesel**, where the latter **could directly be used** in existing drop-in fuel infrastructure

E-fuel **prices not yet on competitive level**. Cost parity achievable via **industrialization** and increased future **CO_2 price**

Final efficiency of e-fuels in engines at **levels between 10-16%**

Source: Roland Berger, Concawe; Expert interviews; Desk research

Different production processes exist to derive renewable fuels, either from hydrogen electrolysis or bio-waste feedstock



Specific processes & catalysts

Fuel type

Waste

Flue Gas Waste Stream

Power Plant

Steel Mill

CO split of

CO_2

CO

Biomass

Gasification (Pyrolysis)

CO

H_2O Water shift

H_2

CO_2

Solar

Wind

Renewable power

Electro-lysis

H_2

Syngas
H2 + CO

Methanation Process

Syngas-to-ethanol (e.g. Coskata Process)

Distillation

Isobutene (Syngip process)

Isooctane

Syngas-to-gasoline (STG) (Haldor Topsoe Process)

Methanol MeOH

Methanol-to-gasoline (MTG) (Exxon-mobile process)

Dimethylether (DME)

Fischer-Tropsch Process

Hydrocracking/ Refining

H_2

e-Methane (SNG)

e-EtOH /e-EtBE

e-Isooctane

e-Gasoline

e-LPG

e-Gasoline

e-MeOH / e-MtBE

Otto

e-DME
e-Diesel
e-Gasoline

Diesel

e-Kerosene

Turbine

e-H_2

Fuel cell

Synthetic e-fuels

Bio-waste feedstock is limited, therefore we are back to the discussion **'food vs. fuel'**

H_2

Waste bio-oil (e.g. used cooking oil, UCO or animal fat)

Hydrotreatment

Isomerization

Bio HVO

HVO-Diesel

Diesel

HVO Kerosene

Turbine

Enzymes

Waste cellulosic material (e.g. wood/straw; no sugar/starch)

Cellulose Hydrolysis

Fermentation

Ethanol Distillation

Cellulosic EtOH

Otto/Gas

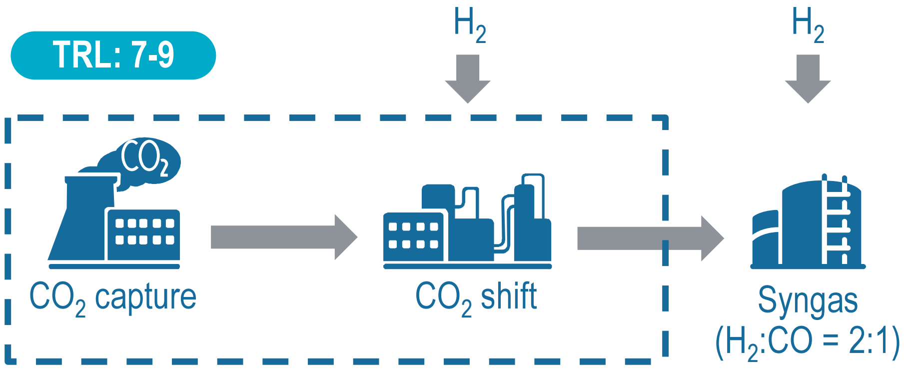
Biowaste fuels

Source: Press research; company publications; Roland Berger

Sustainable CO_2 is key for e-fuels – However, capture from industrial waste streams still more cost-efficient than from ambient air

Excursus: Overview of CO_2 capture and CO_2 shift

CO_2 capture utilization and storage (CCUS) from point sources + CO_2 shift



- > CO_2 is captured from **industrial waste streams**, e.g. from biomass fermentation/ combustion, iron and steel, fertilizer, power generation
- > CO_2 is **split to CO** to create syngas (typically not integrated with capture process)

Capture costs 2019[1]: 20-250 EUR/t CO_2

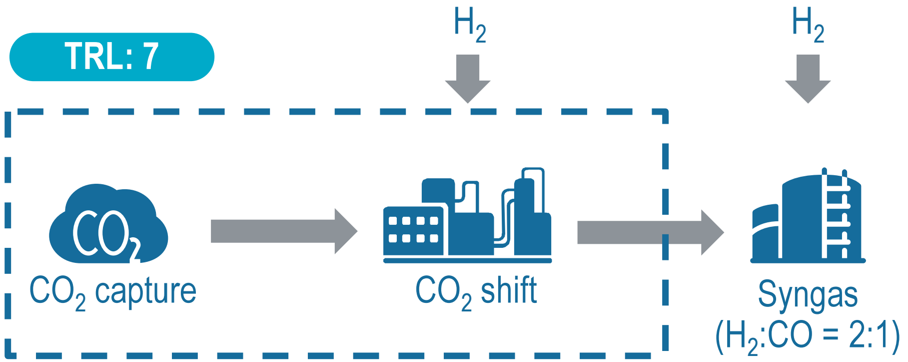
Capture costs 2030[1]: 15-50 EUR/t CO_2

Investment [EUR m/kt][2]: EUR 0.3-2.0 m

Technology providers (selection):

TOSHIBA Schlumberger SIEMENS
Linde Air Liquide C-capture

CO_2 direct air capture (DAC) + CO_2 shift



- > CO_2 is captured ('filtered') **from ambient air** using solid or liquid solvents
- > CO_2 is **split to CO** to create syngas (typically not integrated with capture process)

Capture costs 2019(3): 100-500 EUR/t CO_2

Capture costs 2030(3): 50-200 EUR/t CO_2

Investment [EUR m/kt](3): EUR 2.0-3.0 m

Technology providers (selection):

CLIMEWORKS Carbon Engineering Global Thermostat

1) Global CCS Institute; capture costs highly depend on specific industrial source, lowest costs for biomass fermentation and natural gas processing; 2) Only investment for CO_2 capture taken into account, additional investments necessary for industrial plant itself; 3) New York Times Magazine Feb. 12, 2019; GreenBiz Apr. 18 and Aug. 29, 2019; Carbon Engineering 2018

Source: Global CCS Institute; New York Times; GreenBiz; Company Websites; Expert Interviews; Roland Berger

Catenary heavy-duty trucks could offer a zero-emission alternative with high range, depending on the catenary system

Catenary and trolley heavy-duty trucks

Not input for TCO assessment, but starting point

Brief description: Catenary HD trucks receive power via a pantograph from a DC overhead line, sometimes combined with a CNG or diesel-combustion engine

Use cases: Catenary HD trucks are applicable to long-haul tracks, depending to the catenary system

High-level assessment:

Costs: Similar to BET, increasing costs for pantograph, decreasing costs for smaller battery (before infrastructure investment cost)

Application: Charging while driving, i.e. no stops needed, smaller batteries, but limited flexibility of routes

Efficiency: Similar to BET, when operating in pure electric mode

Emission: Meet emission restrictions, in case of non-hybrid

Infrastructure: Currently only short test track infrastructure available

Catenary heavy-duty truck	[Unit]	State of the art (2018-2019)[4)]
Powertrain power	[kW]	350[1]; 130[2]
Truck type		6x4 tractor[1] 4x2 tractor[2]
Torque	[Nm at rpm]	n/a[1]; 1050 at n/a[2]
GCWR	[tonnes]	40
Average range per charge	[km]	65-160[1;] 15[2]
Charging time	[min]	511[1]; 8[2]
Energy consumption	[kWh/100 km]	88-147[1]; 120[2]
CO_2 emission	[gCO_2 /km][3)]	0[1]; n/a[2]
Battery capacity	[kW]	115-200[1]; 18.5[2]
Battery size	[tonnes]	n/a
Lifetime battery	[years]	5
Vehicle costs	[EUR]	158k-188k[1]

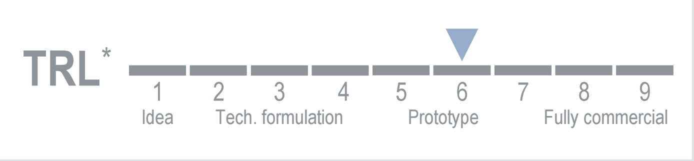
1) Non-hybrid 2) Diesel-hybrid: Electric engine only 3) Tank-to-Wheel 4) Only ready-to-road trucks are taken into account

Source: Desk research, Roland Berger

Only few demonstration projects for catenary and trolley trucks have been developed – Underutilization of infrastructure is a challenge

Catenary and trolley heavy-duty trucks

Overall technological readiness: Prototypes developed and demonstration projects in operational environment partly complete or ongoing (e.g. in the USA, Sweden, Germany)



Demonstration projects / deployment examples (selection only)

Project	Country	Start	Scope	Project volume
eHighway/Elisa	🇩🇪	2018	Tests on 10 km of A5 highway with 5 trucks on 670 volts of DC power allowing for a max. speed of 90 km/h; Partners: Siemens Mobility, Scania, Mercedes, Fahrner Logistics, Huettemann Logistics	EUR 70 m
Cat trolley assist system	🇸🇪	2018	Tests on 0.7 km industry yard track at a mine with 4 trucks allowing for 337 t payload on 10% grade, saving 90% fuel and engine costs; Partners: Caterpillar, Boliden, ABB, Eitech, Zeppelin Univ.	n/a.
e-way	🇸🇪	2016	Tests on 2 km of E61 highway with 2 hybrid trucks (bio-fuel and additional batteries) allowing for a max. speed of 90 km/h; Partners: Siemens Mobility, Scania, Mercedes	n/a.

Major prototypes (selection only)

Name	OEM	Product features	Application/Country	Since	Cost
R 450	SCANIA	Powertrain power: 130 kW (e) + 330 kW (diesel); Range per tank: 15 km (by battery); Torque: 1050 NM; Battery capacity: 18.5 kWh; 10% diesel savings compared to conventional diesel	ELISA 🇩🇪	2018	n/a
ECAT	TransPower	Powertrain power: 300 kW (e); Range per tank: 140 km (by battery); Torque: 1050 Nm; Battery capacity: 115 kWh	eHighway 🇺🇸	2017	n/a
CCAT	TransPower	Powertrain power: 130 kW (e) + n/a kW (CNG); Range per tank: 140 km (by battery) + 160 km (by CNG); Torque: n/a Nm; Battery capacity: 115 kWh	eHighway 🇺🇸	2017	n/a

*) Technology Readiness Level ▼ ≤ 5 ▼ 6-7 ▼ 8-9

⬚ Example of use case I

Source: Desk research, Roland Berger

The comparison of alternative powertrain technologies reveals a lower technology readiness of fully zero-emission trucks today

State-of-the-art today: high-level assessment overview

Summary

	Fuel cell electric	Battery electric	Lower-carbon fuels	Synthetic fuels/ e-fuels	Catenary and trolley
Technology Readiness Level	**TRL 7: Prototype stage**	**TRL 7-8: Pre-series-stage**	**TRL 9: Fully commercial**	**TRL 8: Technological readiness at pilot stage**	**TRL 6: Prototype developing ongoing**
Use Case	> Considered for long-haul range	> Mainly low-medium range/drayage	> Medium and long-haul range	> Medium and long-haul range	> Long-haul range with limited flexibility of routes
Cost[1]	> Relatively high vehicle and fuel cost	> High battery cost, but potentially lower fuel costs	> Lower fuel costs	> Very high fuel production costs	> High battery and infrastructure cost
Emission	> Potential to meet emission regulation standards	> Potential to meet emission regulation standards	> Limited emission reduction potential[1]	> Local emissions (NO_X) remain	> Potential to meet emission regulation standards
Operational Flexibility	> Long daily driving ranges; shorter refuelling times (compared to battery-electric trucks)	> Long recharging time; size/weight of battery limits payload; battery capacity limits range	> Similar to diesel (LNG), some range constraints with CNG	> Same as diesel; use of e-diesel for currently available trucks without retrofitting possible	> Charging while driving; smaller batteries; limited flexibility of routes
Infrastructure	> Limited refuelling infrastructure available > Refuelling station utilisation challenges in early rollout years	> Limited charging infrastructure available > Recharging station utilisation and grid upgrade challenges	> Growing refuelling infrastructure	> Use of existing infrastructure[2]	> Only short test tracks available > Infrastructure utilization, investment and grid upgrade challenges

1) Compared to equivalent diesel performance 2) Refers to existing infrastructure of conventional diesel fuel

Source: Roland Berger

B.4 Policy analysis

While policy approaches on low emission HDT are different across intl. markets, FCH increasingly move into focus of transport policy

Insights on policies and support schemes[1]

as of July 2020

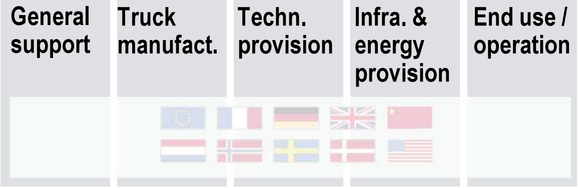
Comparison of policy approaches of key international markets

- Overall, general public and policy makers **push for higher decarbonisation ambition**
- **Increasing support for low emission solutions for heavy-duty trucks**, however at **different levels** between technologies and markets
  - **CO_2 emission standards** for HDT introduced in all key markets
  - China sets a precedent with a strong **government incentive schemes**
  - EU with a **high-profile agenda on decarbonisation** (EU Green Deal)

Analysis of the European policy landscape

- EU legislation **increasingly pushes for stricter standards** in emission reduction and fuel quality (partly already binding)
- Hydrogen application not yet in focus of existing policies, but **upcoming legislation to 'kick-start clean hydrogen economy'** (European Commission, May 27, 2020)
- **EU Green Deal aims for a 90% reduction in transport emissions by 2050** and is a **driving force for low emission vehicles, fuels, and related infrastructure** offers development potential for FCH heavy-duty trucks
- **EU Hydrogen Strategy** lays out **three key steps** for the **hydrogen agenda** in Europe until 2030 (European Commission, July 8, 2020)

Policies and support schemes for FCH HDT commercialisation



- Approach towards **application of H_2 still fragmented in EU Members States**
- Alike other H_2 developments, **subsidies and tax exemptions offer potential for FCH HDT,** yet are not implemented in a cohesive way across Europe
- FCH HDT **commercialisation** to also **further benefit from specific support schemes** that drive the zero and low emission vehicles development for different industry players

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1) As of July 2020

Source: European Commission; Desk research; Roland Berger

Public discussions and legislation increasingly push for higher decarbonisation ambition, including emission targets for HD trucks

HD road freight decarbonisation trajectory

Markets		HDT CO_2 standards	Long-term target
North America	**USA**	**2027 GHG Phase 2 standards** [-15-27% compared to 2018 baseline]	n/a
	Canada	**2027 GHG Phase 2 standards** [-15-27% compared to 2018 baseline]	**2050** Net-Zero Emission target
Europe	**EU**	**2030 CO_2 standards** [-30% compared to 2019/20 baseline]	**2050** Net-Zero Emission target with a 90% reduction in transport emissions
Asia	**China**	**2020 Fuel consumption standards** [-15% compared to 2015 baseline]	**2030** expected CO_2 emission peak, no overall reduction target
	South Korea	Euro VI based overall emission standards (no specific CO_2 regulation)	**2050** Discussion on net-zero emission target
	Japan	**2025 Fuel economy standards** [avg. -13% compared to 2015 baseline]	**2050** 80% reduction of transport emissions

> **Increasingly stricter CO_2 emission targets** are implemented for key HDT markets worldwide

> **Country-specific factors** make for a **difficult direct comparison of stringency** across standards and long-term targets:
  - Technology baselines
  - Testing methodologies
  - Test cycles
  - Allowed payloads

Note: Emission reduction targets refer to different baseline years and technologies and are as such not like for like comparable

Source: UN, United States Environmental Protection Agency; Government of Canada; European Commission; Statista; ICCT; Desk research; Roland Berger

Low carbon solutions for heavy-duty trucks experience increased support, however at different levels between technologies and markets

Support for alternative propulsion technologies

Exemplary

	North America	Europe	Asia
1 **Fuel cell electric**	◑ Regional activities, e.g. California action plan for trucks, increasing activities in Quebec	◑ H_2 strategies, e.g. plans in GER; regional H_2 supply networks	● Strong political and industry support (Japan, South Korea)
2 **Battery electric**	◑ US industry push from established and new OEMs	◑ Increasing OEM activity on BEV truck development	● Sales quota for high adoption rate of BEV, including trucks (China)
3 **Alternative fuels**[1]	◕ Policy support for uptake of fuels & truck models (US)	◕ EU legislative push with fuel quality policies, toll exemptions	◔ Chinese truck market with increasing use of LNG
4 **Catenary**	○ Uptake restricted to demonstration projects	◔ Public-private demonstration projects, esp. in Sweden and Germany	○ Public bus models introduced; no road freight application (China)

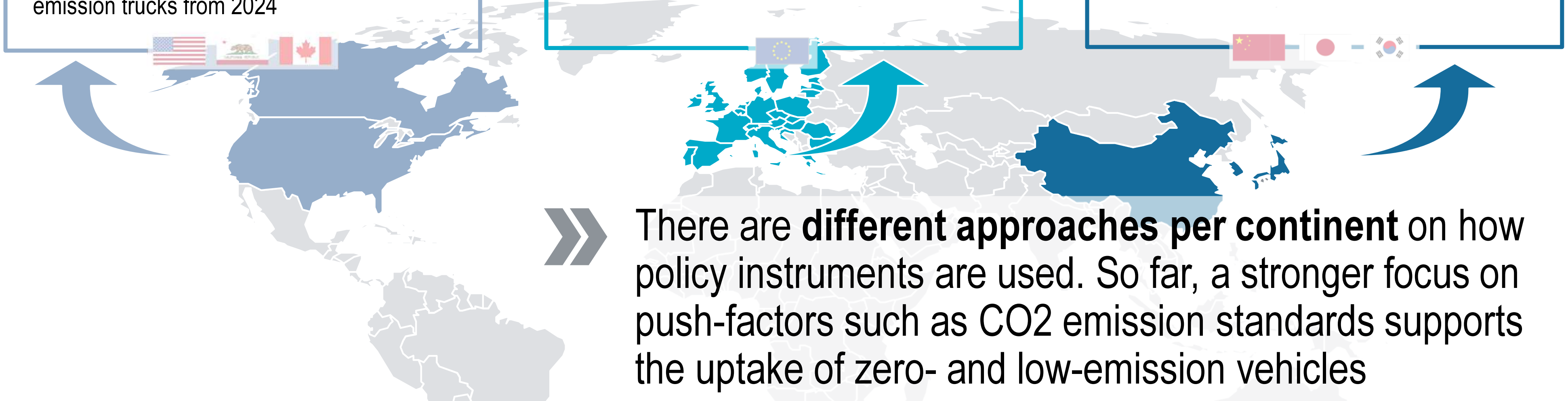
[1] Biofuels, LNG, CNG

● High support ○ Low support

Source: UN, United States Environmental Protection Agency; Government of Canada; European Commission; Statista; ICCT; Desk research; Roland Berger

North America, Europe, and Asia introduced CO_2 emission standards for HDT – China with strong focus on incentive schemes

Key insights on policy approaches by continent



North America

- **USA** and **Canada** with **fuel consumption and CO_2 emission standards; Canada** with **specific FCH strategic initiatives**
- **US Cleaner Trucks Initiative** for more stringent NO_x emissions (upcoming)
- **California** with a precedent regarding the implementation of the **Clean Air Act** as key framework for stricter targets on air quality, setting the **cornerstone for industry action**
- California also set **Advanced Clean Truck Regulation** including sales quota for zero-emission trucks from 2024

Europe

- **EU** focus on **CO_2 emission reduction** in vehicle standards and **fuel quality**
- **Truck manufacturer-specific CO_2 emissions targets** from 2025
- Individual country plans to ban fossil fuel vehicles from 2040 (e.g. France)
- **EU Green Deal** as driving force of policy development. also regarding revision of policies, e.g. Eurovignette, energy taxation, Euro VI

Asia

- **China** with **CO_2 emission standards** and **fuel consumption** regulation
- **Japan** and **South Korea** with **Euro VI based emission standards**
- China recently prolonged a strong **government NEV[1] incentive scheme** (subsidies and tax exemption) by 2 years until 2022[2]
- **S. Korea** provides strong subsidies for **hydrogen and fuel cell technology**

» There are **different approaches per continent** on how policy instruments are used. So far, a stronger focus on push-factors such as CO2 emission standards supports the uptake of zero- and low-emission vehicles

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1) NEV = New energy vehicles 2) Phase-out was planned for 2020, yet was prolonged as a consequence of the Covid-19 crisis

Source: European Commission; ICCT; Desk research; Roland Berger

With the transport sector as a main source of air pollution in Europe, targeted air quality measures are set across the continent

Selected examples of air quality approaches

European Union

> Two **EU Ambient Air Quality (AAQ) Directives**[1] set air quality standards and requirements for Member States (incl. monitoring, obligation to adopt national air quality plans, accountability in court)

> The **National Emissions Ceilings (NEC) Directive** (2016/2284/EU) sets national emission reduction commitments for 2020 and 2030 targeting six main pollutants[2]

> **National Air Pollution Control Programmes** (NAPCPs) are required in all EU Member States since 2019

> For HDT, the EURO VI regulation sets stricter **type approval standards** aimed at improved air quality through
  - Not-to-exceed emission limits
  - Stricter testing cycles
  - Independent market surveillance

National approaches

France / Paris

> **Low emission zones in place in several cities**, excl. access for vehicles below Euro 4

> **Access regulation for delivery trucks** in several cities with time restrictions

> **Plan to ban all diesel cars in 2024** in Paris**,** exemption for delivery trucks

UK / London

> **Plan to ban new petrol, diesel and hybrid car sales** from 2035, trucks not covered

> **Ultra Low Emission Zone** (ULEZ) in the City of London since 2019 and complete **ban of petrol and diesel cars** since March 2020 in **selected central parts**

Germany / Stuttgart

> **National framework of low emission zones in place** incl. vehicle bans

> **Transit bans** in several cities for **medium- and heavy-duty vehicles**

> 'Smog alarm' programme in Stuttgart for times of high particulate concentration

Spain / Madrid

> **Low emission zone in place in several cities** with eased restrictions in Madrid (2019)

> **Weight restricted access** for trucks during daytime and holidays incl. bans for heavy-duty trucks to access central city areas

1) Directives 2008/50/EC and 2004/107/EC 2) Sulphur dioxide, nitrogen oxides, volatile organic compounds, ammonia, methane and fine particulate matter

Source: European Commission; Desk research; Roland Berger

EU legislation increasingly pushes for stricter standards in emission reduction and fuel quality, hydrogen application not yet in focus

Key EU legislation – Binding / in force

Focus	Norm	Insights
Truck specifications	**CO_2 Emission Standards Regulation** (EU) 2019/1242	> Manufacturer-specific tailpipe CO_2 emission targets for new HDT: from 2025 -15%; from 2030 -30% > Incentive mechanism for zero- and low-emission vehicles with less stringent requirements and +2 t weight
	Monitoring & Reporting Reg. - VECTO (EU) 2018/956	> Manufacturer requirement to monitor and report annually the CO_2 emissions and fuel consumption of each new vehicle they produce for the EU market
	Euro VI - Exhaust emission regulation (EC) No 595/2009	> Set of regulations with strict targets in real-world NOx and particle number emissions, stricter on-board diagnostics (OBD) requirements and new testing requirements and cycles > 2019-Step E requires cold engine start targets and PEMS[1] to measure particle numbers
	Weights and Dimensions Directive (EU) 96/53/EC[2]	> Derogation of max. dimensions and weights for international traffic: Length for better aerodynamic performance and road safety (+ approx. 0.8m)[3]; Weight for accommodating alternative powertrains (+ max. 1 t)
Infrastructure	**Alternative Fuels Infrastructure Directive** 2014/94/EU	> Requirements for set-up of networks of refuelling stations for alternative fuels along primary road networks; National Policy Frameworks for the development of the alternative fuels market and deployment > H_2 not included as alternative fuel for network of mandatory refuelling stations
	RED II (EU) 2018/2001	> Overall target of 32%, transport sub-target of min. 14% of renewable energy share by 2030 > Transport sub-target requires 3,5% share of advanced biofuels, with a cap of 7% for conventional biofuels > Guarantee of Origin (GO) scheme extended for renewable and low carbon gases for more transparency
	Fuel Quality Dir. 2009/30/EC	> Reduction of the GHG intensity of vehicle fuels by 6% by 2020, regulates sustainability of biofuels
Other requirements	**Clean Vehicles Directive** 2009/33/EC, amended by (EU) 2019/1161	> National minimum procurement targets for clean mobility solutions (LDV, HDV) in public procurement: until 2025 6-10% of (waste) collection trucks and HDV; until 2030: 7-15% of (waste) collection trucks and HDV > Introduction of definition of 'clean vehicles': clean HDV are trucks/busses using alternative fuels[4]

1) Portable emissions measurement system 2) Including several amendments 3) From Sept. 2020 4) Hydrogen, BEV, PHEV, natural gas (CNG, LNG, incl. biomethane), liquid biofuels, synthetic and paraffinic fuels, LPG

Source: European Commission, Desk research; Roland Berger

Upcoming legislation likely takes an even stricter stance on emissions – Developments highly relevant for hydrogen and fuel cell tech

Key EU legislation – Upcoming

Status as of May 2020

Focus	Norm	Insights
Truck specifications	**Review of CO_2 Emission Standards Regulation** (2022)	> General review in 2022, incl. a review of 2030 targets, extension of scope to other HDVs, ZLEV incentive mechanism
	Euro VII	> Expected focus on vehicles over their respective life time, testing methodology to cover all driving conditions, and a broadened scope to include additional truck categories
Infrastructure	**Revision of AFID**[1] (exp.2021)	> Update on requirements for refuelling stations for alternative fuels with potentially compulsory targets for H_2 network
	Revision of RED II (exp. 2021)	> Revision linked to EU Green Deal will probably include requirements to further decarbonise transport fuels > Assumed bridging of fuel quality with regard to regulate renewable content and origin of transport fuels
	Revision of TEN-T (exp. 2020)	> Introduction of designated national authorities to speed up (cross-border) permit-granting processes, set a maximum time limit and foster the implementation of the TEN-T (network)
	Revision of Eurovignette Directive (exp. 2020)	> Scope extension of vehicles covered by current legislation, application of 'polluter pays' and 'user pays' principles, introduction of charging based on CO_2 standards, incl. potential 50-75 % reduction for ZEV
	Revision of Energy Taxation Directive (exp. 2021)	> Alignment of taxation of energy products and electricity with EU energy and climate policies and establishment of link to environmental performance of different energy products, e.g. electricity and fuels
	Revision of European Gas Market Strategy (exp. 2021)	> 'Gas decarbonisation package' to match Green Deal ambition currently being drafted by the EC > Expected reforms on the existing gas market regulation, of 'green' and low-carbon gases (incl. hydrogen) and a framework for integration into climate policy
Other requirements	**Legislation to match EU Green Deal ambition**	> Overarching framework for (earlier) revisions with focus on decarbonisation and long-term sustainability, e.g. Euro VII, Eurovignette, Energy Taxation, Gas decarbonisation package

1) Alternative Fuels Infrastructure Directive

Source: European Commission, Desk research; Roland Berger

Clean H_2 becomes a building block for a renewable energy system in the EU, but Member States still follow fragmented approaches

Direct support for H_2 in selected countries

- **Europe with a systemic ambition** (emphasis on renewable energy and clean hydrogen), but lacking of holistic policies: **fragmented approaches across countries**
- **Regional ecosystem approach** so far favoured through the European support of so-called **Hydrogen valleys** and **FCH JU Regions and Cities Initiative**
- Most countries **lacking a comprehensive policy approach** along the entire value chain: strong focus on **mobility end-user** support
- In 2020, **multiple new national H_2 strategies** have been launched alongside **significant budget announcements** (e.g. GER, FRA, SPA, POR, etc.) which will **improve** the **availability of direct support**

		Production		Distribution		Applications		
		Supply[1]	Demand[2]	Supply[1]	Demand[2]	Supply[1]	Demand[2]	
🇪🇺	Incentives	⬜	🟦	⬜	🟦	⬜	🟦	**Framework regulation & targeted project support:** e.g. **altern. fuel**, **clean vehicle** and **RED II** directive complemented by **FCH 2 JU** support
	Regulations	⬜	🟦	⬜	⬜	🟦	🟦	
🇳🇱	Incentives	⬜	🟦	⬜	🟦	⬜	🟦	**Central long term strategy and budget:** e.g. **H_2 mobility** impl. plan and deploy. plan centrally channel support efforts
	Regulations	⬜	⬜	⬜	⬜	⬜	🟦	
🇩🇪	Incentives	⬜	🟦	⬜	⬜	🟦	🟦	Focus **on transport, additional incentives** for **stationary applications:** e.g. Clean Air Action and National Hydrogen Strategy
	Regulations	⬜	⬜	⬜	⬜	⬜	🟦	
🇬🇧	Incentives	⬜	🟦	⬜	🟦	⬜	🟦	**Balanced approach:** e.g. **OLEV** and **ULEZ** (Ultra Low Emission Zone) drivers for transport and piloting incentives for **heating sector** ongoing
	Regulations	⬜	🟦	⬜	🟦	🟦	🟦	
🇫🇷	Incentives	⬜	⬜	⬜	🟦	🟦	🟦	Focus **on transport and heating** applications mainly via **demand-/user-side** through **subsidies and incentives**
	Regulations	⬜	⬜	⬜	🟦	⬜	🟦	
🇳🇴	Incentives	⬜	⬜	⬜	⬜	⬜	🟦	**Substantial (tax) incentives:** e.g. **few incentives for infra. via Enova** agency, but **tax breaks** facilitate lower cost for ZEV
	Regulations	⬜	⬜	⬜	⬜	🟦	🟦	

🟦 Instruments in place ⬜ No instruments in place

[1] Targeting the 'producer' side (e.g. electrolysers OEM for production, RFS OEM for distribution, FCEV OEM for applications)

[2] Targeting the 'consumer' side (e.g. electrolysers operator for production, RFS operator for distribution, FCEV end-consumer for applications)

Source: Roland Berger

The analysis of individual national regulatory frameworks shows a strong overall focus on support for the H_2 demand side

Direct H_2 support in Europe

Selection

		Production		Distribution		Applications		
		Supply	Demand	Supply	Demand	Supply	Demand	
🇮🇹	Incentives	⬜	⬜	⬜	🟦	⬜	🟦	Incentives and regulatory instruments dedicated to mobility, e.g. decree 257 for HRS implementation
	Regulations	⬜	⬜	⬜	🟦	⬜	🟦	
🇩🇰	Incentives	⬜	⬜	⬜	⬜	🟦	🟦	Focus on both maritime and road transport with strong incentives and restrictive concessions
	Regulations	⬜	⬜	⬜	⬜	⬜	🟦	
🇪🇸	Incentives	⬜	⬜	⬜	⬜	⬜	🟦	Focus on mobility via financial incentives and enabling regulations for infra. for alternative fuels
	Regulations	⬜	⬜	⬜	🟦	⬜	🟦	
🇦🇹	Incentives	⬜	⬜	⬜	⬜	⬜	🟦	Favourable regulatory framework led by deeply committed government and industries
	Regulations	⬜	⬜	⬜	⬜	⬜	🟦	
🇸🇪	Incentives	⬜	⬜	⬜	⬜	⬜	🟦	Focus on the transport sector with preferential conditions for private FCEVs and FCEBs
	Regulations	⬜	⬜	⬜	⬜	⬜	🟦	
🇧🇪	Incentives	⬜	⬜	⬜	⬜	⬜	🟦	Exemption of taxes for FCEVs and associated grants as most meaningful public action
	Regulations	⬜	⬜	⬜	⬜	⬜	🟦	
🇬🇷	Incentives	⬜	⬜	⬜	⬜	⬜	⬜	Regulatory framework on H_2 to be developed in the near future (exp. certification system, investments, P2G
	Regulations	⬜	⬜	⬜	⬜	⬜	⬜	
🇵🇱	Incentives	⬜	⬜	⬜	⬜	⬜	⬜	Lack of regul. on H_2 but expected policies implementation following 'Polish persp. on H_2'
	Regulations	⬜	⬜	⬜	⬜	⬜	⬜	
🇨🇭	Incentives	⬜	⬜	⬜	⬜	⬜	⬜	No policy dedicated to H_2 despite strong projects in mobility and potential injection into the gas grid
	Regulations	⬜	⬜	⬜	⬜	⬜	⬜	

🟦 Instruments in place ⬜ No instruments in place

Source: Roland Berger

Subsidies and tax exemptions have been much used to foster H_2 development – Use of such instruments promising for FCH HDT

Possible regulatory instruments and link to H_2 support

		Description	Potential beneficiaries	Currently in use in
Technology supply[1]	**Investment subsidy**	**One-time non-repayable subsidy** directly received by the organization investing into production facilities	FCH industry realising supply side investments	🇪🇺 🇫🇷 🇩🇪 🇬🇧 🇳🇱 🇳🇴 🇸🇪 🇩🇰
	Tax break	**Exclusion from tax payments** / reduction of taxes for a defined sector to incentivize private investment	FCH industry realising supply side investment to increase product availability	🇫🇷 🇩🇪 🇬🇧 🇳🇱 🇳🇴 🇸🇪 🇩🇰
	Customs tariff breaks	**Deferral of taxes** for later payment / refund on inputs imported for manufacturing goods locally	FCH industry realising supply investment (e.g. electrolysis equipment production)	🇳🇴
	Guarantee	Legally binding **indemnity bond** backed by a public institution to ensure loan repayment in case of default	Large scale public / private investment projects following specific political objectives	🇪🇺 🇫🇷 🇩🇪 🇬🇧 🇳🇱 🇳🇴 🇸🇪 🇩🇰
Technology demand[2]	**CAPEX / OPEX subsidy**	**Fixed-time subsidies** to reduce initial investment requirements / increase confidence in investment	FCH OEMs and infrastructure operators, project promoters, individual customers	🇪🇺 🇫🇷 🇩🇪 🇬🇧 🇮🇹 🇳🇱 🇳🇴 🇸🇪 🇩🇰 🇪🇸
	Tax breaks	**Deduction** / **tax breaks** / **tax credits** to stimulate purchase of new technologies and drive investment	End-customers of FCH products, FCH OEMs, infrastructure operators, projects	🇫🇷 🇩🇪 🇬🇧 🇳🇱 🇮🇹 🇳🇴 🇸🇪 🇩🇰 🇧🇪
	Repayable grants / loans	**Funding with expected payback** after a certain period / predetermined level of success	Potential project promoters for FCH deployment, individual customers of the technology	🇫🇷 *No H_2 funded project identified*
	Match funding	Tool to **guide industrial activity** in a specific area of interest through **boundary conditions**	Hydrogen projects (industrial advances in technology / applications), individual customers	🇪🇺 🇩🇪
	Usual energy instruments	**Contracts for difference** / **Feed-in tariffs** / **capacity compensation** to stimulate investments	FCH industry and infrastructure operators, investors (e.g. HRS, facilities, etc.)	*Not existing for H_2 / FCH sector (currently)*
Other	**Permissible derogations**	**Derogation from legislative requirements** under specific conditions that favour alternative technology solutions	FCH OEMs and individual customers (e.g. logistics users, etc..)	🇪🇺

1) Instruments supporting the build-up of H_2 and FCH technology production capacities (regular industrial policy tools with generally no specific H_2 / FCH focus)
2) Instruments supporting the deployment of H_2 and FCH technology in the market (mainly relying on public financial support)

Source: Press review, Roland Berger

FCH HDT commercialisation to further benefit from specific support schemes that drive ZLEV development across industry segments

Support schemes[1] for ZLEV commercialisation

Exemplary

General support of uptake (e.g. political) | **Truck manufacturing** | **Technology provision** | **Infrastructure and energy provision** | **End use / operation**

- 🇪🇺 Trans-European Transport Network (TEN-T) with available funding: Connecting Europe Facility (CEF), European Fund for Strategic Investment (EFSI), Horizon 2020 / Horizon Europe, European Structural and Investment Funds (ESIFs)
- 🇪🇺 H_2-specific: Public private partnership Fuel Cell and Hydrogen Joint Undertaking (FCH 2 JU), incl. funding schemes
- 🇪🇺 H_2-specific: Clean Hydrogen Alliance with support for Projects of Common European Interest
- 🇰🇷 🇫🇷 H_2-specific: Government roadmaps[2], incl. funding and focus specifically on H_2: Hydrogen Economy Roadmap (KR), Hydrogen Deployment Plan (FR)
- 🇩🇪 H_2-specific: Nat. Organisation Hydrogen and Fuel Cell Technology (NOW GmbH) implementing the Nat. Innovation Programme Hydrogen and Fuel Cell Techn.

Truck manufacturing

- 🇪🇺 Super-credit system with less stringent requirements for ZLEV manufacturers
- 🇪🇺 National targets for ZLEV in public procurement
- 🇺🇸 Sales quota for ZEV and plug-in hybrid cars
- 🇨🇳 Sales quota for PHEV, FCEV, BEV, hybrid vehicles

Technology provision

Push factor for technology providers

Potential for further support schemes?

Infrastructure and energy provision

- 🇪🇺 Target for share of renewable energy use in fuels
- 🇪🇺 National targets for refuelling points for alternative fuels
- California programme to co-fund hydrogen fuelling stations
- 🇨🇳 National targets, funding and standards for EV charging infrastructure
- 🇯🇵 Funding for alternative fuels refuelling stations

End use / operation

- 🇳🇱 One-off purchase tax exemption[2]
- 🇨🇭 Temporary exemption from vehicle tax
- 🇳🇴 Road toll exemptions for ZLEV[2]
- California programmes for fleet replacement (vouchers and loans)
- 🇨🇳 Subsidies and purchase tax exemptions

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1) Support schemes refer to targets and credit systems set in policies, incentive schemes and government initiatives that foster zero and low emission vehicles
2) Example, other countries offer the same or similar support.

Source: European Commission; ICCT, Desk research; Roland Berger

Governments are developing strategies and make strong commitments to develop hydrogen sectors, also often addressing HDT

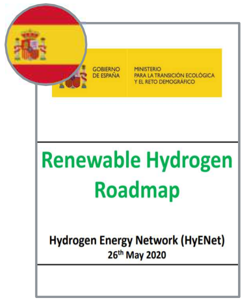
Example of hydrogen strategy plans and roadmaps

as of August 2020


European Commission
A Hydrogen Strategy for a climate neutral Europe
#EUGreenDeal
8 July 2020

Hydrogen strategy for a climate neutral EU

Commission's economic recovery plan 'Next Generation EU' highlights hydrogen as an investment priority to boost economic growth and resilience, create jobs and consolidate global leadership.


GOBIERNO DE ESPAÑA
MINISTERIO PARA LA TRANSICIÓN ECOLÓGICA Y EL RETO DEMOGRÁFICO
Renewable Hydrogen Roadmap
Hydrogen Energy Network (HyENet)
26th May 2020

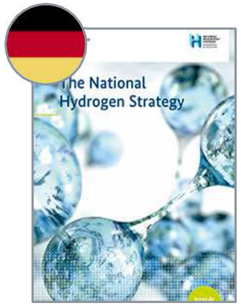
Renewable hydrogen roadmap

According to the government's roadmap for hydrogen, Spain could install 4 GW of electrolyser capacity by 2030 and export renewable hydrogen to other EU states. Due to its renewable power potential, Spain aims at becoming an EU hydrogen giant.


EN-H_2
ESTRATÉGIA NACIONAL PARA O HIDROGÉNIO

EN-H2 national hydrogen strategy

The Portuguese hydrogen strategy is expected to generate investments in the order of EUR 7-9 billion by 2030. Its central strategic points revolve around the creation of an anchor project and the decarbonisation heavy transport.


The National Hydrogen Strategy

The national hydrogen strategy

According to the strategy, "only hydrogen produced on the basis of renewable energies is sustainable in the long term". Therefore, The German government set the goal to use green hydrogen, to support a rapid market ramp-up and to establish corresponding value chains.

Government strategy on hydrogen

The Dutch government shared its hydrogen strategy via a letter to the house of representatives. The intention is to underline the importance of the development of clean hydrogen and the unique starting point of NL.


Plan de déploiement de l'hydrogène pour la transition énergétique

Hydrogen deployment plan for the energy transition

The plan is set to ensure hydrogen development as an asset for France's energy independence, leveraging France's position including many leading industry players on the international stage.

Note: Government across Europe launched national hydrogen strategies as part of their post-COVID-19 recovery plans. The above publications are examples only and do by no means constitute a judgment on market maturity for FCH technology

Source: Government websites, Press Clippings, Roland Berger

C. Business cases and market potential

C.1 Modelling approach

The economic potential of FCH HD trucks is assessed with a TCO analysis, market potential assessment and tangible case studies

Overview

Business cases and market potential

I High level analysis

II Specific examples

1 TCO[1] assumptions

> Development of Excel-based TCO model built on assumptions in line with RB OEM project experience and Advisory Board member feedback

2 TCO results

> Analysis comparing the total cost of ownership of trucks with conventional and alternative powertrains

3 Sensitivity analyses

> Specific analysis of the main cost drivers of the TCO model, review of sensitivity of results to pre-defined changes

4 Market potential

> Assessment of a potential market development in Europe, focusing on the uptake of FCEV technology

Based on defined use cases

+

5 Case studies

> Analysis of specific examples of real life operations to provide a tangible illustration of the potential implications of FCEV introduction for the heavy-duty transport industry

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1) Total cost of ownership

Source: Roland Berger

For the TCO and market potential analysis, we define three use cases that represent key segments of the HDT sector

Segmentation of HDT sector[1]

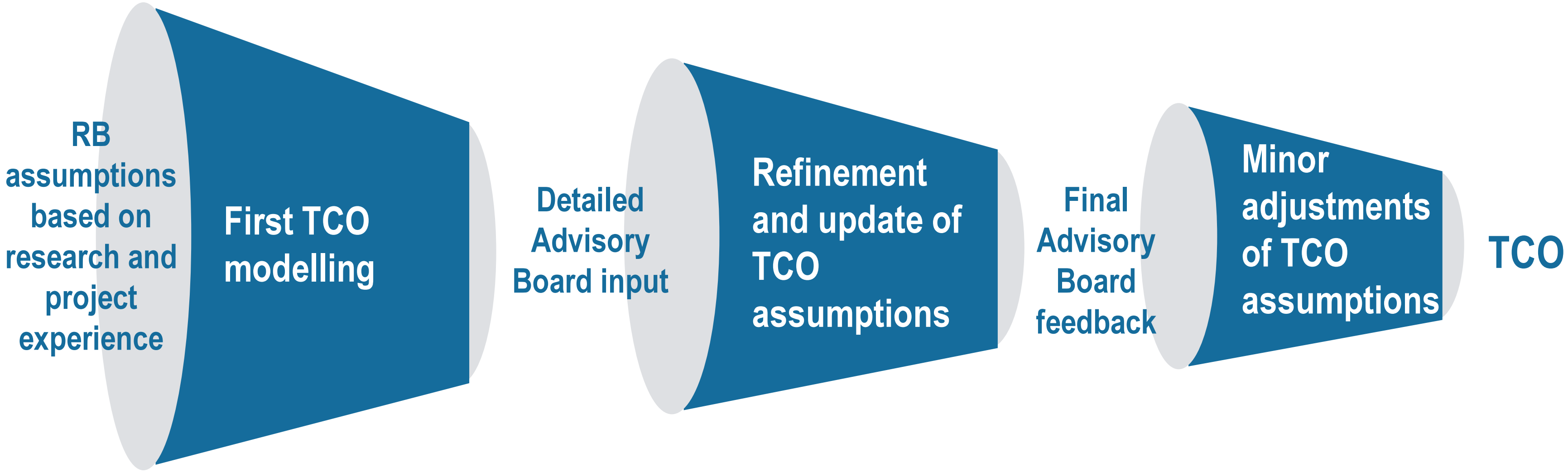
	Step 1 Choose use cases	Step 2 Choose technologies	Step 3 Evaluate use cases	Step 4 Choose/evaluate case st.
Description	A ≥18 t on-road truck of a logistics provider running on international line haul routes (example)	Fuel cell electric, ICE with regular fuels, battery electric would be technology examples, which must be prioritised	Use cases are detailed in terms of average route and truck characteristics to assess OPEX, CAPEX, etc.	"Gothenburg-Hamburg-Stuttgart-Rome" as a case study example for intern. line haul of a logistics provider to compare technologies
Goal	Definition of those use cases to be considered throughout the study	Definition of technologies to compare to FCH technology throughout the study	Understanding of major drivers of fuel cell electric HDT's advantageousness	Concretisation and validation of results of step 3
Tasks	> Define truck types, route types, vehicle user types > Chose 3 combinations of truck type, route type, vehicle user type	> Define technological alternatives > Chose technological alternatives to be considered	> Assess OPEX, CAPEX etc. of chosen technology per use case > Compare results across use cases	> Identify specific routes > Chose 3 routes / use case > Assess OPEX, CAPEX etc. of chosen technology per case study

1) The key segments of the HDT sector that serve as a basis for the three selected uses cases are described in further detail in chapter C.2.1 use cases.

Source: Roland Berger

The TCO model acts as a key pillar for the market potential analysis and case studies – Development of assumptions to be finalised

TCO model development process



TCO development steps

RB assumptions based on research and project experience

First TCO modelling

Detailed Advisory Board input

Refinement and update of TCO assumptions

Final Advisory Board feedback

Minor adjustments of TCO assumptions

TCO

Main focus	> Alignment on modelling approach > Development of assumptions > Set up of Excel model structure	> Bilateral exchange and alignment of assumptions with Advisory Board members industry experience > Adjustment of TCO model to reflect revised assumptions	> Minor refinement of TCO model assumptions > Selected sensitivity analyses > Market potential analysis
Result	> **Preliminary TCO model based on RB assumptions**	> **Updated TCO model incl. assumptions aligned with Advisory Board**	> **Final TCO model used for market potential analysis and case study calculation**

Source: Roland Berger

The methodology is based on the use cases and key assumptions – Capital, fuel, O&M and infrastructure costs make up the TCO

Schematic methodology of TCO modelling

Application scenario

Use case:

- Use case 1 (40t, tractor 4x2)
- Use case 2 (27t, rigid 6x2)
- Use case 3 (18t, rigid 4x2)

Deployment context and target operating model:

- Annual mileage
- Route characteristics
- Payload
- Market assumption (Niche to Mass)

Comparison of reference category Diesel with alternative technologies

Truck specifications and performance

- Powertrain technology
- Engine
- GCWR
- Truck type
- Motor vehicle tax
- Energy/fuel tax
- Road toll
- CO_2 emissions per fuel type

Infrastructure specifications

- HRS[1], H_2 production facility
- Catenary grid
- Mass vs. niche market

1. Capital cost

- Investment/depreciation
- Financing cost

2. Fuel/Energy cost

- Fuel/Energy consumption
- Fuel/Energy price (depends on production, input prices)

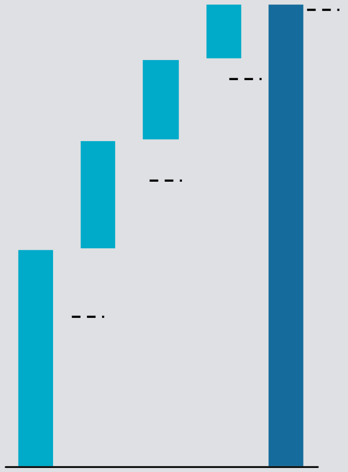
3. Other O&M cost

- Maintenance, personnel, utilities
- Road toll, taxes

4. Infrastructure cost

- Investment/depreciation
- O&M cost

Total Cost of Ownership (TCO) in EUR/Truck and EUR ct/tonne-km



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1) Hydrogen refuelling station 2) Niche <5.000 units/year; Rather niche <10.000 units/year; Rather mass >50.000 units/year (~10% of market); Mass <150,000 units/year (~30% of market)

Source: Roland Berger

The European HDT market is modelled based on TCO comparison of the different propulsion technologies in use case sub groups

Link between TCO model and market model

TCO Model

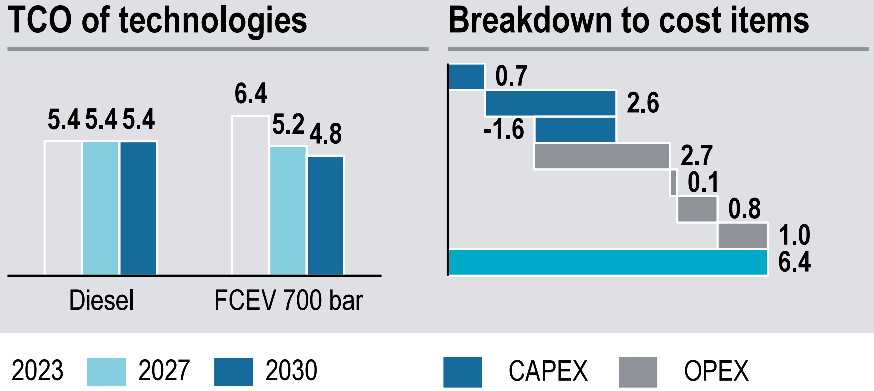
General
- Duration 1st & 2nd life
- Maintenance cost
- Insurance and Taxes

Energy/Fuel
- Prices
- CO_2 Emissions
- Infrastructure

Truck
- Cost
- Consumption
- Payload

&

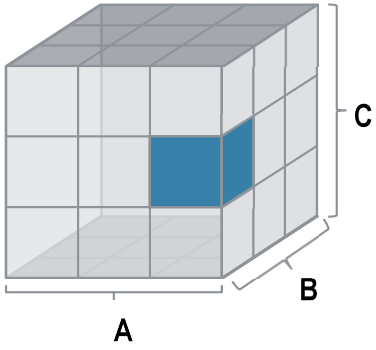
Use case I – Tractor 4x2
- TCO comparison of Diesel, Diesel e-fuels, FCEV (350 bar, 700 bar, LH_2), BEV and catenary technology



Source: Roland Berger

Market Model

Break down use case by:
- A – Customer groups
- B – Annual mileage group
- C – Range requirements group



For each use case, sub group technology decision based on:
- TCO (based on TCO models)
- Technology acceptance

Outputs:
- **Market volume**
- **Sales share** of each use case
- **Technology share** in each use case

Further details on the market modelling approach to be found in chapter C.2.3

Use case I – Tractor 4x2

C.2 Results

The decarbonisation of road transport is a call to action – Business cases are at the centre of discussion on zero-emission alternatives

Rationale on business cases and market potential analyses

Key considerations

- The road freight sector is a **significant source of CO_2 emissions** in the EU with HDV accounting for ~ 25% of specific road transport CO_2 emissions
- FCH heavy-duty trucks are attributed an **important role in zero-emission transport** and a **near-term market uptake is assumed**
- Currently, there is **very limited field data** on FCH heavy-duty trucks – Assumptions on **performance** and predicted **cost developments are based on prototypes** and **industry knowledge** are to be verified in first demonstrations and early commercial deployments
- A detailed investigation of business cases (TCO) illustrates the **economic and environmental potential** for the industry and identifies **fields of action for decision-makers** setting up targeted support schemes
- The analysis of **short- and mid-term market potential** (2023 / 2027 / 2030) integrates the views on **vehicle costs, technology acceptance** and the determined **CO_2 emission reduction trajectory** until 2050

Source: Roland Berger

Current data and industry stakeholder perspectives are integrated in the business case analyses – Influencing factors are considered

Key influencing factors to enable a future FCEV market

1 Technology

- Industrialisation levels for **lower component costs**
- **Infrastructure availability** (local and trans-regional)
- Increasing **field data** beyond the **current prototype state of development**
- **Development of specific heavy-duty trucks** suitable for fuel cell and hydrogen technology
- Focus on **specific road freight segments** that allow for rather short-term decarbonisation potential (i.e. logistics vs. special purpose vehicles)

2 Policy and support

- Regulation providing for **framework conditions** favouring FCH technology to **ensure scale effects** – infrastructure, investment costs, etc.
- **Activation of all market actors** (e.g. OEMs, technology providers, end customers) to ensure the **commitment of the whole sector**
- **Support of FCH technology** vis-à-vis other zero-emission technologies (in certain applications)
- Stringent **trajectory** towards the **2050 CO_2 emission reduction targets**

3 Customer acceptance

- **Share of business risks** across the sector and with other parties
- **Subsidies / incentives** that allow **comparable business cases** to current diesel trucks
- **Security** on **performance and reliability** of powertrain technology
- **Change in composition of fleets** with higher share of alternative powertrain vehicles
- Potentially **acceptance of some operational changes**, e.g. intra-day refuelling stops

Source: Advisory Board members; Roland Berger

The TCO model shows the cost competitiveness of FCH technology and its market potential – Important drivers for uptake are identified

Insights derived from analyses

Analyses

Business cases (TCO)

- A **significant cost down potential for FCEV at scale** is identified for all H_2 onboard storage technologies from 2023 to 2030[1]
- **Main cost drivers** are cost of powertrain (CAPEX) and **energy / fuel costs** (OPEX)

Market volume potential

- **FCEV have a high potential** within the whole truck market – **steep increase in sales share from 2023 to 2030** in the analysed market segments based on the cost assumptions

High potential for FCH technology with cost competitiveness from 2027 onwards

Insights

How to get to a FCEV market?

- Analysis shows that it is **specifically the economies of scale that will make competitiveness of FCH technology possible** – the main technology elements is already mature and in place
- **Uptake of technology and facilitation of market scaling** are crucial:
  - Industrialisation with **lower component costs** and **volume ramp-up**
  - **'Affordable' hydrogen costs**
  - **Infrastructure availability**
- **Policies** needed that target and ensure **these framework conditions**
- **Industry and end users** of trucks **need to signal strong commitment to provide [for]** (OEMs, technology provider, HRS infrastructure and H_2 supplier) **and deploy** the **FCH trucks** (logistics operator and users)

---

[1] Research on hydrogen onboard storage technologies is still ongoing – Remaining uncertainties regarding different storage technologies also impact the cost down potential in future scenarios; ongoing FCH JU projects like the PRHYDE project specifically focus on this research & development field

Source: Roland Berger

The TCO results indicate that FCH HD trucks could become a viable alternative in the first half of the decade if scale up is pushed

Overview of TCO results

See chapter C.2.2

Base case assumptions

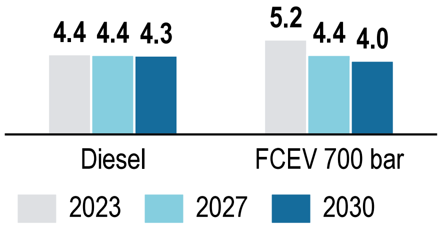
- > **Base case assumptions** are the basis for the TCO calculation of **each use case**
- > **Parameters** in the TCO model are set to **match the most common usage** (i.e. annual and daily mileage) for each use case
- > **Specific assumptions** for the different alternative powertrain **technologies are made over time**

TCO results per use case

- > The **high level TCO results** indicate a cost premium of up to ~22% in 2023 for FCH trucks compared to diesel
- > A **significant cost down potential for FCEV at scale** is indicated for all H_2 storage technologies across the use cases

Use case I example

[EUR ct/tonne-km]

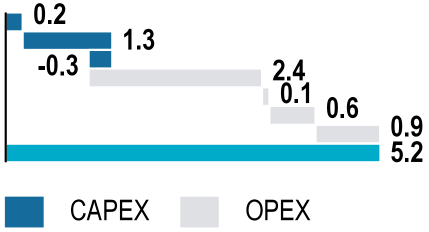


Cost drivers per use case

- > The analysis of **main cost drivers** shows that **fuel cell costs** (CAPEX) and **energy / fuel costs** (OPEX) have the most influence on the TCO of all FCEV applications

Use case I example

FCEV 700 bar, 2023 [EUR ct/tonne-km]



Sensitivity analyses

- > **Sensitivity analyses confirm the results** that TCO for FCEV are lower than BEV for most cases
- > **Specific parameters** with the **highest impact** are identified
- > Sensitivity results show that **FCEV could become an viable alternative to diesel, esp. in 2030**, assuming favourable conditions

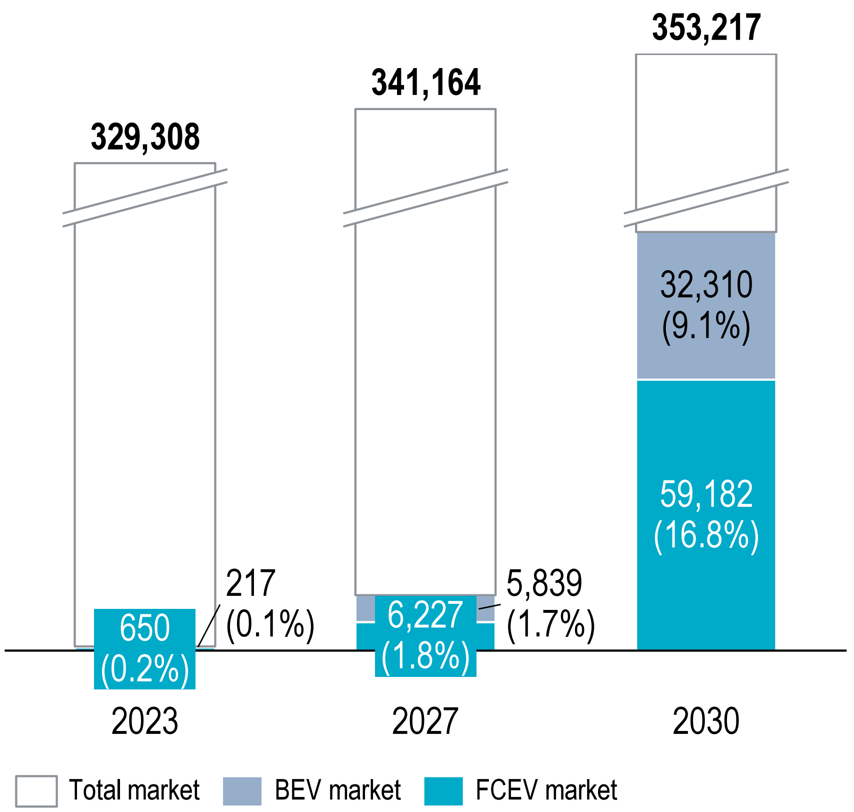
Source: Roland Berger

The market potential analysis shows a clear potential for alternative technologies and a changing technology split until 2030

Overview of market potential results (base scenario)

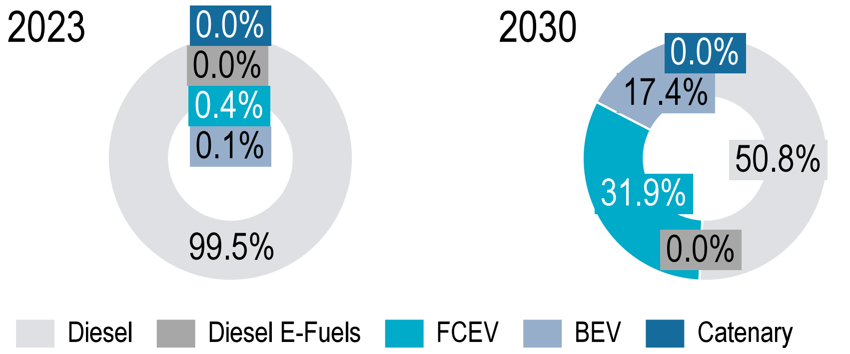
See chapter C.2.3

European market potential of FCEV [# of truck sales][1]



- The **market potential** analysis focuses on **selected market segments**[2] with a sales share of ~53%
- Overall, **FCEV have a high potential** within the whole truck market – **steep increase in sales share** from 0.2% in 2023 to **16.8% in 2030**
- Within the specific market segments, the **technology split** shows **clear changes between 2023 and 2030**: FCEV technology represents ~32% in 2030

Market segment technology split [%]



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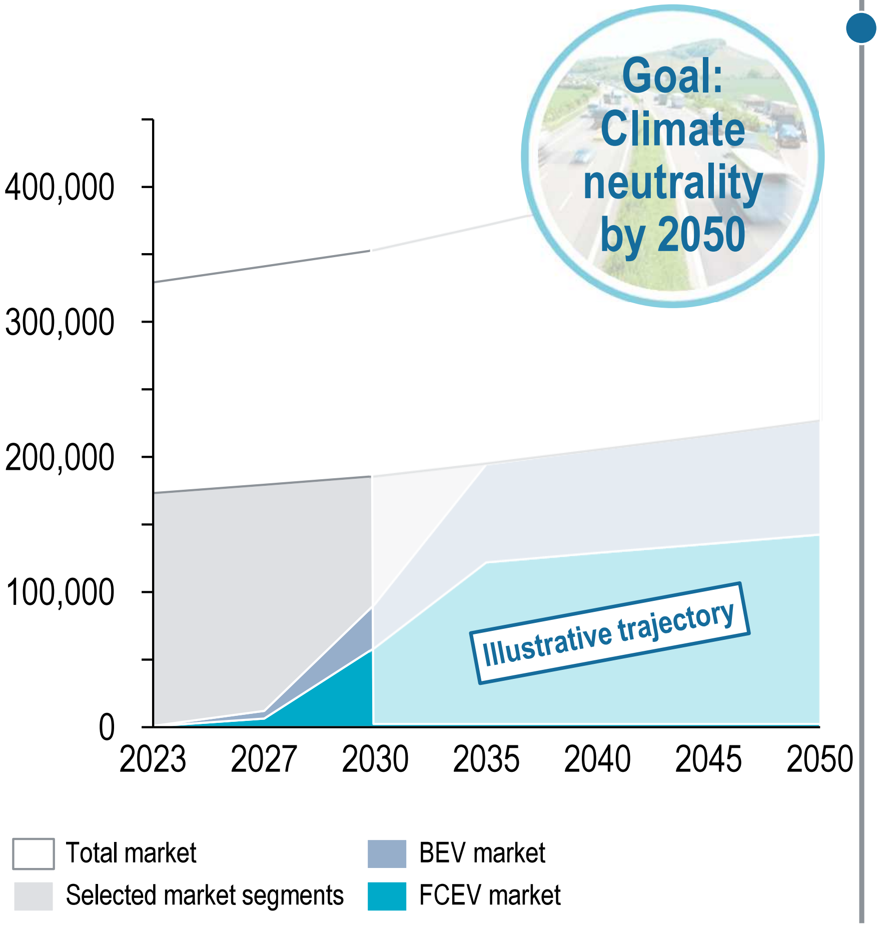
[1] Results based on absolute EUR/truck results, not payload corrected

[2] The market potential analysis refers to specific market segments: international logistics, national logistics, manufacturing industry, wholesale, retail and regional logistics, i.e. ~

Source: IHS market forecast; Roland Berger

The market development over the next ten years is crucial for achieving the 2050 climate goals – Fleet replacement required

Assessment of 2050 market potential



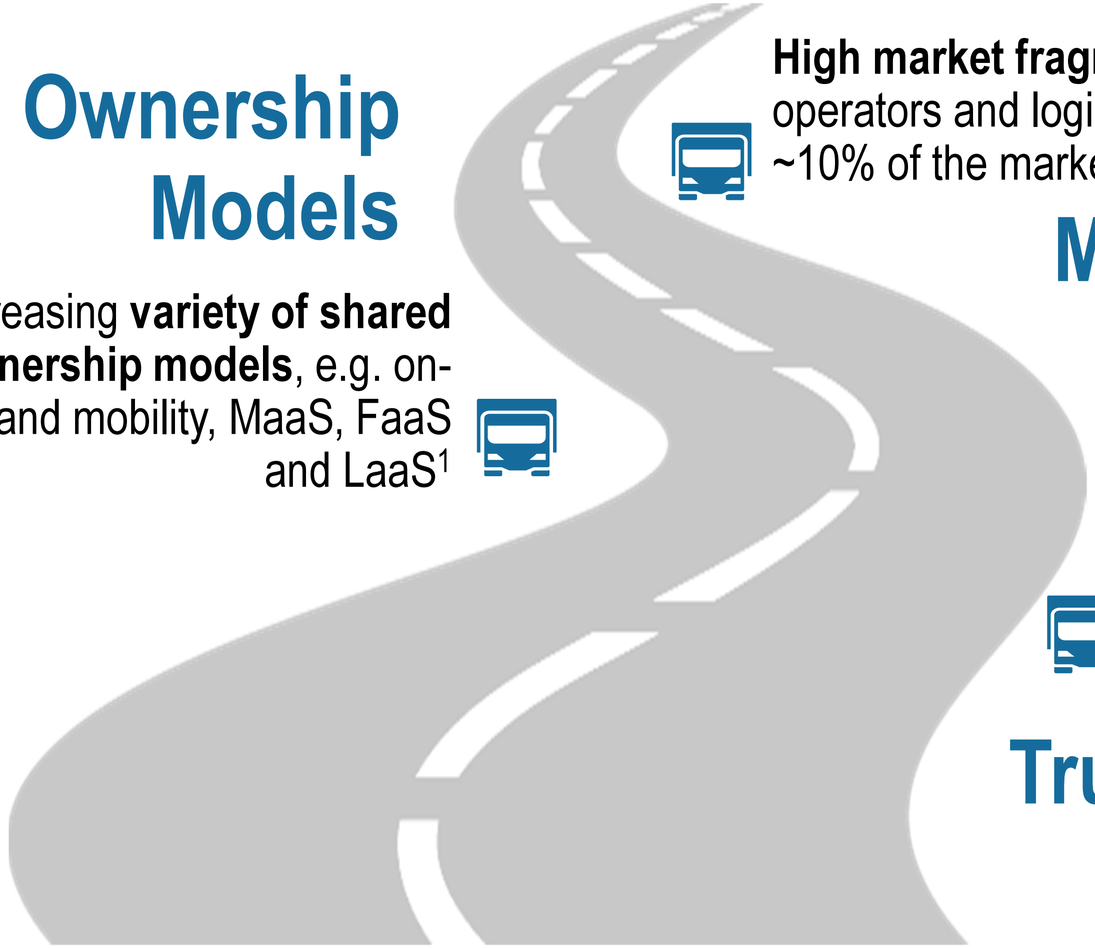
- The **CO_2 emission reduction targets for 2050 in transport can be reached** for the heavy-duty truck segment – if the projected **growth rate of zero emission technology until 2030** materialises
- As **zero-emission trucks become cost-competitive,** new sales of diesel trucks and other **CO_2-intensive technology** should be fully **replaced from 2035** onwards
- The **projected trajectory is necessary to replace** the majority of the fleet of **diesel** trucks until 2050 assuming 10 to 15 year replacement cycles of trucks
- Put simply, to achieve **95% emission** reduction in transport by 2050 **requires** almost **only zero emission vehicles sales by 2035**
- Critical factors:
  - **Push to market** for zero-emission trucks to ensure **scaling effects for cost competitiveness** and market uptake
  - **Enable infrastructure availability** to allow for widespread deployment
  - **Change within fleets** and **diesel phase-out** until 2035 as diesel trucks have a total lifetime of 10+ years
  - **Specific mandatory targets for all market actors** – OEMs in scope of HDT legislation, yet contribution across the whole sector necessary

Source: Roland Berger

C.2.1 Use cases

Europe's transport sector is highly fragmented with a variety of ownership models – Deployed truck types as common ground

Road freight sector in the EU (1/3)



Ownership Models

Increasing **variety of shared ownership models**, e.g. on-demand mobility, MaaS, FaaS and LaaS[1]

Market fragmentation

High market fragmentation, as Top 10 of operators and logistics providers account for ~10% of the market

Truck types

Tractor-trailer and rigid trucks are most common in the heavy-duty segment – vehicles deployed in different use case, applications and industry sectors

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1) MaaS: Mobility as a Service; FaaS: Freight as a Service; LaaS: Logistics as a Service

Source: Roland Berger

Changes in the market are expected to affect the logistics landscape and the structure of operating market players

Road freight sector in the EU (2/3)

Transport and logistics market segments		Fleet size	Market share1)	Trend	
Segment	Definition				
Owner-driver	> Truck driver owns truck > Works as subcontractor and/or covers market niche	1	~15-25%	Affected by market consolidation but covering market niches	↘
Small/mid-sized fleet operator	> Works as subcontractor and/or covers market niche > Lower professionalisation due to lack of economies of scale	2-20	~35-40%	Affected by market consolidation due to competitive disadvantages	↘
Municipalities	> Fleets operated by public authorities > Transport not a core function	up to 100	~5-10%	Ongoing privatisation partly resulting in decreasing relevance	↘
Special vehicle fleet operator	> Focus on specific transport needs > High professionalisation in their segment	1-5	<5%	Stable demand in the coming years expected (depending on industry segment)	↗
Large fleet operator	> Large logistics providers or large corporate fleets > Highly professionalised, e.g. some with own repair shops	>100	~25-35%	Growth due to cost advantages (e.g. due to own repair shops, improved utilisation)	↗

Trend: ↘ Decreasing → Stable ↗ Increasing

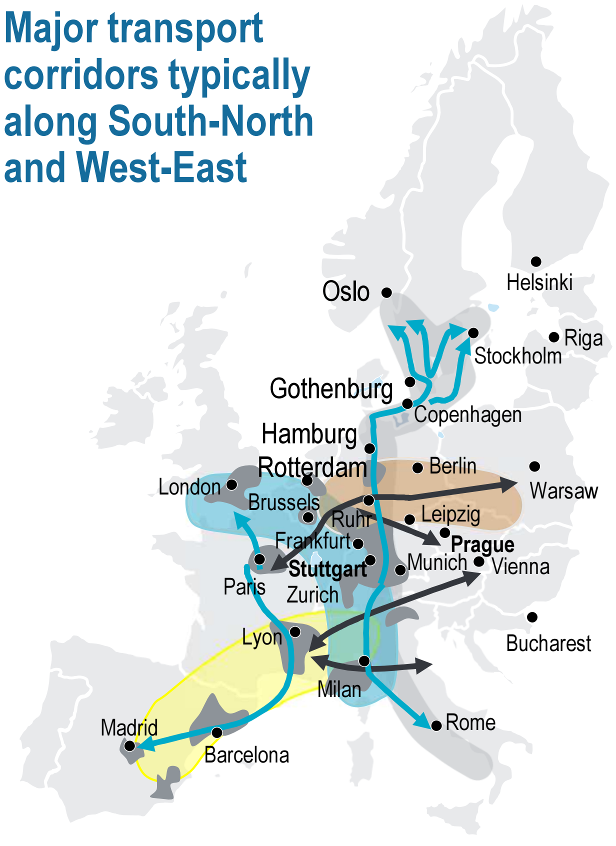
1) Estimate based on market insights for Western Europe

Source: Expert interviews; desk research; Roland Berger

The road freight sector is a strong pillar of the exchange of products and goods across Europe, yet a significant source of CO_2 emissions

Road freight sector in the EU (3/3)

Major transport corridors typically along South-North and West-East



→ Transportation North-South
→ Transportation East-West

Conurbations and logistics hubs
Scandinavia-Mediterranean-corridor

'Blue Banana'-corridor (UK-BE-NL-GE-CH-IT)
'Golden Banana'-corridor (Mediterranean cost)
New East-West corridors, e.g. Germany-Poland

6,6 m **trucks drive in the EU** (medium- and heavy-duty)

300 k **new heavy-duty trucks** are sold in Europe **every year**

~5% **of total EU CO_2 emissions** come from heavy-duty road transport

~27% of specific **road transport CO_2 emissions** in the EU come from **lorries, buses and coaches**

Source: European Commission; EEA; ACEA; Colliers; Savills; desk research; Roland Berger

The EU is tackling this by introducing stricter CO_2 standards targeting the heavy-duty sector – Starting point for the study's use cases

Rationale behind the selected use cases

> **Regulation (EU) 2019/1242** on CO_2 emission standards for heavy-duty trucks sets **tailpipe CO_2 emission performance targets** for **new trucks – Targets are set at level of sub-groups**
  - HDT sub-groups refer to delivery vehicles:
    - all 6x2 tractor and rigid trucks (all weights)
    - all 4x2 tractor and rigid trucks above 16 tonnes
  - HDT sub-groups also account for different use profiles: urban, regional, long haul

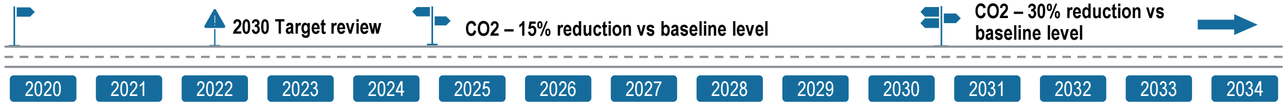
These **truck types** are responsible of **up to 70% of total HDV CO_2 emissions – 4x2 tractors contribute by far the most**, accounting for **up to 38% of these emissions**

> **CO_2 emission targets are binding**[1] and **manufacturer-specific**

> **Incentive mechanism for zero- and low-emission vehicles (ZLEV)**[2] with less stringent requirements is put in place

OEMs identified long-haul heavy-duty trucks as the market segment with the **highest potential** to ensure their efforts in complying with the legislation

Regulation (EU) 2019/1242 timeline



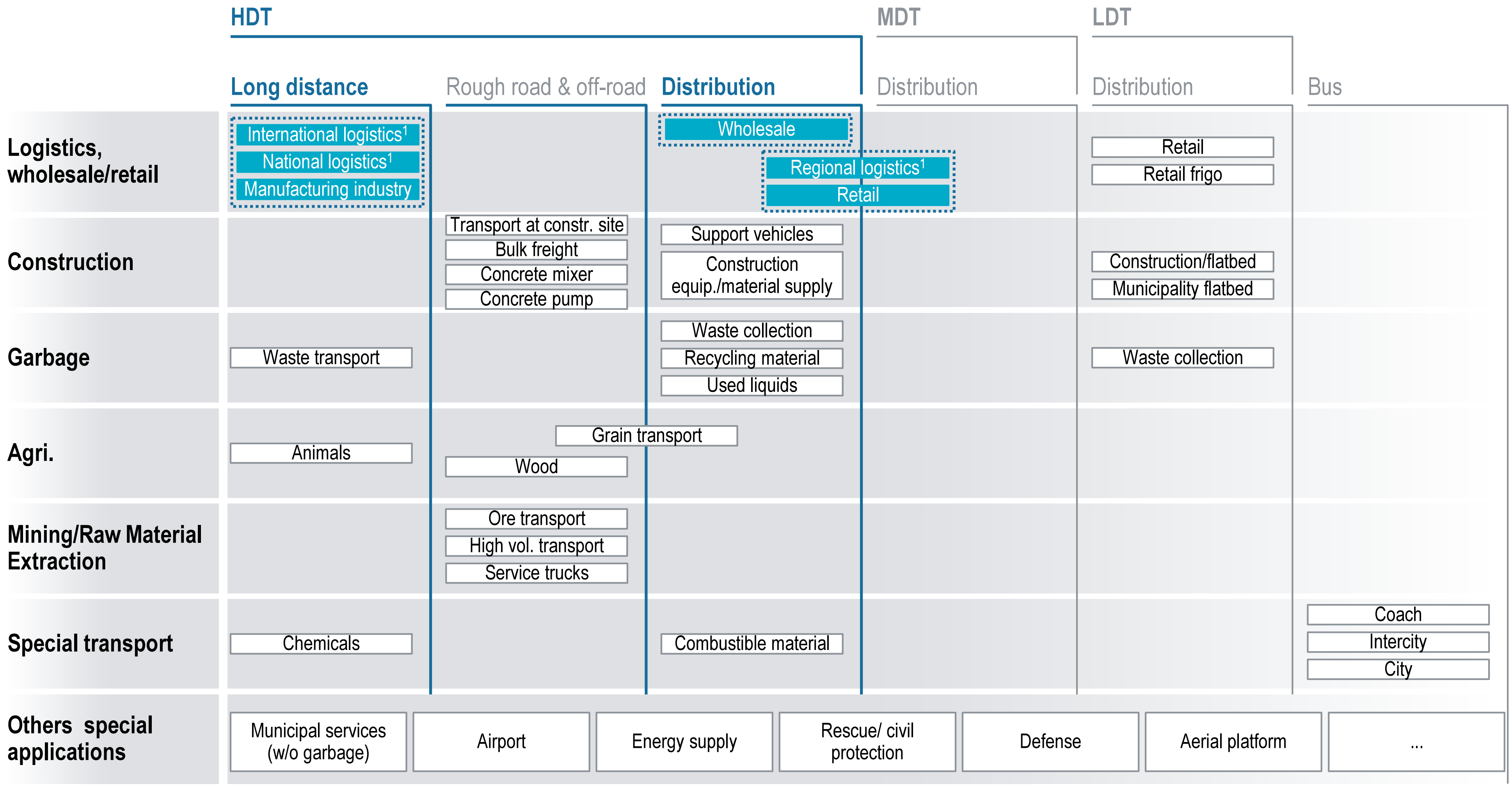
Selected use cases reflect the specific scope of the regulation

> Prioritisation of market segments in line with EU regulation
  - Focus on freight delivery vehicles
  - Consideration of use profiles in HDT sub-groups (urban, regional, long-haul)

> Definition of use case specific characteristics for truck and route in line with use profiles

Source: European Commission; Impact Assessment on Regulation (EU) 2019/1242; Desk research; Roland Berger

We prioritised six road transport segments and combined these to represent three use cases as the focus throughout the study



	HDT			MDT	LDT	
	Long distance	Rough road & off-road	Distribution	Distribution	Distribution	Bus
Logistics, wholesale/retail	International logistics[1] National logistics[1] Manufacturing industry		Wholesale Regional logistics[1] Retail		Retail Retail frigo	
Construction		Transport at constr. site Bulk freight Concrete mixer Concrete pump	Support vehicles Construction equip./material supply		Construction/flatbed Municipality flatbed	
Garbage	Waste transport		Waste collection Recycling material Used liquids		Waste collection	
Agri.	Animals	Grain transport Wood				
Mining/Raw Material Extraction		Ore transport High vol. transport Service trucks				
Special transport	Chemicals		Combustible material			Coach Intercity City
Others special applications	Municipal services (w/o garbage) Airport Energy supply Rescue/ civil protection Defense Aerial platform ...					

🟦 = First level prioritisation for fuel cell electric ⬚ = Prioritised use cases 1) Logistic = line haul and on-demand

Source: Roland Berger

The prioritised use cases account for approximately 53% of sales in the European HDT market

Use case characteristics

	Use case I	Use case II	Use case III
Segment	International logistics National logistics Manufacturing industry	Wholesale	Regional logistics Retail
Truck segment	HDT (40 t)	HDT (27 t)	HDT (18 t)
Truck characteristics	Tractor 4x2 	Rigid 6x2 	Rigid 4x2 
Route type	Long distance	Long distance	Distribution
Route characteristics	~140,000 km p.a. ~570 km per day	~95,000 km p.a. ~380 km per day	~60,000 km p.a. ~250 km per day
Average new truck sales in Europe p.a.[1]	~100 k trucks (~28% of market)	~20 k trucks (~6% of market)	~70 k trucks (~20% of market)
Typical operators	National and International logistics companies Manufacturing companies with own trucking fleet	Wholesalers with own trucking fleet	Logistics companies Retailers with own trucking fleet

[1] Total European market is approximately 360,000-370,000 new trucks p.a.

Source: Roland Berger

Approach and underlying data for drive cycle analysis and use-case definition

Use case approach

Input

- The analysis of use cases and corresponding drive cycles is based on
  - business intelligence due to former project experience
  - an online survey through a panel of truck fleet operators (approx. 1,400 participants)
  - additional selective phone interviews

Results

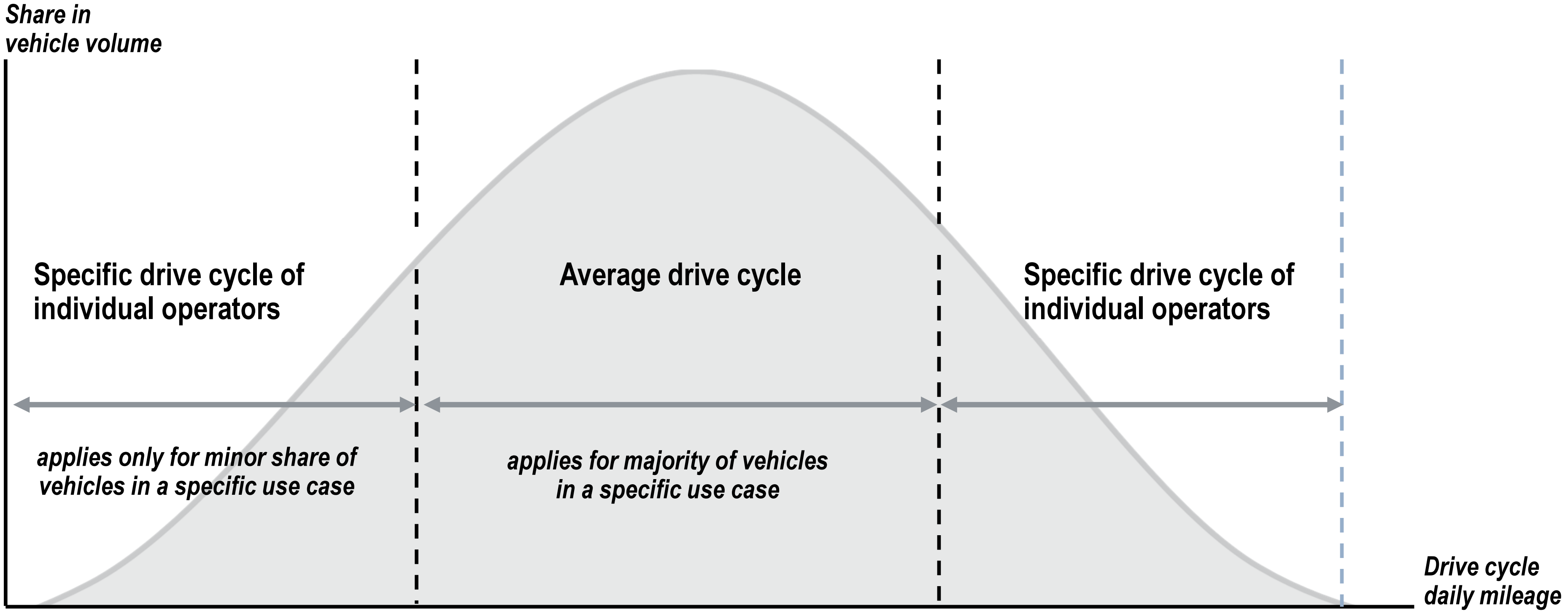
- Average **drive cycles** have been derived based on the abovementioned sources and shall indicate a "typical" drive cycle for the respective use case; data include averages from survey responses (e.g. average daily mileage)

> **Note:** Calculations are based on average calculations from the online survey, telephone interviews and own research and are to be considered as an indication but not as representative

Source: Roland Berger

For the prioritised use cases we have analysed average drive cycles as well as selected "extremes" per region

Use cases and drive cycles



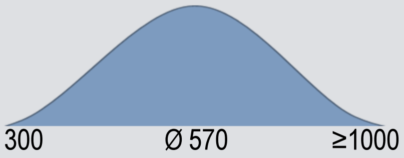
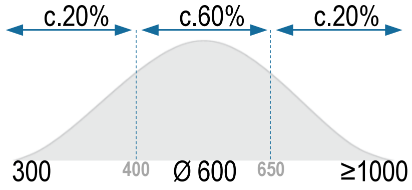
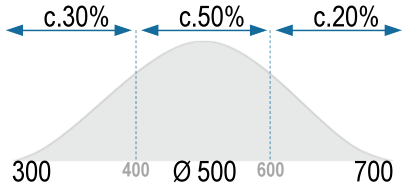
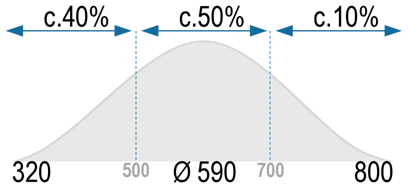
- > **Average drive cycles** were derived based on various customer feedbacks (phone interviews and online survey)
- > **Specific drive cycles** represent rather "extreme" cases (e.g. in terms of mileage, trip characteristics etc.)

!

Source: Roland Berger

Use case I – Tractor 4x2

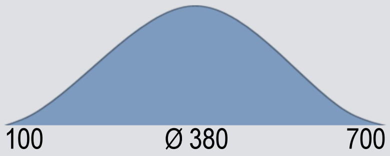
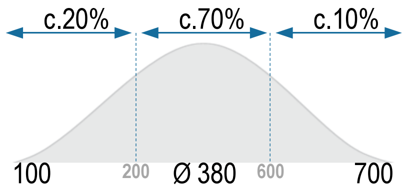
Definition of use case I

	Customer profile	Vehicle configuration	Route characteristics	Drive cycle analysis
Use case I	> International logistics > National logistics > Manufacturing industry	> Tractor 4x2 > GVW: 40 t > Engine: 330 kW	> Daily Mileage: Avg. 570 km > One shift per day	
International logistics	> International logistics provider > Transport and cargo services > Largely own operated HDT fleet, some subcontracting to control capacity	> Vehicles mostly tractor, 4x2 > GVW: 18 t - 40 t > Large cabin/sleeper cabin > Engine: 330 kW	> Daily Mileage: 500-700 km > Mixed goods > Average payload: 25 t > One shift per day	
National logistics	> Mostly national transports for wholesalers and manufacturing	> Most vehicles are tractor, 4x2 > GVW: 40 t > Engine: 270 -330 kW > Sleeper cabins, usually tractor with single trailer	> Daily Mileage: 450-500 km > Manufacturing goods, general cargo > One shift per day for most trucks, some trucks with two	
Manufacturing	> Logistic companies transporting manufacturing supplies/ parts/ components and equipment (e.g. to manufacturing plants)	> Vehicles are mostly tractors, 4x2 or 6x2 or Rigid, 6x2 or 6x4 > GVW: 40 t > Engine: 370 kW	> Daily Mileage: 320-800 km > Goods for manufacturing purpose > Average payload 24 t > One shift per day	

Source: Roland Berger

Use case II – Rigid 6x2

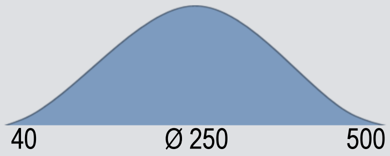
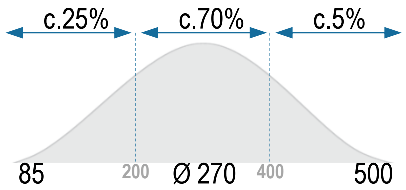
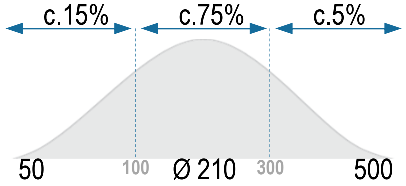
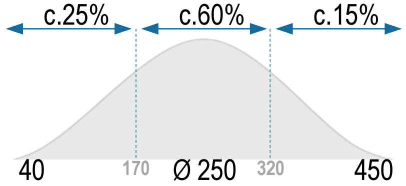
Definition of use case II

	Customer profile	Vehicle configuration	Route characteristics	Drive cycle analysis
Use case II	> Wholesalers with own trucking fleet	> Rigid 6x2 > GVW: 27 t > Engine: 270 kW	> Daily Mileage: Avg. 380 km > One shift per day	
Wholesale	> Logistic firm specialised on transporting great quantities to businesses	> Vehicles are mostly Rigid 6x2 or 4x2 > GVW: 27 t > Engine: 270 kW	> Daily Mileage: 200-600 km > Mixed goods, merchandise > Average payload: 10 t	

Source: Roland Berger

Use case III – Rigid 4x2

Definition of use case III

	Customer profile	Vehicle configuration	Route characteristics	Drive cycle analysis
Use case III	> Logistics companies > Retailers with own trucking fleet	> Rigid 4x2 > GVW: 18 t > Engine: 220 kW	> Daily Mileage: Avg. 250 km	
Regional line haul	> Regional logistics provider > Transport in regional area, cargo varies largely (e.g. supplier, merchandise etc.)	> Majority of vehicles are rigid, 4x2 > GVW: 18 t > Engine: ~260 kW	> Daily Mileage: 200-400 km > Mixed general cargo > Average payload: 12 t > One shift per day	
Regional on demand	> Regional distribution of goods (e.g. office equipment, medicine, etc.)	> Mostly Rigid 4x2 > GVW: 40 t > Engine: 110-220 kW	> Daily Mileage: 100-300 km > General cargo > Average payload: 6 t	
Retail	> Mostly national, in specific regional transports > Often in MDT sector	> Most vehicles are rigid, 4x2 > GVW: 18 t > Engine: ~190 kW	> Daily Mileage: 170-320 km > Mixed goods, merchandise > Average payload: 9 t > 3-5 trips per day, depending on distance to retail customers	

Source: Roland Berger

C.2.2 Business cases

TCO analysis builds on industry data points, studies and justified assumptions – Future commercialisation of technology in focus

Guiding principles for TCO analysis

TCO

- TCO model is designed to reflect a **like-for-like comparability** of truck performance for operators, i.e. truck operators get a similar product as with a diesel truck today
- **Adjustments and optimisation** potential should be **addressed within** the **case studies** (i.e. lower range requirements of different duty-cycles, reflection of lower operational flexibility requirements, e.g. allowing for intra-day charging)
- Niche to mass **market scenarios**[1] **assumed** to show the capabilities of the technology at industrial scale production (not based on today's **prototype cost)**
- **Assumptions based on research** and available **industry project experience** applied, **justified assumptions otherwise**
- **Adjustments based on AB member input** if available, i.e. assumption corrected if based on multiple AB member feedback or concrete data source (iterative feedback)
- **Current EU regulatory framework** is taken into account

[1] Assumptions: Truck production p.a.: Niche <5,000 units/year; Rather niche <10,000 units/year; Rather mass >50,000 units/year (~10% of market); Mass >150,000 units/year (~30% of market)

Source: Roland Berger

The relevant powertrain technologies are considered in the TCO model – Hydrogen application as focus technologies

Relevant powertrain technologies for TCO model

Powertrain technology		TCO relevance
Fossil fuel	**Diesel**	✓
	LNG/CNG	addressed in chapter B
Remaining local emissions	**e-diesel**	✓
Zero emission	**CGH_2 (350 bar)**	✓
	CGH_2 (500 bar)	addressed in chapter E
	CGH_2 (700 bar)	✓
	LH_2 (-253 °C)	✓
	H_2 ICE	addressed in chapter E
	BET	✓
	Catenary	✓

Comments

> The TCO model uses **conventional diesel technology** as the **reference case**

> **Hydrogen application** at 350 and 700 bar and liquid hydrogen remain as **focus technologies**[1]

> **e-Diesel, BET and Catenary** are included as main technologies for comparison

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1) Research and development on storage technologies is still ongoing and current uncertainties regarding the further technological development need to be taken into account. This area is addressed by projects such as the FCH JU-funded PHRYDE project investigating refuelling protocol requirements for medium and heavy-duty hydrogen vehicles.

Source: Roland Berger

The TCO model consists of several input factors that include detailed parameters and build on specific technology assumptions

TCO model structure

Total cost of ownership [EUR/truck and EUR ct/tonne-km]

General input

- Utilisation [days/year]
- Duration of 1st/2nd life
- Registration fee
- Motor vehicle tax
- Maintenance cost
- Insurance cost
- Assumptions on range buffer (e.g. for batteries)
- Road toll

Truck technology specific input

- Consumption
- Truck costs (w/o powertrain)
- Lifetime of equipment [km]
- Diesel powertrain costs
- Ad-Blue system
- E-drive costs
- Fuel cell cost
- H_2 tank costs
- Battery capacity
- Battery costs
- Catenary equipment costs
- Weight and payload

Fuel / energy and infrastructure input

- Fuel / energy cost[1]
  - Diesel (+ Ad-Blue cost)
  - e-Diesel
  - Electricity cost (charged, i.e. including fast-charging for BEV, overhead line infrastructure for Catenary)
  - H_2 costs (refuelled, i.e. including HRS)
- Ad-Blue cost
- CO_2 emissions

- The **TCO model builds on detailed parameter** assumptions for all considered **powertrain technologies per use case**
- The **parameters are used to calculate the TCO** in a step-by-step approach and provides aggregated results – all **parameters can be changed for individual cases** (override function[2])
- The **assumptions are based on varied sources**, e.g. publicly available data (studies, publications), RB project experience and AB member insights

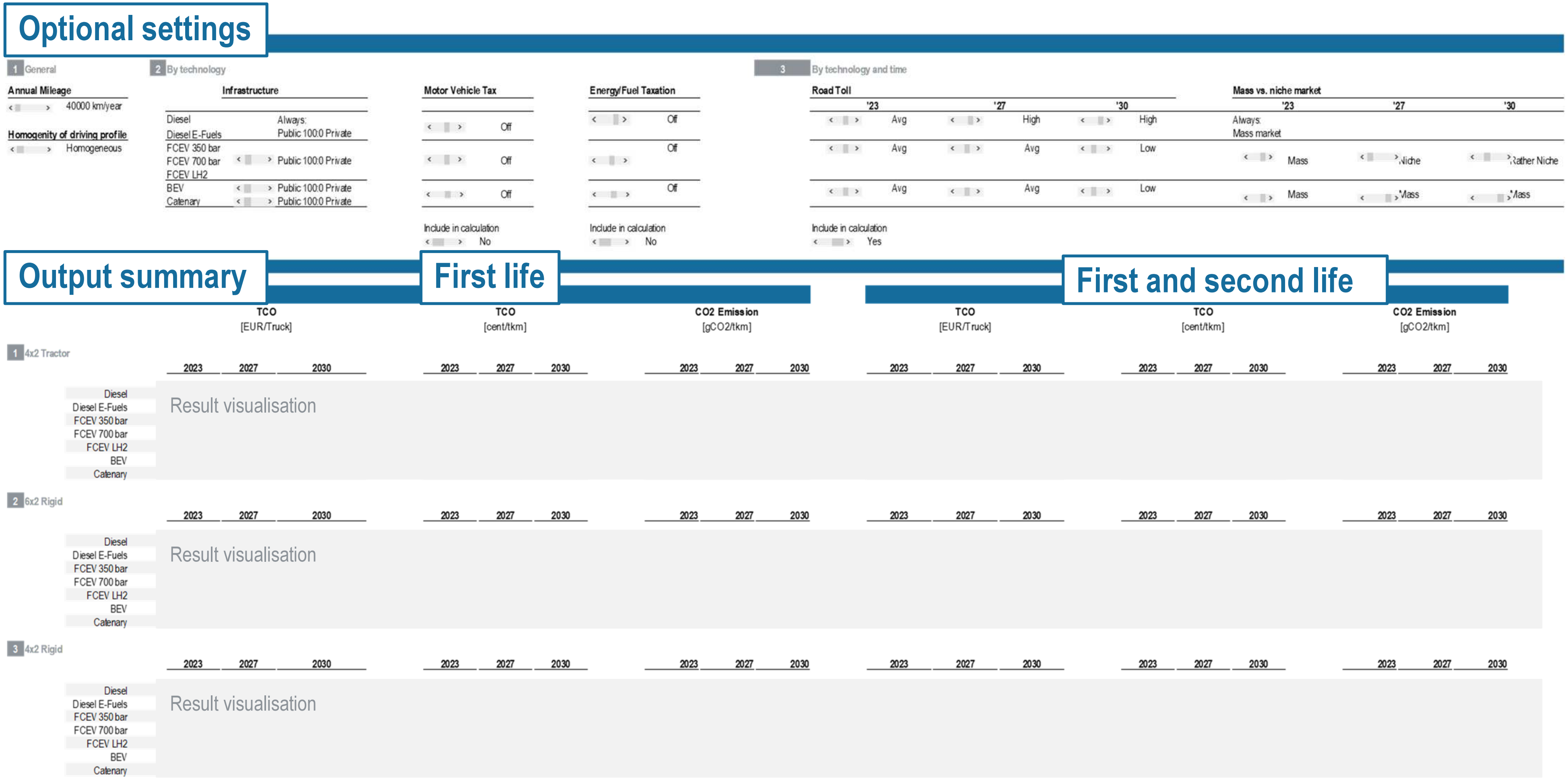
[1] Cost of energy includes infrastructure surcharges and taxes

[2] TCO model of the study will be made available through the website of the FCH JU for further use of interested stakeholders

Source: Roland Berger

The model output is presented in a comprehensive 'cockpit' sheet that brings together the information from the input sheets

Cockpit of TCO tool (Excel)



Optional settings

1 General

Annual Mileage
40000 km/year

Homogenity of driving profile
Homogeneous

2 By technology

Infrastructure		**Motor Vehicle Tax**	**Energy/Fuel Taxation**
Diesel Diesel E-Fuels	Always: Public 100:0 Private	Off	Off
FCEV 350 bar FCEV 700 bar FCEV LH2	Public 100:0 Private	Off	Off
BEV	Public 100:0 Private	Off	Off
Catenary	Public 100:0 Private		
		Include in calculation No	Include in calculation No

3 By technology and time

Road Toll '23	'27	'30	**Mass vs. niche market** '23	'27	'30
Avg	High	High	Always: Mass market		
Avg	Avg	Low	Mass	Niche	Rather Niche
Avg	Avg	Low	Mass	Mass	Mass

Include in calculation
Yes

Output summary

First life

First and second life

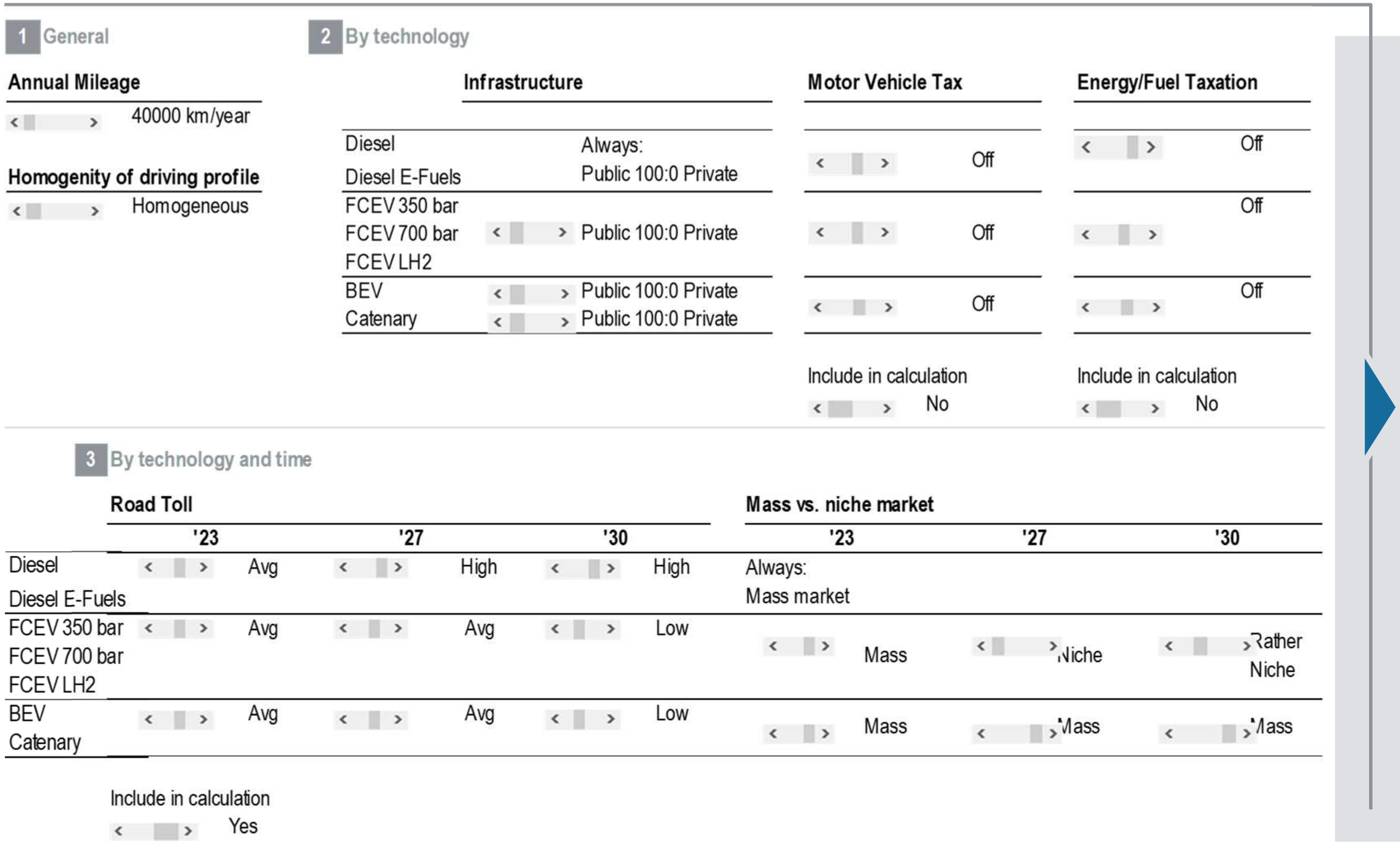
	TCO [EUR/Truck]			TCO [cent/tkm]			CO2 Emission [gCO2/tkm]			TCO [EUR/Truck]			TCO [cent/tkm]			CO2 Emission [gCO2/tkm]		
1 4x2 Tractor	2023	2027	2030	2023	2027	2030	2023	2027	2030	2023	2027	2030	2023	2027	2030	2023	2027	2030
Diesel Diesel E-Fuels FCEV 350 bar FCEV 700 bar FCEV LH2 BEV Catenary	Result visualisation																	
2 6x2 Rigid	2023	2027	2030	2023	2027	2030	2023	2027	2030	2023	2027	2030	2023	2027	2030	2023	2027	2030
Diesel Diesel E-Fuels FCEV 350 bar FCEV 700 bar FCEV LH2 BEV Catenary	Result visualisation																	
3 4x2 Rigid	2023	2027	2030	2023	2027	2030	2023	2027	2030	2023	2027	2030	2023	2027	2030	2023	2027	2030
Diesel Diesel E-Fuels FCEV 350 bar FCEV 700 bar FCEV LH2 BEV Catenary	Result visualisation																	

Source: Roland Berger

The TCO model 'cockpit' also allows for adjustments of truck utilisation patterns, infrastructure, taxation aspects, and market size

Modification of optional settings

Detailed view of optional settings



1 General

Annual Mileage

40000 km/year

Homogenity of driving profile

Homogeneous

2 By technology

	Infrastructure	Motor Vehicle Tax	Energy/Fuel Taxation
Diesel Diesel E-Fuels	Always: Public 100:0 Private	Off	Off
FCEV 350 bar FCEV 700 bar FCEV LH2	Public 100:0 Private	Off	Off
BEV	Public 100:0 Private	Off	Off
Catenary	Public 100:0 Private		
		Include in calculation No	Include in calculation No

3 By technology and time

	Road Toll '23	Road Toll '27	Road Toll '30	Mass vs. niche market '23	Mass vs. niche market '27	Mass vs. niche market '30
Diesel Diesel E-Fuels	Avg	High	High	Always: Mass market		
FCEV 350 bar FCEV 700 bar FCEV LH2	Avg	Avg	Low	Mass	Niche	Rather Niche
BEV Catenary	Avg	Avg	Low	Mass	Mass	Mass

Include in calculation

Yes

Scroll bars allow for **easy adjustment** of settings:

- Annual mileage
- Driving profile
- Infrastructure (private / public)
- Motor vehicle tax
- Energy / fuel taxation
- Road toll
- Mass vs. niche market[1]

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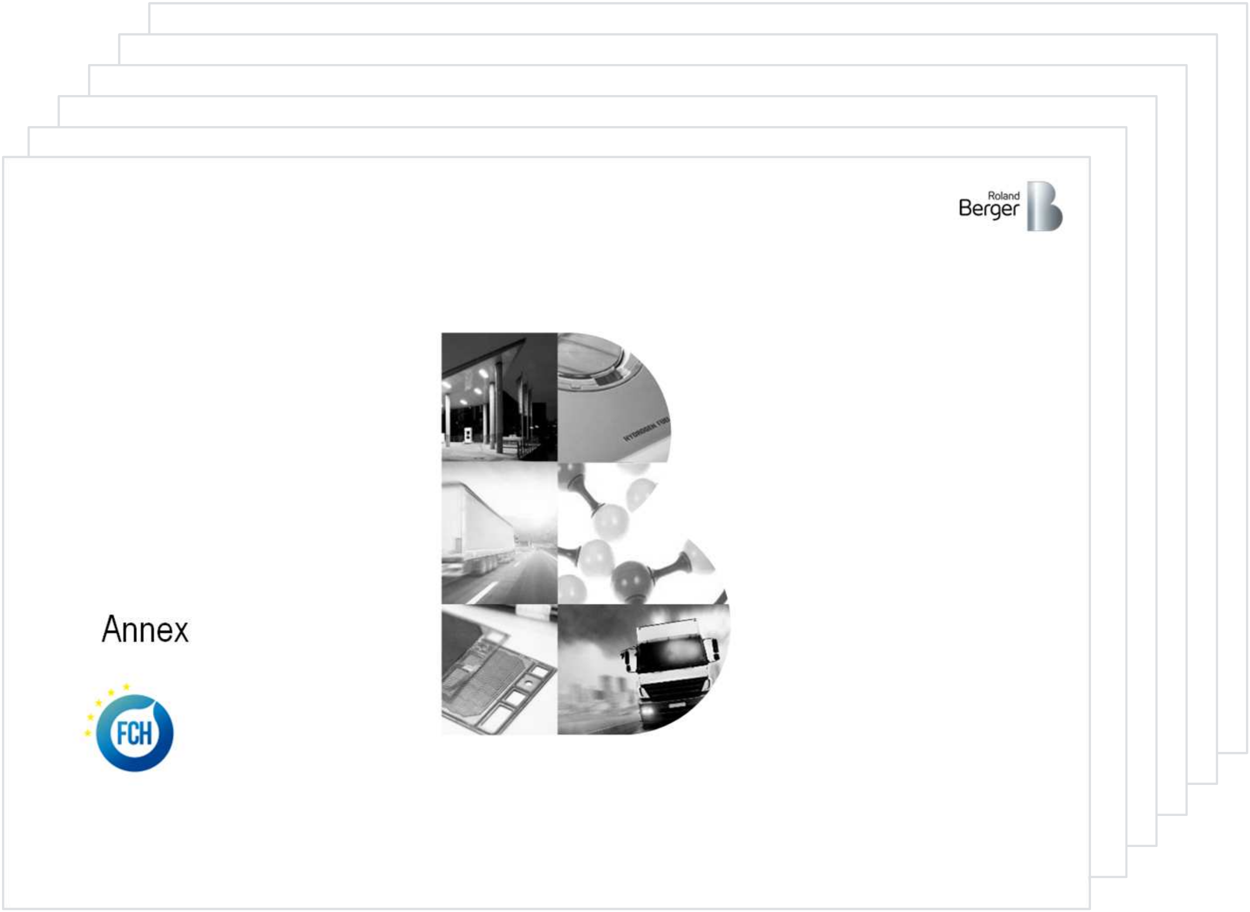
[1] Niche <5.000 units/year; Rather niche <10.000 units/year; Rather mass >50.000 units/year (~10% of market); Mass >150,000 units/year (~30% of market)

Source: Roland Berger

Detailed explanation of the assumptions used for the TCO model are included in the annex – Comments facilitate transparency



Annex

Annex to Report 1[1]

> Overview of the TCO assumptions

> Explanation of calculations

> Transparency on sources

[1] Annex included at the end of this document

Source: Roland Berger

The study's Advisory Board played an important role in defining the TCO assumptions with industry experience & technology know-how

Detailed view on specific Advisory Board input

General input	**Duration of 1st/2nd life**[1]	> Point of discussion revolved around the **uncertainty of a mature 2nd life market for FCEV** (~10 years) after a regular 1st life span (~5 years), combination of 1st & 2nd life considered based on current LNG/CNG experience (trucks often remain with first buyer)
	Maintenance costs	> **Lower maintenance costs for FCEV, BEV and Catenary** considered
Truck technology specific input	**Fuel cell costs**	> **Fuel cell costs** discussed with Advisory Board members largely supporting niche scenario as probable option; **scale-up scenarios developed based on expert discussion**
	Hydrogen tank size	> **Hydrogen tank size defined** according to use case and vehicle type (dynamic adjustment with equal logic as for BEV incl. range buffer)
	Consumption	> **Consumption factors** defined based on **fuel efficiency calculation** reflecting AB member feedback
	Payload factor	> **Different average loading factors for use cases I - III** considered due to different use patterns based on AB member feedback
Fuel / energy and infrastr. input	**H_2 costs**	> **H_2 costs** defined reflecting Advisory Board member feedback on **higher refuelling station CAPEX investment, lower electrolysis utilisation** but also lower CAPEX

1) Advisory Board member discussion on the residual value after the first life of a FCEV and limited second life market in the early years of deployment

Source: Advisory Board; Roland Berger

Different H_2 on-board storage systems are in development by the industry – 700 bar and LH_2 deemed most promising for long-haul

H_2 storage technology maturity status

TCO – Main principles

Main on-board hydrogen storage technologies

		Status today[1]
350 bar	350 bar technology **suitable for short-range operations** with lower hydrogen on-board storage requirements	> First FC truck rollout in EU with 350 bar is currently underway > Established technology for FC buses > Pursued by OEMs as compromise (e.g. refuelling protocol available)
700 bar[2]	700 bar technology provides **more flexibility for hydrogen sourcing** (e.g. through pipeline supply or on-site electrolysis)	> First FC truck concepts for EU with 700 bar announced > Established technology for FC passenger cars > Pursued by OEMs for higher energy density, interoperability of HRS and H_2 supply flexibility > Dilemma of using 700 bar in the short-term vs. waiting for further development of LH_2
LH_2	Liquid hydrogen could be a viable refuelling alternative by 2030 mainly due **to scale of production** and potentially **lower refuelling infrastructure cost**	> First FC truck concepts for EU with LH_2 announced > Technology in R&D stage with limited demonstration within passenger cars around from 1998-2008 > Pursued by one OEM to achieve high range at lower vehicle cost (due to for higher energy density), but limited H_2 supply options in Europe today

To consider for study results

- Some **uncertainty remains** regarding the technological development of H_2 storage, but ongoing R&I projects are addressing this barrier
- TCO results show the potential of different storage technologies, but **maturity status needs to be considered**
- The potential to integrate the storage in the available vehicle architecture, project cost developments and technical feasibility (e.g. for LH_2 tanks) have been identified as **potential barriers[3]**

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1) The ongoing FCH JU funded PRHYDE project investigates refuelling protocol requirements to help facilitate the future standardisation of fuelling protocols for FCH HDT 2) For further information on storage and LH_2 costs, please refer to chapter C.2.2. Sensitivity analyses 3) Further information on potential barriers for commercialisation can be found in Report 3

Source: Roland Berger

HRS are sufficiently mature in some market segments, but specific HDT HRS need development to balance truck and fuel supply needs

HRS technology status

TCO – Main principles

	350 bar – compressed gaseous refuelling	700 bar – compressed gaseous refuelling	LH_2 cryogenic liquid refuelling at -253 °C
Status	> Existing refuelling technology similar as for FC bus > Refuelling protocol available	> Existing refuelling technology for cars only (volume limitations today) > Refuelling protocol in development	> Past refuelling technology for cars only (developments stop c. 2008) > Refuelling protocol to be developed
Pro	> Short-term availability > H_2 supply from gaseous source, e.g. gas tube trailers, pipeline, on-site > Lower cost of on-board storage	> Higher range of FC trucks > H_2 supply from gaseous source, e.g. gas tube trailers, pipeline, on-site	> Highest range of FC trucks > (Potential) lowest cost of on-board storage > Refuelling energy requirements
Con	> Lower range of FC trucks due to space limitations in vehicle > Refuelling energy requirements for compression	> Higher cost of on-board storage > Refuelling energy requirements for compression and pre-cooling	> Technology development stage only > H_2 boil-off losses of vehicle tank > H_2 supply limited to LH_2 sources[1]

Key topics

> HRS need to be supplied with sufficient amounts of H_2, especially for large, heavily utilised stations of > 1,000 kg per day capacity (main options: LH_2, on-site production, pipeline)

> LH_2 supply is an option for all the above HRS types, however, currently only three hydrogen liquefaction plants are operational in Europe. A significant sequential ramp-up of production capacity alongside HRS and truck rollout is necessary, especially for LH_2 refuelled trucks

> Further refuelling/storage technology options like 500 bar and cryo-compressed H_2 are investigated at R&D stage and could offer possibilities to improve the TCO economics in parts of the value[2]

Industry stakeholders need to address H_2 on-board storage, refuelling station design and H_2 supply chain as a whole to identify the best overall TCO option with sufficient flexibility for logistics operators

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1) Today, only three hydrogen liquefaction plants operational in Europe. A significant sequential ramp-up of production capacity alongside HRS and truck rollout is necessary

2) The FCH JU-funded PRHYDE project investigates different storage and refuelling technologies, addressing uncertainties through the development of standards and protocols

Source: Expert interviews; Desk research; Roland Berger

Roll-out of alternative drivetrain technology has further optimisation potential – FCEV and BEV could benefit from similar levers

Optimisation potential levers for specific future HDT projects

Examples – not exhaustive

	FCEV trucks	**BEV trucks**
Vehicle cost	> **FC cost reduction** related to spill-over effects from other applications, e.g. LDVs, FC buses > **Optimised refuelling pressure** for specific truck use case > **Relaxation** of **weights** and **dimensions req.**	> **Battery cost reduction** related to spill-over effects from, e.g. light-duty vehicles > **Increased battery cycle life** due to HD specific cell chemistry > **Relaxation** of **weights** and **dimensions req.**
Vehicle operation	> Reduced required fuel tank size via **intra-day fuelling** during breaks > Very **homogenous driving** patterns for fuelling and H_2 **tanks** size **optimisation** > FC **waste heat integration** for heating purposes during winter times	> Reduced required battery size via **intra-day charging** during breaks > Very **homogenous driving** patterns for charging and **battery** size **optimisation** > **Higher power charging** stations, e.g. 1 MW chargers for reduced charging time
Energy & infrastructure cost	> **Switch to "blue" hydrogen** only or blends > **Supply** of stations **from pipelines**, large **on-site electrolysis** or with **lower** delivery **distance** > **Optimisation** of **primary energy** sourcing > Infrastructure **CAPEX reduction by** further **adjustment to** actual **fleet** size	> **Switch to** lower power-rating **private charging** stations and overnight charging > **Optimisation** of **primary energy** sourcing > Specific **reduction of** grid and other **surcharges** > Infrastructure **CAPEX reduction by** further **adjustment to** actual **fleet** size

Source: Desk research; Roland Berger

Alternative fuel infrastructures are in early phases – Advantages and constraints can be identified today and at scale

Alternative fuel infrastructures at scale

TCO – Main principles

	FCEV hydrogen refuelling infrastructure	BEV recharging infrastructure	Catenary infrastructure
Advantages	> Relatively quick refuelling time > Handling and utilisation similar to diesel Potential retrofit of existing gas pipelines > Hydrogen capacity for energy storage allows for plannable supply of green hydrogen	> Existing technology with some synergies due to expanding infrastructure for passenger vehicles > Set-up of private charging points realisable depending on truck depot situation	> Charging while driving possible > Higher efficiency of traffic flows > Potential for digitalised technology developments (e.g. autonomous driving)
Disadvantages	> Supply of refuelling stations only possible either through on-site hydrogen production or via trailer delivery (pipeline early stage) > Lack of standardised storage technology/ pressure levels – Refuelling stations cannot be used by all applications[1]	> Long charging time with current technology > Very limited possibility of intra-trip charging > High dependence on local energy grid > Imbalance in supply/demand (e.g. daytime vs. night) – Potential mismatch in renewable energy production and consumption > Volatility of energy prices (at peak hours)	> High upfront infrastructure investment costs > Comprehensive construction measures necessary for installation, hence availability outside of main highways unlikely > Limited flexibility of routes due to dependence on infrastructure
Potential constraints	> Production cost of H_2, > Availability of green hydrogen > Remaining uncertainties regarding storage technologies	> Electrical lines potentially over dimensioned: high need during limited hours, with underutilised capacity during majority of time > Potentially required expensive grid upgrades to allow for high energy discharge at station	> High infrastructure surcharges put on energy price to recover investments > Adaption of energy grid required in motorway areas without high power connection > Reorganisation of urban / rural traffic flows
Key topics	> Availability > Storage technology / pressure levels > Hydrogen supply and fuel costs	> Charging times > Grid upgrades to allow energy supply > Changing energy prices	> Infrastructure investment costs > Potential surcharges on energy price > Flexibility of routes

[1] The current FCH JU-funded PRHYDE project investigates refuelling protocol requirements for medium and heavy-duty hydrogen vehicles.

Source: Desk research; Roland Berger

C.2.2.1 TCO results

The results indicate that FCH HD trucks could become a viable alternative in the first half of the decade if scale up is pushed

Overview of results

Base case assumptions

> **Base case assumptions** are the basis for the TCO calculation of **each use case**

> **Parameters** in the TCO model are set to **match the most common usage** (i.e. annual and daily mileage) for each use case

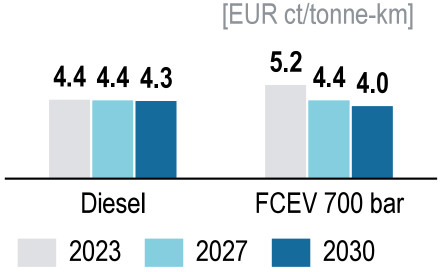
> **Specific assumptions** for the different alternative powertrain **technologies are made over time**

TCO results per use case

> The **high level TCO results** indicate a cost premium of up to ~22% in 2023 for FCH trucks compared to diesel

> A **significant cost down potential for FCEV at scale** is indicated for all H_2 storage technologies across the use cases

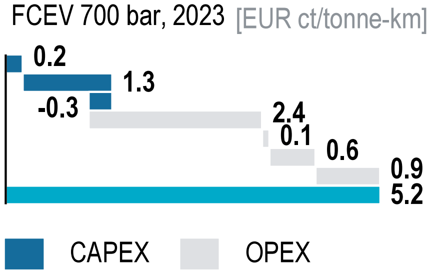
Use case I – Example for illustration only



Cost drivers per use case

> The analysis of **main cost drivers** shows that **fuel cell costs** (CAPEX) and **energy / fuel costs** (OPEX) have the most influence on the TCO of all FCEV applications

Use case I – Example for illustration only



Sensitivity analyses

> **Sensitivity analyses confirm the results** that TCO for FCEV are lower than BEV for most cases

> **Specific parameters** with the **highest impact** are identified

> Sensitivity results show that **FCEV could become an viable alternative to diesel, esp. in 2030**, assuming favourable conditions

Source: Roland Berger

The TCO modelling is based on two different approaches to also reflect weight-related factors that could impact the truck payload

Impact of powertrain and payload weight on TCO results

TCO results – Main principles

	Advantages	Constraints
kEUR/truck basis The kEUR/truck basis shows the TCO in thousand EUR per truck and reflects the overall costs of the vehicle directly	> Direct representation of the vehicle costs as they will arise over the vehicle lifetime, incl. costs of powertrain and tank system > Easy-to-grasp figure that allows for direct comparison	> No representation of weight-related constraints > No representation of volume-related factors (addressed in analysis with included footnotes) > No clear conclusion possible on payload performance of a vehicle - which is of interest for truck operators and logistics users
EUR ct/tonne-km[1] basis The EUR ct/tonne-km basis shows the TCO per EUR cents per tonne-km[1] and reflects the costs of transporting one tonne payload on one kilometre of the route	> Representation of the difference in operational performance regarding weight-related factors that vary across the different technologies – Example: BEV carry a battery that increases in weight with size. Due to the defined permissible gross vehicle weight of trucks, the higher the weight of the battery, the more it potentially reduces the weight of goods that can be transported. If the size implies payload reductions, then the TCO shown on a tonne-km basis is higher. – A similar logic applies for FCH storage techn.	> Truck weight adaptions due to different powertrains and tank systems need to be considered > Limitations of existing truck architecture[2] and the different technologies need to be explained, e.g. the differences in tank systems for the different hydrogen storage technologies – Example: Hydrogen at 350 bar technology has a larger tank system for the same amount of H_2 due to a lower energy density (of H_2 at 350 bar) – The resulting limited representation of volume-related factors is addressed in footnotes

---

1) A tonne-kilometre is a unit of measure of freight transport which represents the possible transport of tonne of goods by a given transport mode (road, rail, air, sea, inland waterways, pipeline etc.) over a distance of one kilometre [Eurostat] 2) Please refer to chapter E for more details on barriers related to existing truck architecture.

Source: Eurostat; Roland Berger

The TCO cost breakdown illustrates the different positions relevant for the evaluation and shows the main cost drivers

Guiding principles on TCO cost breakdown[1]

TCO results – Main principles

⬜	**Truck w/o powertrain**	All costs related to truck design, truck engineering and integration and standardisation with existing truck architecture/chassis
⬜	**Powertrain**	Powertrain specific costs, such as fuel cell modules, storage tanks, batteries, etc.
⬜	**Residual value of powertrain**	Value of the powertrain after the 1st & 2nd life use
▦	**Total energy/ fuel OPEX**	Cost related to energy and fuel, tax, as well as infrastructure-related surcharges, e.g. costs for HRS, charging and overhead lines
🟦	**Motor vehicle taxation**	Tax on the vehicle, depending on the vehicle value at the time of purchase
🟦	**Maintenance & Insurance**	Service & maintenance fees at workshops and dealers as well as insurance-related costs
🟦	**Road toll**	Road toll costs that apply when driving on motorways

🟦 General input ⬜ Truck specific input ▦ Fuel/energy & infrastructure input

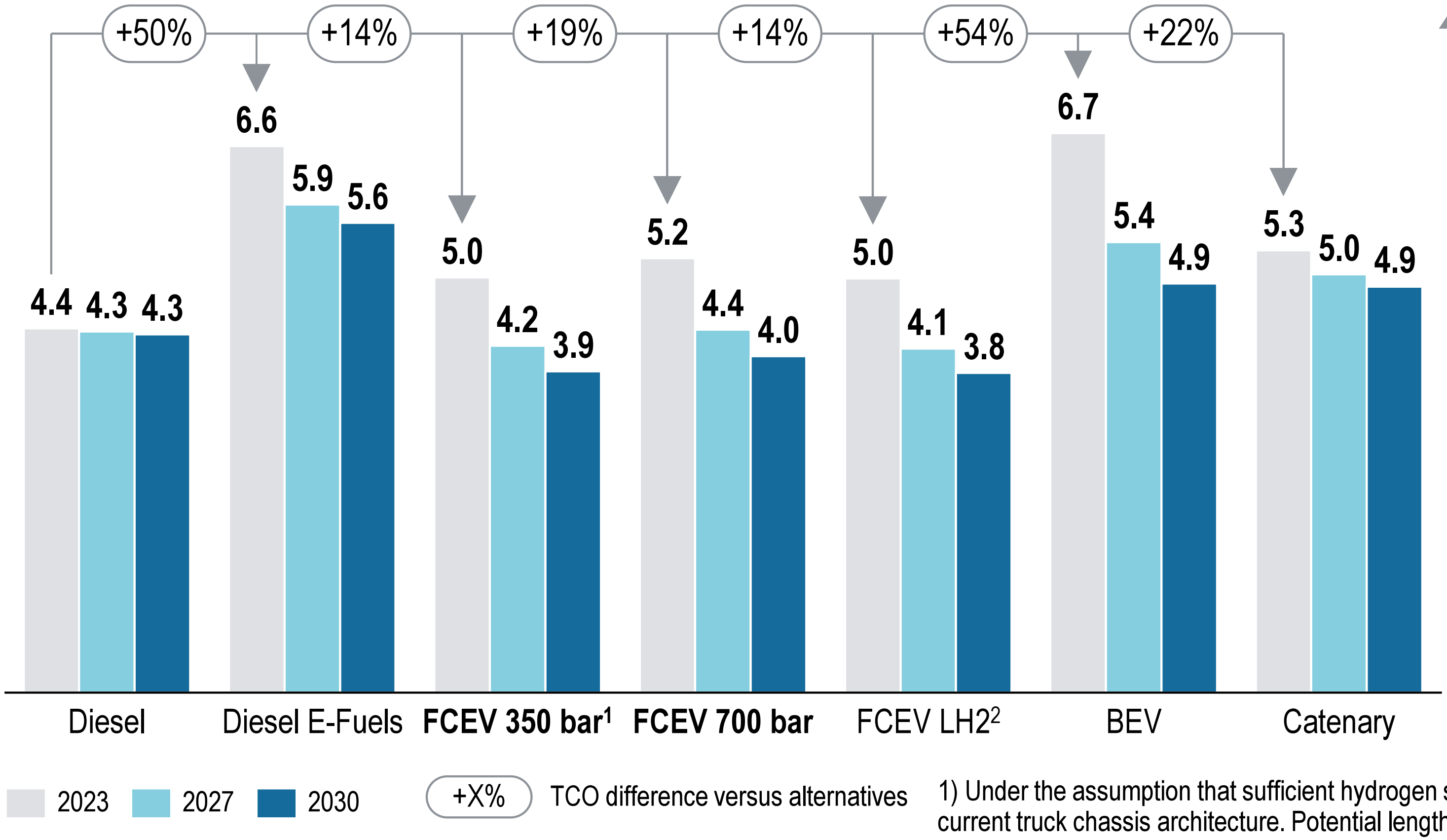
1) Please refer to the Annex for more detailed information on the assumptions included in the TCO calculation

Source: Roland Berger

A positive outlook is established when looking at a longer life time – In 2023 FCH trucks assume a cost premium of up to 19%

High-level TCO assessment – Use case I [EUR ct/tonne-km; 1st & 2nd life]

1 Use case I – Tractor 4x2, 140,000 km annual mileage



Comments

- **When considering 1st and 2nd life,** a significant **cost down potential** for FCEV **at scale** exists
- FCH trucks for use case I have a **cost premium of up to ~19% in 2023 compared to diesel** and could become cheaper if implemented at scale
- **FCH truck technologies** are **more competitive than the alternatives** Diesel E-Fuels, BEV and catenary on a tonne-km basis

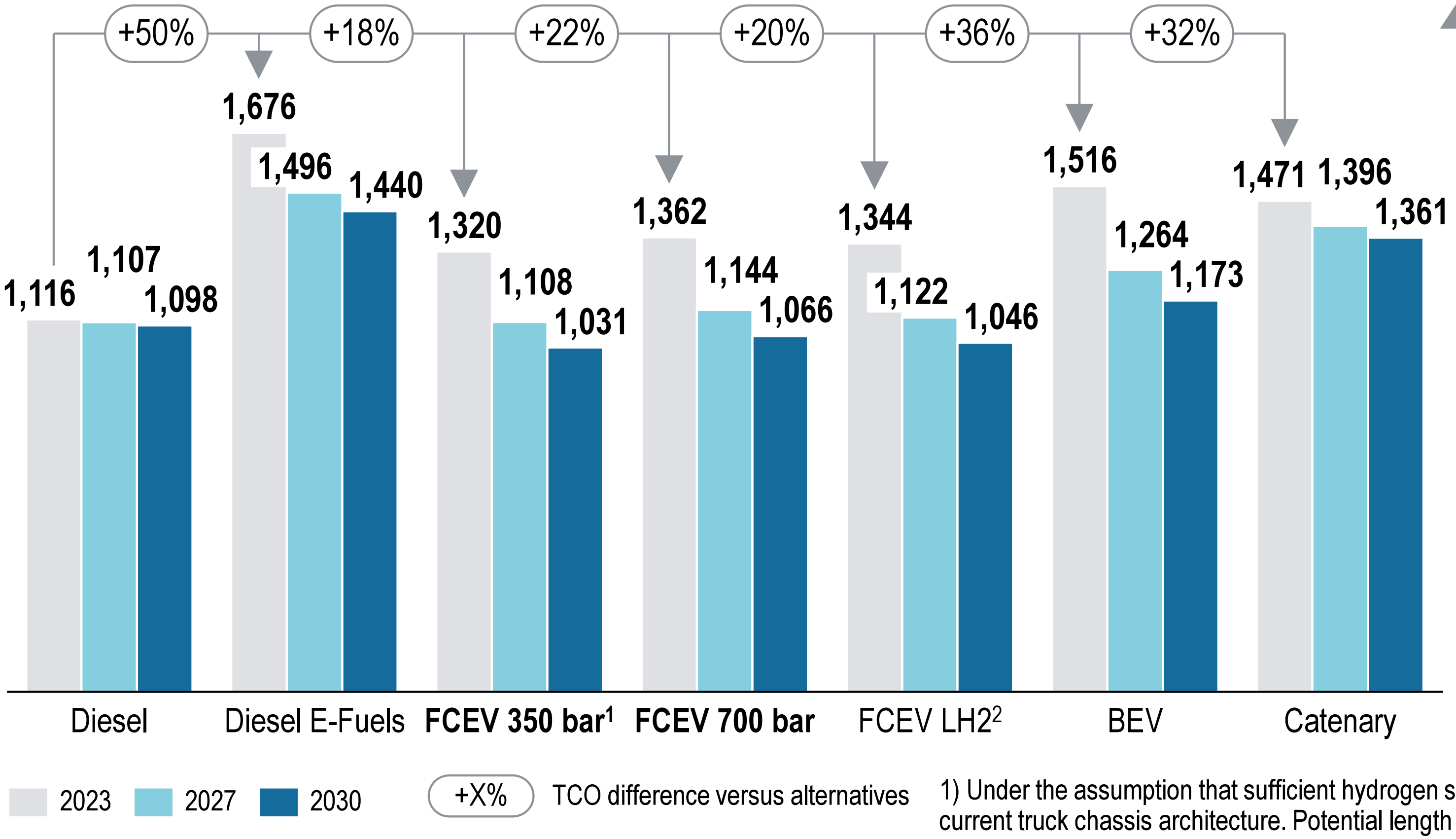
Source: Roland Berger

[1] Under the assumption that sufficient hydrogen storage can be technically integrated in the current truck chassis architecture. Potential length regulation adjustments required.
[2] The technical maturity is at a very early stage and needs to be demonstrated in a truck.

Looking at the EUR/truck comparison, FCH trucks assume a cost premium of up to 22% over diesel trucks in 2023

High-level TCO assessment – Use case I [kEUR/Truck; 1st & 2nd life]

1 Use case I – Tractor 4x2, 140,000 km annual mileage



Comments

- FCH trucks for use case I have a **cost premium of up to ~22% in 2023 on a EUR per truck basis**
- Significant **cost down potential** for FCEV **at scale**
- **FCH truck technologies** are **more competitive than the alternatives** Diesel E-Fuels, BEV and catenary on a EUR/truck basis
- **Gap to** Diesel could **be reduced with** specific **incentives**

Source: Roland Berger

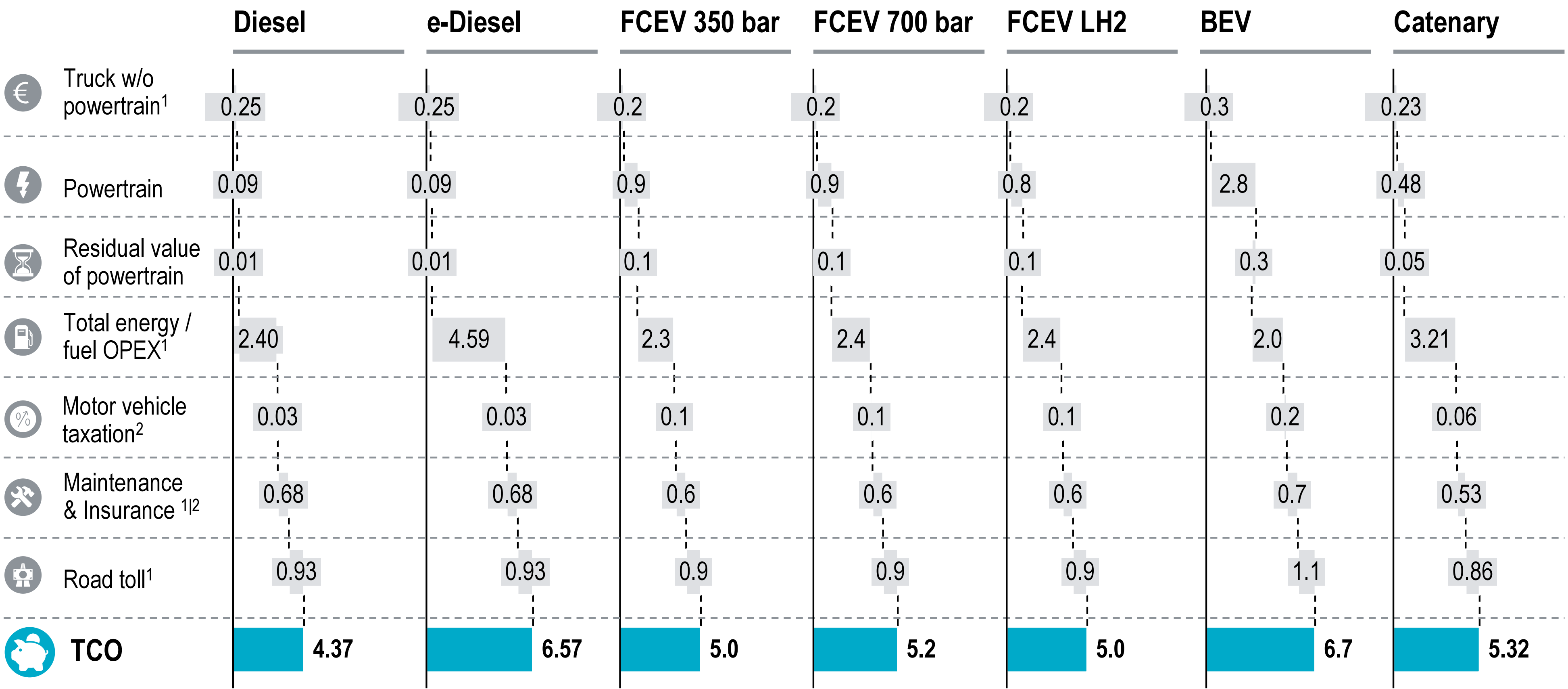
[1] Under the assumption that sufficient hydrogen storage can be technically integrated in the current truck chassis architecture. Potential length regulation adjustments required.

[2] The technical maturity is at a very early stage and needs to be demonstrated in a truck.

The TCO analysis for use case I identifies cost of energy as main cost driver and cost of powertrain as important differentiating factor

Cost drivers of TCO – Use case I [EUR ct/tonne-km in 2023; 1st & 2nd life]

1 Use case I – Tractor 4x2



	Diesel	e-Diesel	FCEV 350 bar	FCEV 700 bar	FCEV LH2	BEV	Catenary
Truck w/o powertrain[1]	0.25	0.25	0.2	0.2	0.2	0.3	0.23
Powertrain	0.09	0.09	0.9	0.9	0.8	2.8	0.48
Residual value of powertrain	0.01	0.01	0.1	0.1	0.1	0.3	0.05
Total energy / fuel OPEX[1]	2.40	4.59	2.3	2.4	2.4	2.0	3.21
Motor vehicle taxation[2]	0.03	0.03	0.1	0.1	0.1	0.2	0.06
Maintenance & Insurance [1][2]	0.68	0.68	0.6	0.6	0.6	0.7	0.53
Road toll[1]	0.93	0.93	0.9	0.9	0.9	1.1	0.86
TCO	**4.37**	**6.57**	**5.0**	**5.2**	**5.0**	**6.7**	**5.32**

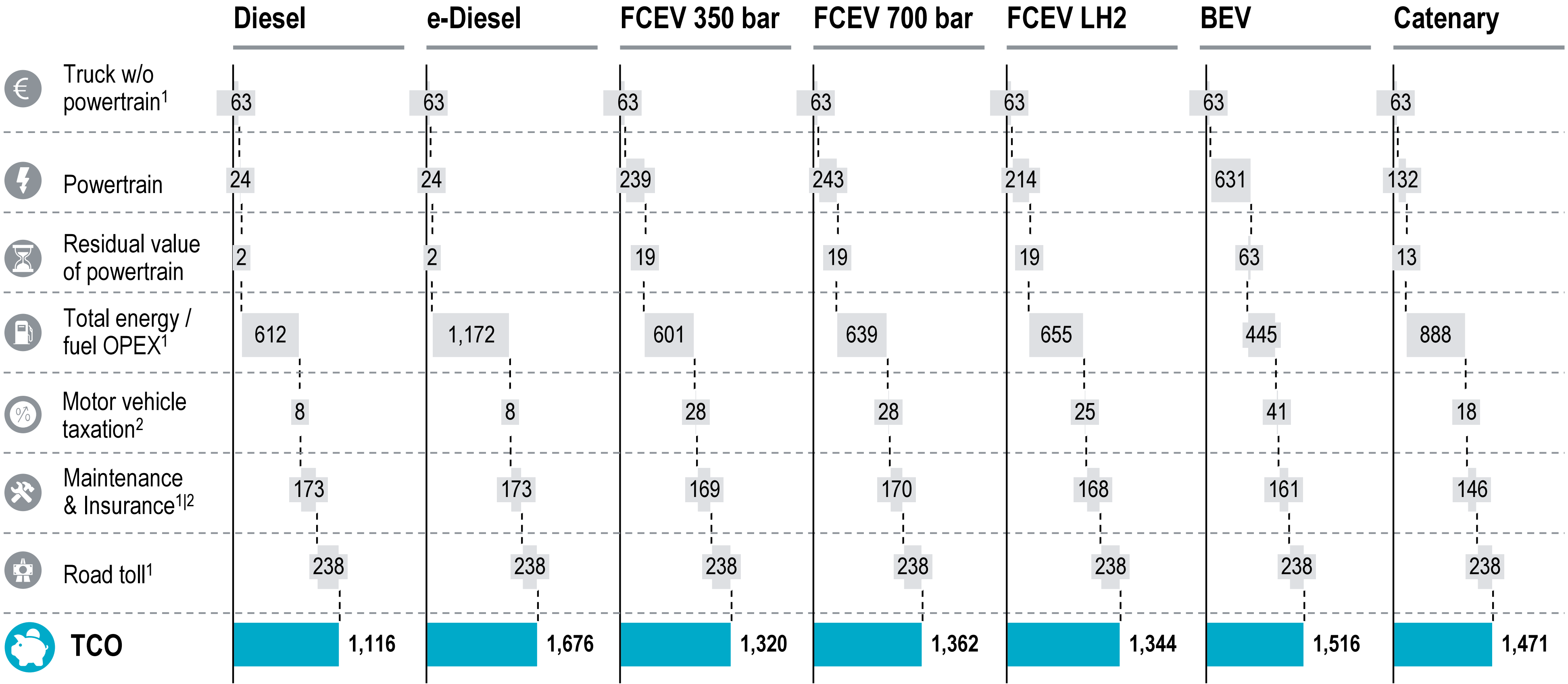
1) Deviations of results are related to payload differences of different technologies 2) Deviations of results are related to calculation based on higher CAPEX

Source: Roland Berger

The TCO analysis for use case I identifies cost of energy as main cost driver and cost of powertrain as important differentiating factor

Cost drivers of TCO – Use case I [kEUR/truck in 2023; 1st & 2nd life]

1 Use case I – Tractor 4x2



	Diesel	e-Diesel	FCEV 350 bar	FCEV 700 bar	FCEV LH2	BEV	Catenary
Truck w/o powertrain[1]	63	63	63	63	63	63	63
Powertrain	24	24	239	243	214	631	132
Residual value of powertrain	2	2	19	19	19	63	13
Total energy / fuel OPEX[1]	612	1,172	601	639	655	445	888
Motor vehicle taxation[2]	8	8	28	28	25	41	18
Maintenance & Insurance[1|2]	173	173	169	170	168	161	146
Road toll[1]	238	238	238	238	238	238	238
TCO	1,116	1,676	1,320	1,362	1,344	1,516	1,471

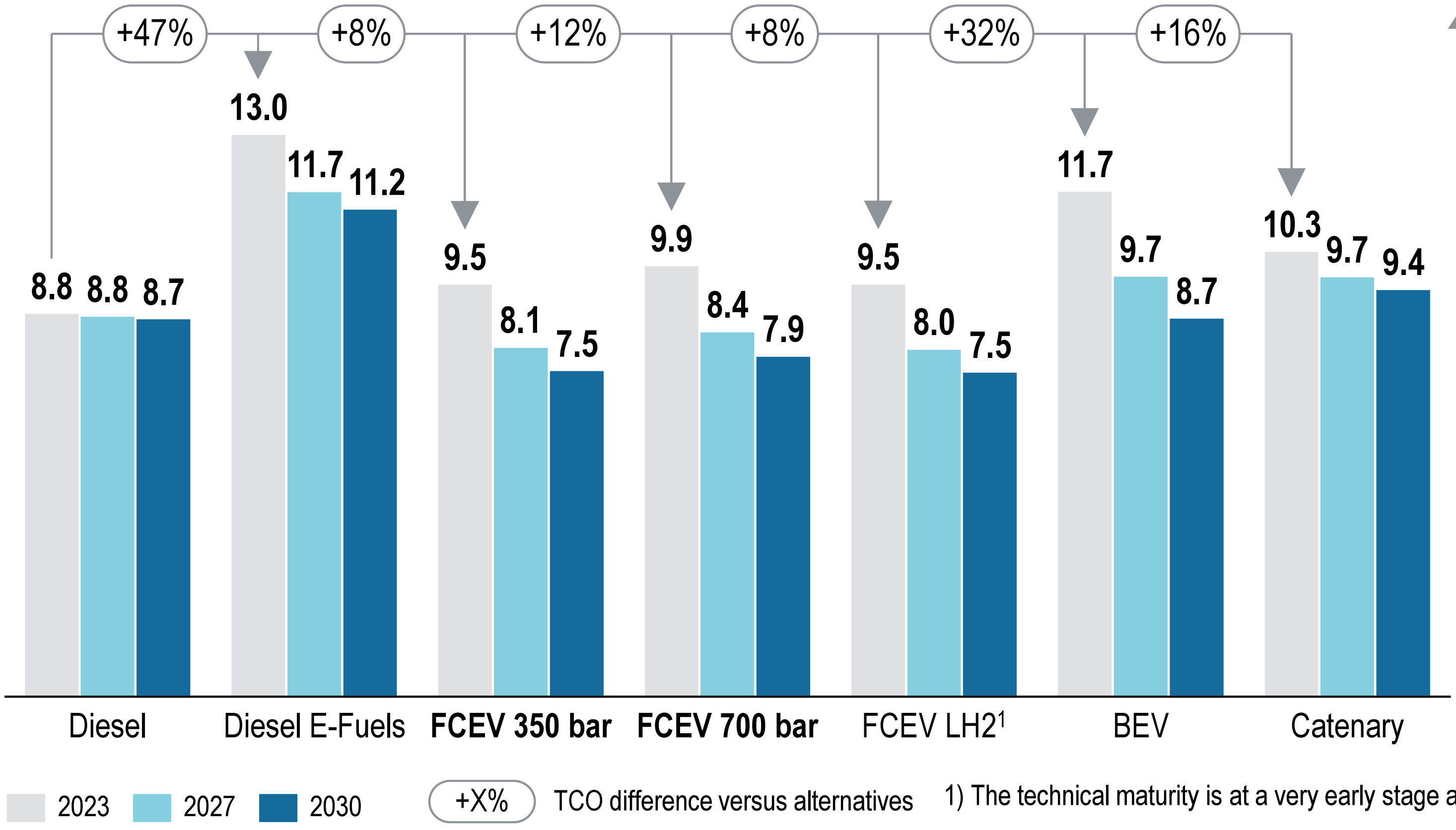
1) Deviations of results are related to payload differences of different technologies 2) Deviations of results are related to calculation based on higher CAPEX

Source: Roland Berger

For use case II, the results indicate that FCH trucks assume a cost premium of up to 12% over diesel trucks (base case assumed)

High-level TCO assessment – Use case II [EUR ct/tonne-km; 1st & 2nd life]

2 Use case II – Rigid 6x2, 95,000 km annual mileage



	2023	2027	2030
Diesel	8.8	8.8	8.7
Diesel E-Fuels	13.0	11.7	11.2
FCEV 350 bar	9.5	8.1	7.5
FCEV 700 bar	9.9	8.4	7.9
FCEV LH2[1]	9.5	8.0	7.5
BEV	11.7	9.7	8.7
Catenary	10.3	9.7	9.4

Comments

- FCH trucks for use case II have a **cost premium of up to ~12% in 2023**
- Significant **cost down potential** for FCEV **at scale**
- **FCH truck technologies** are **more competitive than the alternatives** Diesel e-fuels, BEV and catenary on a tonne-km basis
- **More or less flexible operations could change picture**, e.g. dual-shift swap body operation for FCEV

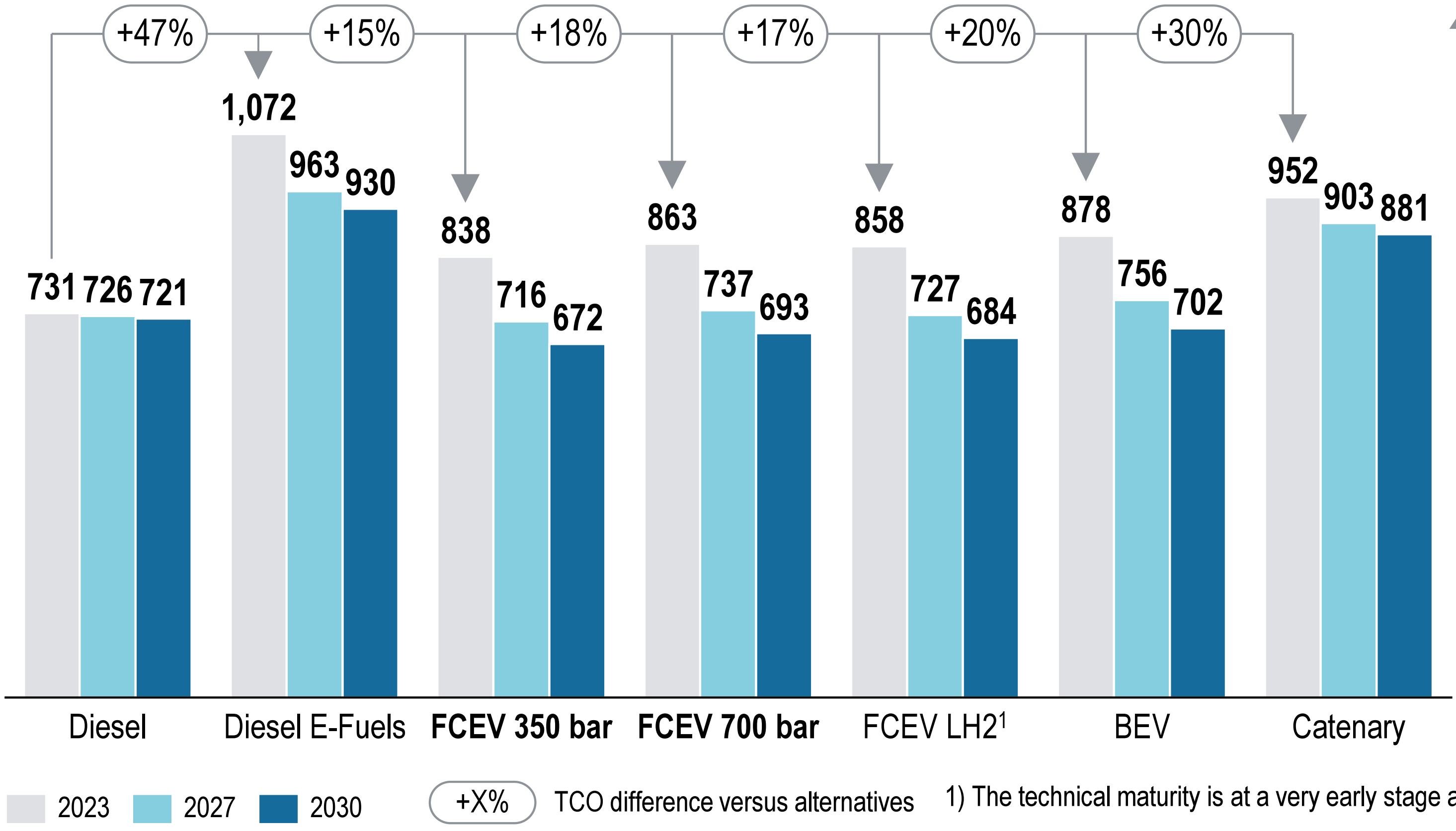
1) The technical maturity is at a very early stage and needs to be demonstrated in a truck.

Source: Roland Berger

Also the results in absolute terms indicate a cost advantage of FCEV trucks – Use case specific requirements could shift the result

High-level TCO assessment – Use case II [kEUR/Truck; 1st & 2nd life]

2 Use case II – Rigid 6x2, 95,000 km annual mileage



Comments

- FCH trucks for use case II have a **cost premium of up to ~18% in 2023**
- Significant **cost down potential** for FCEV **at scale**
- **FCH truck technologies** are **more competitive than the alternatives** Diesel e-fuels, BEV and catenary on a EUR/truck basis
- **More or less flexible operations could change picture**, e.g. dual-shift swap body operation for FCEV

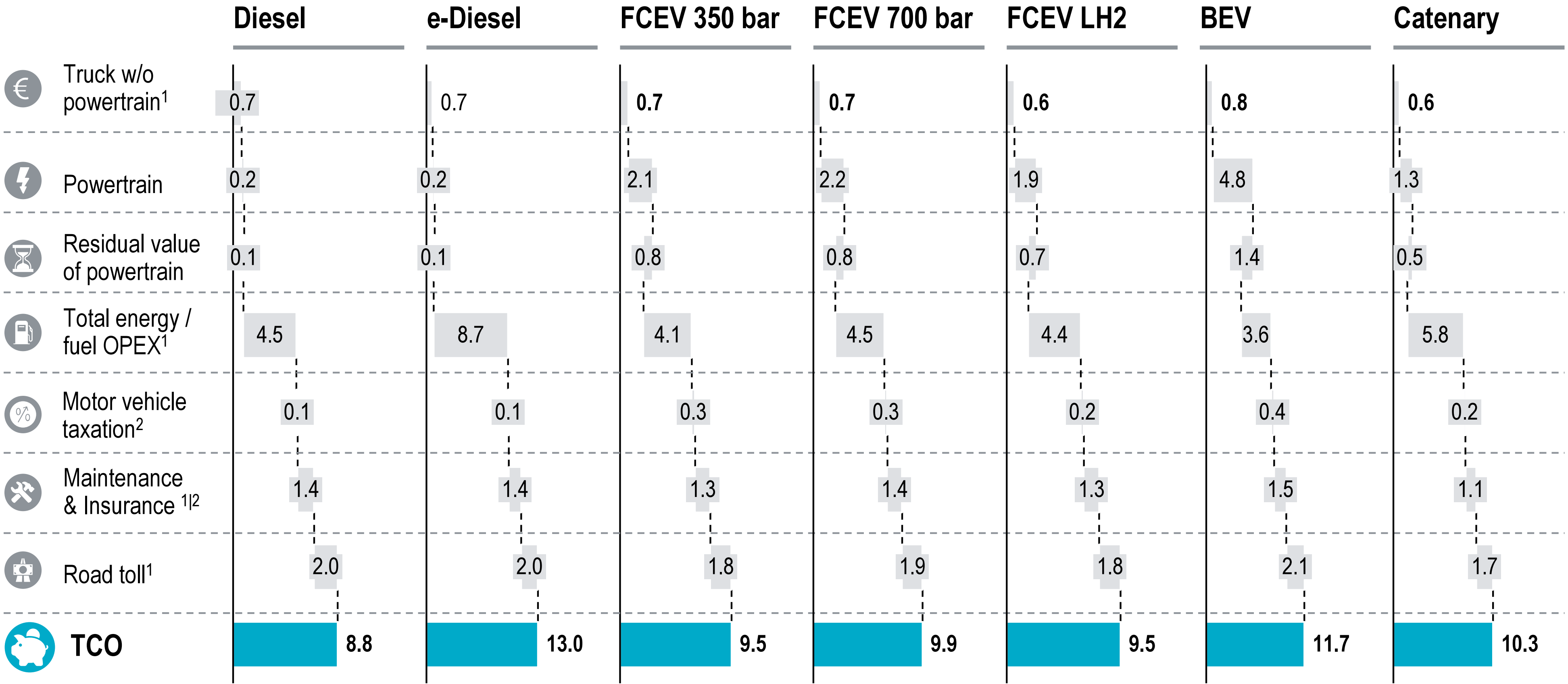
1) The technical maturity is at a very early stage and needs to be demonstrated in a truck.

Source: Roland Berger

The TCO analysis for use case II identifies cost of energy as main cost driver and cost of powertrain as important differentiating factor

Cost drivers of TCO – Use case II [EUR ct/tonne-km in 2023; 1st & 2nd life]

2 Use case II – Rigid 6x2



	Diesel	e-Diesel	FCEV 350 bar	FCEV 700 bar	FCEV LH2	BEV	Catenary
Truck w/o powertrain[1]	0.7	0.7	0.7	0.7	0.6	0.8	0.6
Powertrain	0.2	0.2	2.1	2.2	1.9	4.8	1.3
Residual value of powertrain	0.1	0.1	0.8	0.8	0.7	1.4	0.5
Total energy / fuel OPEX[1]	4.5	8.7	4.1	4.5	4.4	3.6	5.8
Motor vehicle taxation[2]	0.1	0.1	0.3	0.3	0.2	0.4	0.2
Maintenance & Insurance [1|2]	1.4	1.4	1.3	1.4	1.3	1.5	1.1
Road toll[1]	2.0	2.0	1.8	1.9	1.8	2.1	1.7
TCO	8.8	13.0	9.5	9.9	9.5	11.7	10.3

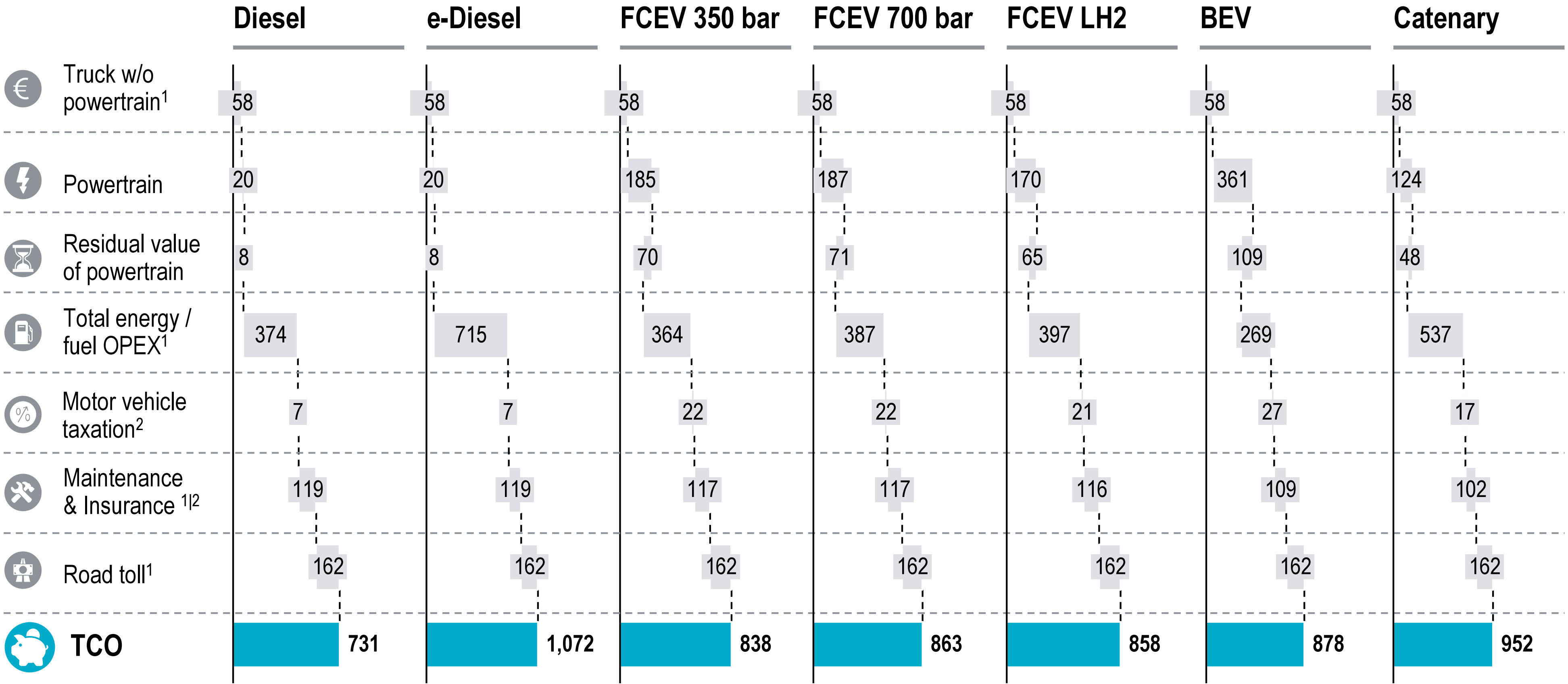
1) Deviations of results are related to payload differences of different technologies 2) Deviations of results are related to calculation based on higher CAPEX

Source: Roland Berger

The TCO analysis for use case II identifies cost of energy as main cost driver and cost of powertrain as important differentiating factor

Cost drivers of TCO – Use case II [kEUR/truck in 2023; 1st & 2nd life]

2 Use case II – Rigid 6x2



	Diesel	e-Diesel	FCEV 350 bar	FCEV 700 bar	FCEV LH2	BEV	Catenary
Truck w/o powertrain[1]	58	58	58	58	58	58	58
Powertrain	20	20	185	187	170	361	124
Residual value of powertrain	8	8	70	71	65	109	48
Total energy / fuel OPEX[1]	374	715	364	387	397	269	537
Motor vehicle taxation[2]	7	7	22	22	21	27	17
Maintenance & Insurance [1|2]	119	119	117	117	116	109	102
Road toll[1]	162	162	162	162	162	162	162
TCO	**731**	**1,072**	**838**	**863**	**858**	**878**	**952**

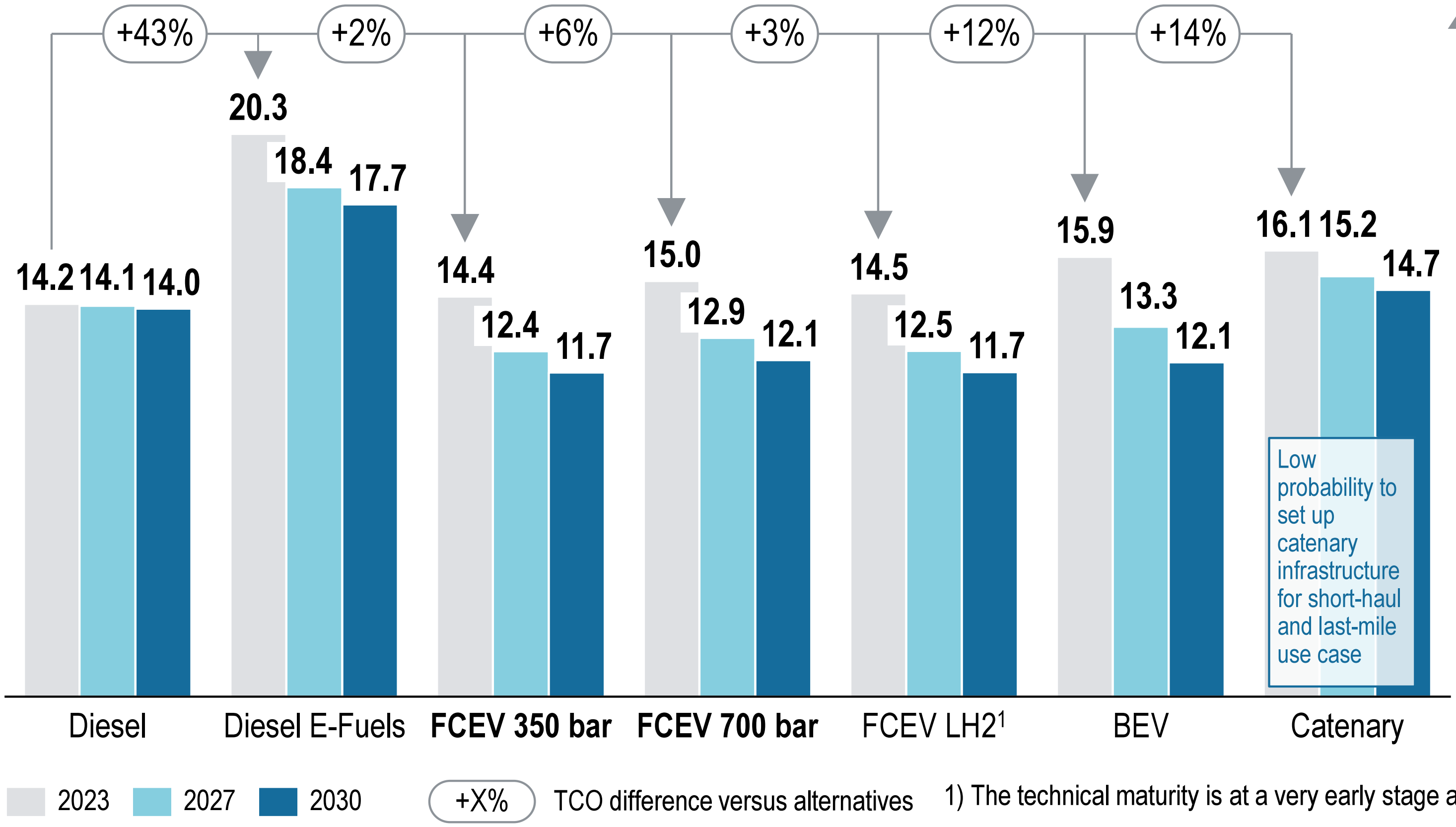
1) Deviations of results are related to payload differences of different technologies 2) Deviations of results are related to calculation based on higher CAPEX

Source: Roland Berger

For use case III, the results indicate that FCH trucks assume a cost premium of up to 6% over diesel trucks (base case assumed)

High-level TCO assessment – Use case III [EUR ct/tonne-km; 1st & 2nd life]

3 Use case III – Rigid 4x2, 60,000 km annual mileage



Low probability to set up catenary infrastructure for short-haul and last-mile use case

Comments

- FCH trucks for use case III have a **cost premium of up to ~6% in 2023**
- Significant **cost down potential** for FCEV **at scale**
- **FCH truck technologies** are **more competitive than the alternatives** Diesel e-fuels and catenary on a tonne-km basis
- **Due to lower** annual **mileage**, **BEV** trucks also **indicate potential for specific, lower flexibility routes**

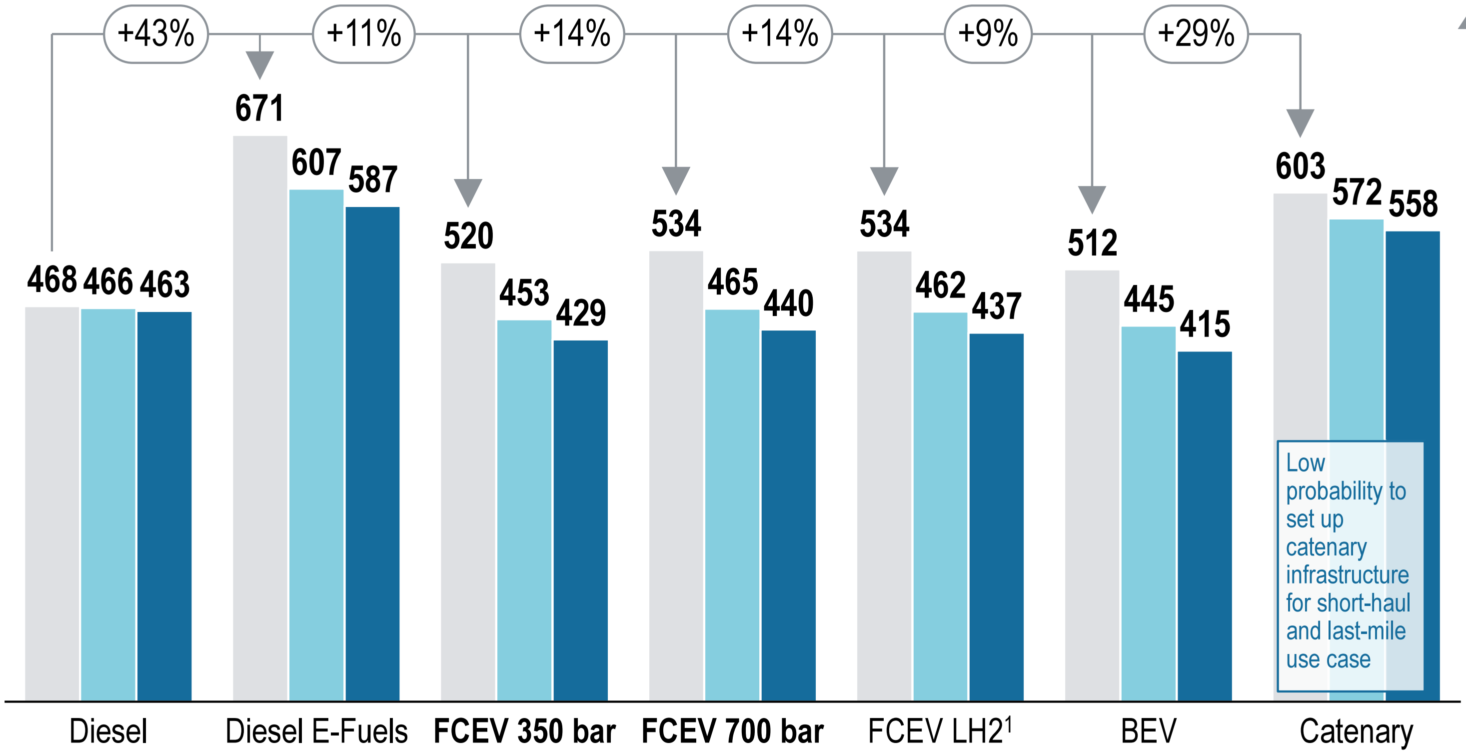
1) The technical maturity is at a very early stage and needs to be demonstrated in a truck.

Source: Roland Berger

In absolute terms, BEV technology could be more competitive than FCEV by 2030 if not payload constrained and operated in one shift

High-level TCO assessment – Use case III [kEUR/Truck; 1st & 2nd life]

3 Use case III – Rigid 4x2, 60,000 km annual mileage



Low probability to set up catenary infrastructure for short-haul and last-mile use case

	Diesel	Diesel E-Fuels	FCEV 350 bar	FCEV 700 bar	FCEV LH2[1]	BEV	Catenary
2023	468	671	520	534	534	512	603
2027	466	607	453	465	462	445	572
2030	463	587	429	440	437	415	558

⬜ 2023 🟦 2027 🟦 2030 (+X%) TCO difference versus alternatives

Comments

- > FCH trucks for use case III have a **cost premium of up to ~14% in 2023**
- > Significant **cost down potential** for FCEV **at scale**
- > **FCH truck technologies** are **more competitive than the alternatives** Diesel e-fuels and catenary on a EUR/truck basis
- > **Due to lower** annual **mileage**, **BEV** trucks also **indicate potential for specific, lower flexibility routes**

---

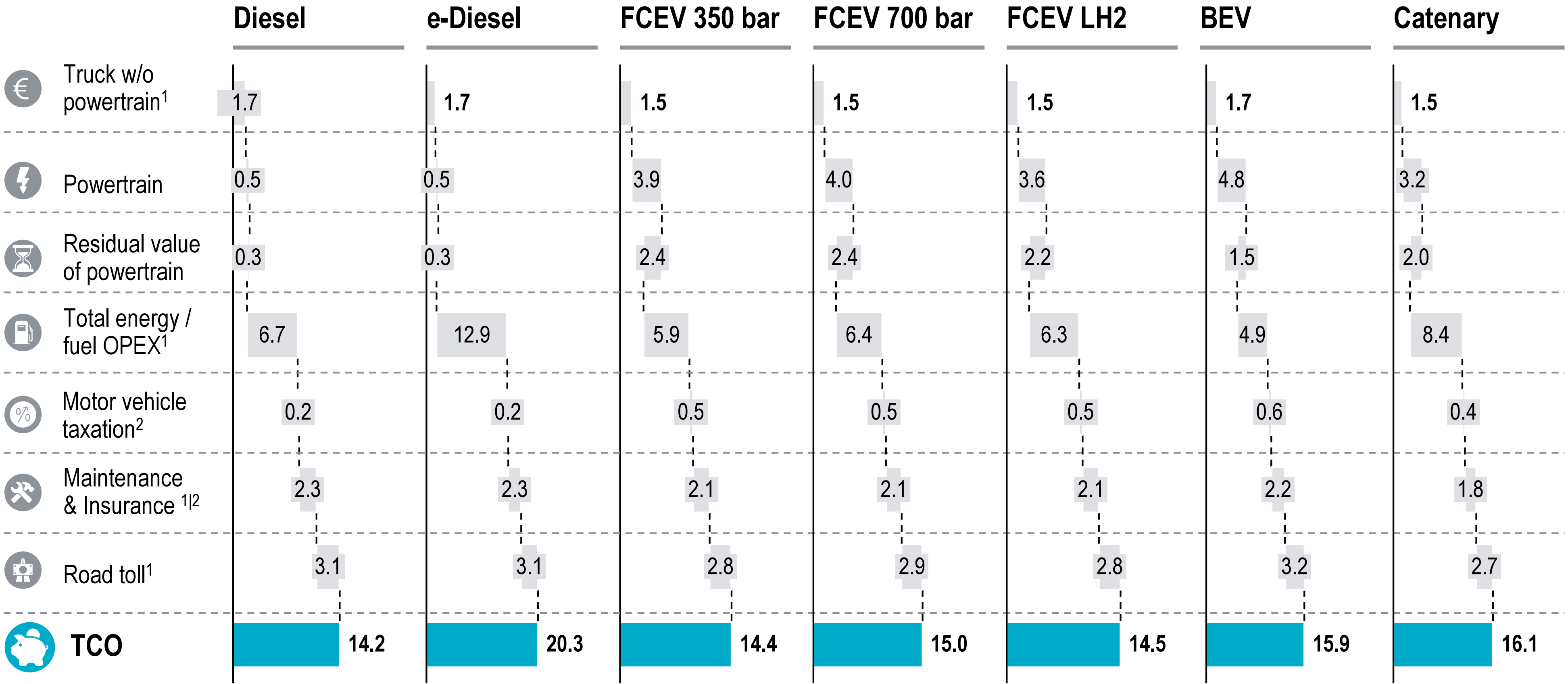
1) The technical maturity is at a very early stage and needs to be demonstrated in a truck.

Source: Roland Berger

The TCO analysis for use case III identifies cost of energy as main cost driver and cost of powertrain as important differentiating factor

Cost drivers of TCO – Use case III [EUR ct/tonne-km in 2023; 1st & 2nd life]

3 Use case III – Rigid 4x2



	Diesel	e-Diesel	FCEV 350 bar	FCEV 700 bar	FCEV LH2	BEV	Catenary
Truck w/o powertrain[1]	1.7	1.7	1.5	1.5	1.5	1.7	1.5
Powertrain	0.5	0.5	3.9	4.0	3.6	4.8	3.2
Residual value of powertrain	0.3	0.3	2.4	2.4	2.2	1.5	2.0
Total energy / fuel OPEX[1]	6.7	12.9	5.9	6.4	6.3	4.9	8.4
Motor vehicle taxation[2]	0.2	0.2	0.5	0.5	0.5	0.6	0.4
Maintenance & Insurance [1|2]	2.3	2.3	2.1	2.1	2.1	2.2	1.8
Road toll[1]	3.1	3.1	2.8	2.9	2.8	3.2	2.7
TCO	**14.2**	**20.3**	**14.4**	**15.0**	**14.5**	**15.9**	**16.1**

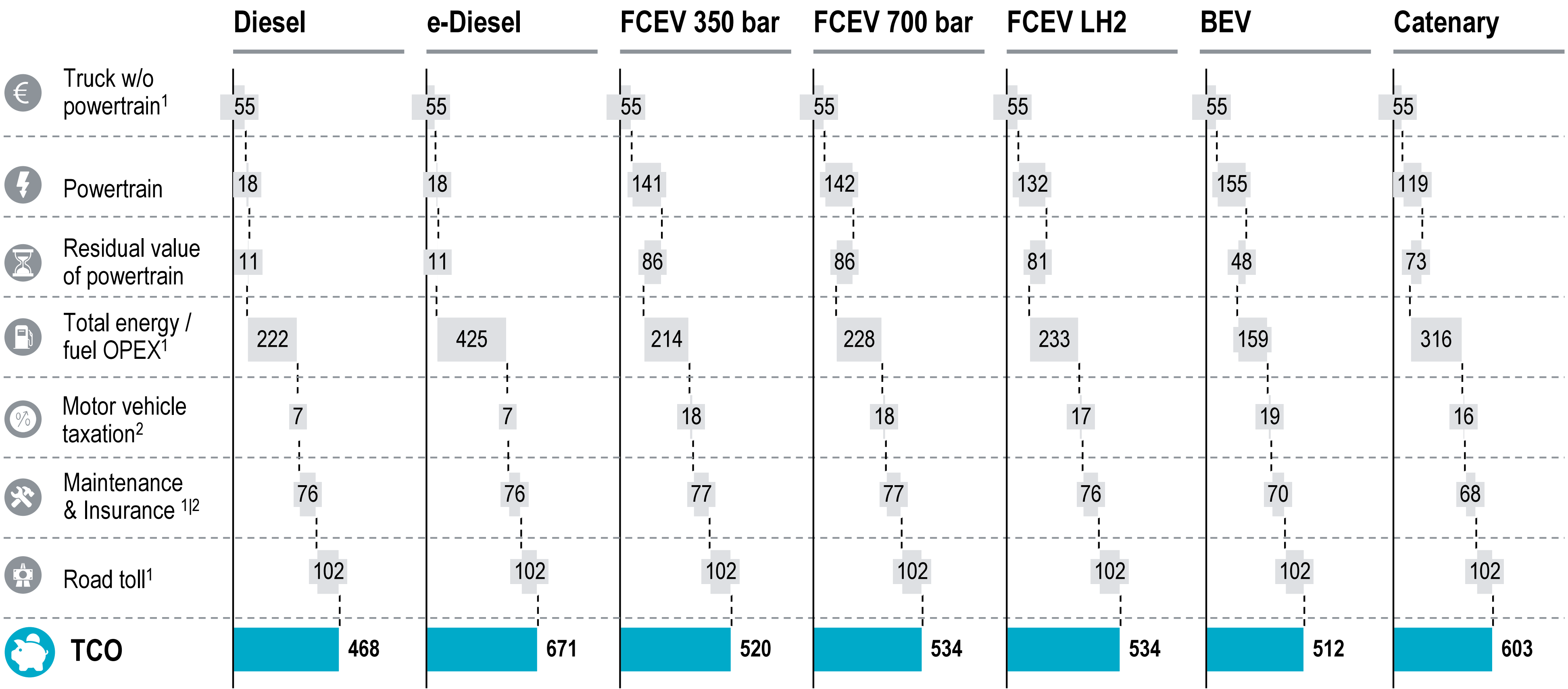
1) Deviations of results are related to payload differences of different technologies 2) Deviations of results are related to calculation based on higher CAPEX

Source: Roland Berger

The TCO analysis for use case III identifies cost of energy as main cost driver and cost of powertrain as important differentiating factor

Cost drivers of TCO – Use case III [kEUR/truck in 2023; 1st & 2nd life]

3 Use case III – Rigid 4x2



	Diesel	e-Diesel	FCEV 350 bar	FCEV 700 bar	FCEV LH2	BEV	Catenary
Truck w/o powertrain[1]	55	55	55	55	55	55	55
Powertrain	18	18	141	142	132	155	119
Residual value of powertrain	11	11	86	86	81	48	73
Total energy / fuel OPEX[1]	222	425	214	228	233	159	316
Motor vehicle taxation[2]	7	7	18	18	17	19	16
Maintenance & Insurance [1]|[2]	76	76	77	77	76	70	68
Road toll[1]	102	102	102	102	102	102	102
TCO	**468**	**671**	**520**	**534**	**534**	**512**	**603**

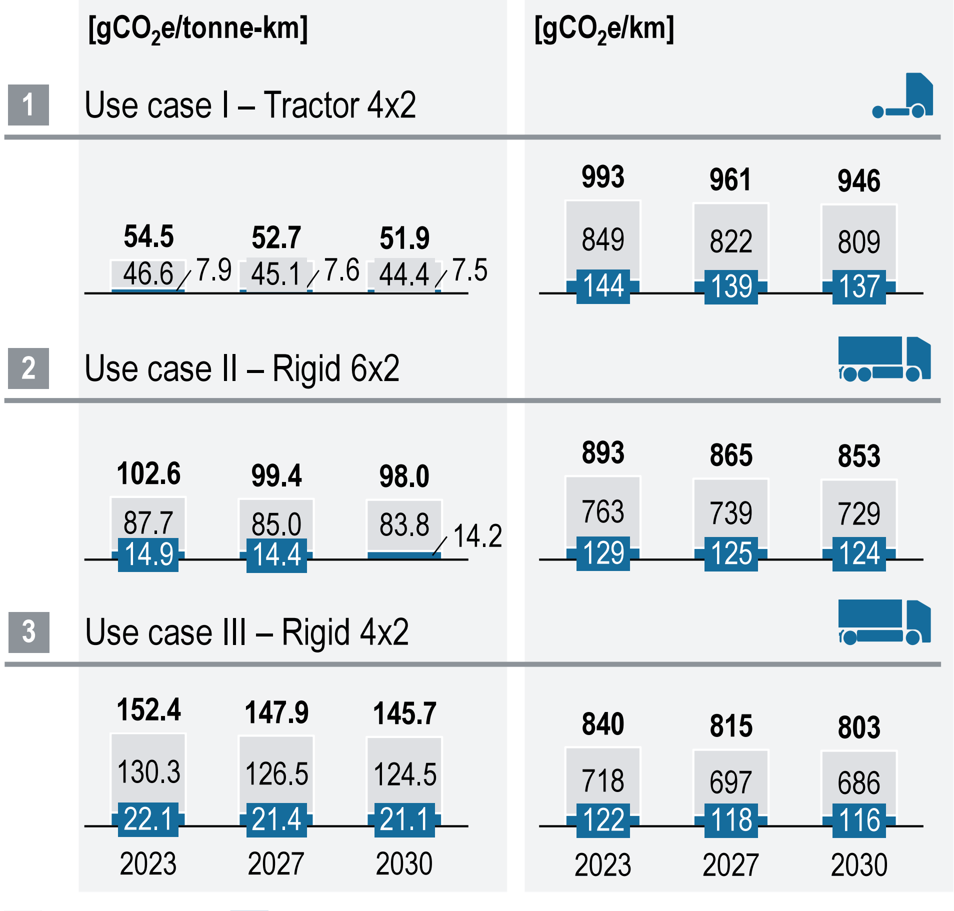
1) Deviations of results are related to payload differences of different technologies 2) Deviations of results are related to calculation based on higher CAPEX

Source: Roland Berger

FCH technology with clear environmental benefits compared to diesel – Significant emission reduction potential with green H_2

Environmental analysis (1/2)

CO_2 savings potential – Well to Wheel



Emission reduction

> Current CO_2 **emissions** produced by diesel trucks can be **eliminated by switching to zero-emission vehicles**

> **Fundamental requirement** for realising the zero-emission potential is the **access to zero-emission fuel and electricity from renewable energy** sources, e.g. green hydrogen

Pollution reduction[1]

> Zero-emission technologies also offer reduction potential for other pollutants:

- FCH trucks allow for a total reduction of NOx pollutants as no combustion is needed
- Particulate matter can potentially also be reduced due to more efficient driving patterns, incl. regenerative braking

---

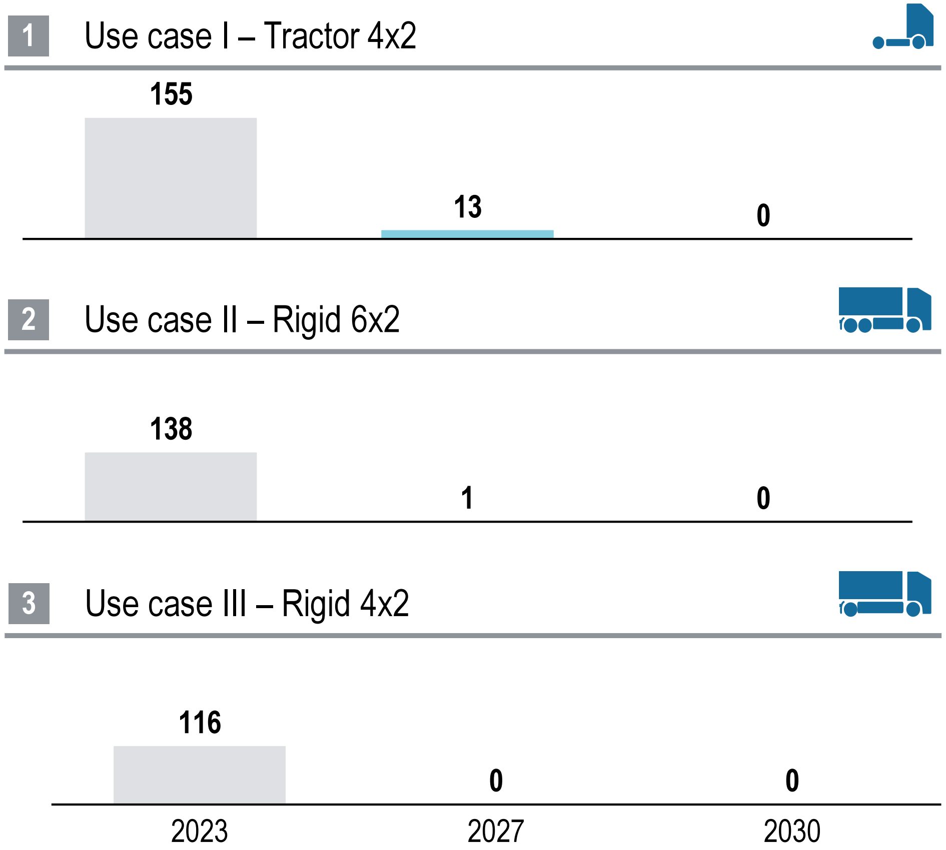
[1] Pollution reduction potential not quantified as specific limits are set for each heavy-duty diesel engine on the vehicle test stand. Limits are set per kWh of the vehicle power with maximum values set by legislation for pollutant mass (e.g. Euro VI with 0.46 gNOx/kWh) and particle number.

Source: Roland Berger

CO_2 mechanisms with the introduction of a CO_2 price could further support FCEV in achieving cost parity with diesel in the short-term

Environmental analysis (2/2)

Estimated CO_2 price for FCEV cost parity[1] [EUR/tonnes CO_2e]



Potential for FCEV cost parity

- The TCO analysis allows to identify the **cost premium of zero-emission technologies** vs. the incumbent diesel trucks – Applying this principle to the **environmental analysis offers insights into the cost premium** from a different angle
- The analysis shows that **FCEV become more cost-competitive over time; cost parity** will be **achievable with increasing industrialisation;** However, a CO_2 price could **support the TCO of ZEV especially in the short term**
- The **long-haul use case I is the most CO_2 emissions intensive** – due to high OPEX for energy/fuel, the cost delta of FCEV to diesel trucks is higher; A **higher CO_2 price** can support closing the gap to reach cost parity in the short-term
- A **key assumption** is that in order to benefit from a potential CO_2 price on diesel, **FCEV are fuelled by green hydrogen only** – the **build-up of a certified supply chain** for green hydrogen should **be supported in parallel**

Note: The TCO assumptions include a cost development for FCH technology ranging from a niche market scenario in 2023 to a rather mass scenario in 2030[2]. As such, the cost down potential of FCEV becomes evident – both in the TCO calculation and in estimating the CO_2 price to reach cost parity with diesel.

---

1) The CO2 price to reach cost parity is estimated on the average of TCO results of the different H2 storage technologies
2) For further references on the TCO assumptions, please refer to the Annex on general assumptions
Source: Roland Berger

General insights can already be derived from generic TCO comparison before elaborating on specific nuances in the case studies

General insights from TCO modelling

1 **Cost of energy** has the **biggest impact** over the truck lifetime while the **powertrain** cost is a key **differentiating factor** (for all technologies, except BEV due to the high cost of the large battery)

2 While **use case I and II** appear to be **best addressed with fuel cell technology**, in **use case III** the battery electric truck would be a stronger competitor for FCEV. Additional power loads (e.g. cooling trucks), longer ranges or multishift operation would further improve the FCEV value proposition

3 **Uncertainties** for alternative powertrains **still exist** due to **limited operating experience** in real driving conditions and **lack of production at scale** (while partly being already addressed by the industry)

4 **Liquid hydrogen** could be a **viable** refuelling alternative **by 2030** mainly due to **scale of production** and **lower infrastructure cost**, while **700 bar technology provides more flexibility** for H_2 sourcing (e.g. pipeline supply, on-site electrolysis production, pot. downwards compatibility with lower pressure levels, use by other vehicle types) and synergy effects with other end applications (e.g. cars and other LDVs)

5 **Road toll** and **CO_2 based mechanisms** are **potential** key **levers to enable business cases** already in the short-term

Source: Roland Berger

C.2.2.2 Sensitivity analyses

The robustness of the TCO results is validated through sensitivity analyses of selected parameters – Identification of main changes

Sensitivity analysis approach

Sensitivity

- Analysis of implications of **changes within certain parameters**
  - 'How sensible' is the TCO result to specific changes of the main cost blocks, e.g. energy assumptions?

Input

- Identification of changes of main cost blocks when **input parameters are changed**
- Identification of **'critical' values** for certain parameters (e.g. when a specific TCO target value has to be achieved)

Process

1. Selection of target criteria
2. Selection of input parameters
3. Establishment of the main cost blocks
4. Determination of sensitivities
5. Interpretation of results

Assessing the effect on TCO of e.g.

- Energy cost
- Market maturity
- Costs of powertrain (e.g. fuel cell, H_2 tank)
- Consumption

Source: Roland Berger

Sensitivity analyses are conducted to reflect uncertainties regarding technical development, pol. incentives and geographical differences

Guiding principles for sensitivity analysis

Sensitivity analysis[1]

- Focus on comparing **FCEV and BEV, using diesel as reference category**, i.e. Diesel e-fuel and catenary are excluded due to limited competitiveness even under sensitisation
- Results shown in payload corrected **[EUR ct/tonne-km]** and absolute values **[EUR/truck]**
- Range of sensitisation to reflect **potential differences in real life use patterns**
- Selection of sensitisation parameter due to **uncertainties regarding technical development**:
  - > Consumption
  - > Powertrain cost
- Selection of sensitisation parameter due to **uncertainties by real life use and location**:
  - > Energy/Fuel costs
  - > Driving pattern
  - > Market maturity
  - > Annual mileage
- Selection of sensitisation parameter due to **potential future political incentives**:
  - > Road toll
- Use case I in focus to **test methodology and assumptions** as most drastic changes can be expected for this use case representing the main transport segments, offering the highest CO_2 savings potential and being of high interest to the industry

1) All assumptions can be found in detail in the Annex to this report

Source: Roland Berger

With the TCO analysis and the Advisory Board expert input, a set of hypotheses was developed on potentials and uncertainties

Hypotheses for sensitivity analyses (1/2)

- The **direct comparison of technologies in 2023 and 2030** will show the **most important changes over the years**. Moreover, in the 2023 perspective, **potential short-term measures** to support the TCO of FCEV **will be identified.**
- When **considering the EUR ct/tonne-km and EUR/truck values**, further conclusions can be drawn on **potential payload restrictions**. The comparison of both perspectives will lead to **further insights into the sensitivity parameter and allow the testing of assumptions** considering payload corrected and absolute values.
- The **most discussed assumptions** in the study's Advisory Board refer to **the powertrain costs**. Especially for the fuel cell module of FCEV, but also for BEV, there were differing views, yet a compromise could be established. Testing these assumptions again will account for the different opinions and factors that will likely lead to higher (or potentially lower) costs, e.g. availability of supply.
- Another much discussed parameter refers to the established **market maturity levels**. The sensitivity analysis will show how the **TCO results change if assuming extreme scenarios for both FCEV and BEV**. This analysis is conducted to 'stress test' the assumptions on market and technology development.
- **Vehicle consumption figures** in the model are **based on energy at wheel considerations**.[1] As a higher/lower consumption can have several reasons (e.g. driving conditions, operational patterns or payload considerations) and **real-life data for FCH trucks is still very limited**, the sensitivity variations will **show the impact on the TCO**. Also, the sensitivity analyses test for higher battery consumption (e.g. heating in winter, cooling in summer).

1) For further information on the consumption assumptions, please refer to the Annex on energy/fuel assumptions

Source: Advisory Board; Roland Berger

With the TCO analysis and the Advisory Board expert input, a set of hypotheses was developed on potentials and uncertainties

Hypotheses for sensitivity analyses (2/2)

- Testing changes in the **assumed energy costs will solidify confidence in the assumptions** and provide evidence for **scenarios in which energy costs are much lower/higher**, especially regarding BEV charging and hydrogen prices.[1] The base assumption on energy/fuel costs **considers the base price**, **existing and anticipated taxes and surcharges** and an **infrastructure utilisation component**. Testing this assumption **answers to existing uncertainties on future charges**. For electric charging, the electricity grid is not everywhere equally dense and suited to supply the high energy demand arising from charging of several vehicles at the same time. Oftentimes, **investments in grid updates/further infrastructure will be needed** that are then added as further surcharges on the energy price. However, it could also be possible that the **base electricity price decreases until 2030**. For hydrogen, the variation in assumed fuel costs refers to **uncertainties around, e.g. availability of hydrogen or a low utilisation of the refuelling infrastructure** that need to recuperate high investments.
- Testing the assumptions on **driving pattern reflects increases in the daily range** and **considers any extreme variations of the average ranges** (if applicable, use case dependent). These assumptions on the driving pattern (homogenous vs. heterogenous) **influence the powertrain** costs – Higher daily ranges require larger powertrains.
- Testing for **changes of annual mileage** will provide a better under**standing on how CAPEX and OPEX of a truck are linked to the daily range/annual mileage assumptions**. The daily range is calculated based on the annual mileage and the days of operation per year.
- **Road toll exemptions are an important lever already considered** in some European countries for lower-carbon and zero-emission vehicles (e.g. CNG/LNG trucks but also BEV and FCEV). The sensitivity analysis will provide **insights into the impact of realistic scenarios** of full exemption for ZEV and a reduced cost.

[1] For further information on the consumption assumptions, please refer to the Annex on energy/fuel assumptions

Source: Advisory Board; Roland Berger

Sensitivity analyses were conducted on seven parameters with parameter variation (high/low) reflected in the calculation

Principle sensitivity of parameters

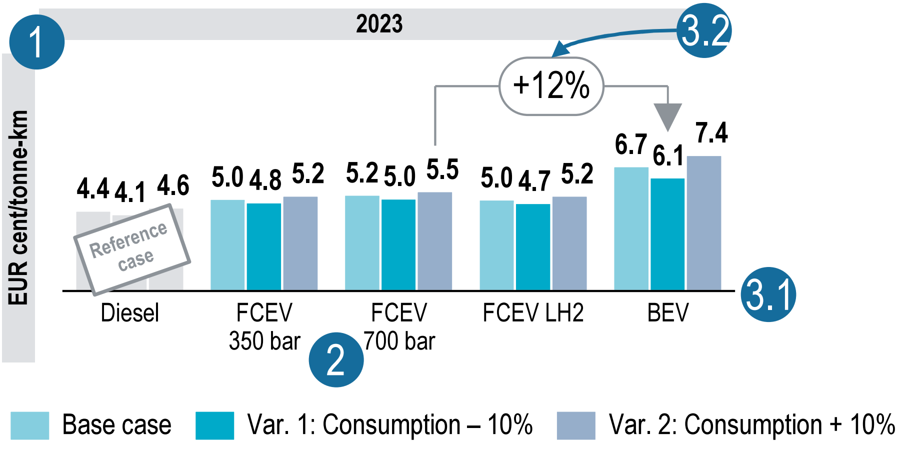
Sensitivity parameters[1]	**Variation 1**	**Variation 2**	**Rationale**
Powertrain	Large battery – 30% FC module – 30% H_2 tanks – 30%	Large battery + 30% FC module + 30% H_2 tanks + 30%	Component costs determine the overall powertrain costs – For ZEV technologies still in development, this is subject to uncertainties, e.g. on technol. progress, sourcing (dis)advantages, supplier diversity, different system configurations. 30% reflect a range of cost developments discussed in the Advisory Board
Market maturity	FCEV niche market BEV mass market	FCEV mass market BEV niche market	Market maturity and related cost development could play out differently for ZEV – Slower/faster market uptake and differing production volumes are likely across ZEV and the different H_2 storage technologies, e.g. 350 bar is an already existing technology while LH_2 is still in development
Energy costs (incl. tax and surcharges)	- 30%	+ 30%	Differences across Europe and uncertainties on cost development > Variation 1 (lower costs): higher infrastructure utilisation, lower regular electricity prices, exemptions of taxes/ surcharges > Variation 2 (higher costs): H_2 dependence on primary energy availability (renewable), electricity grid conditions, price structure of fast charging (e.g. 0.4-0.8 EUR/kWh range in DE for pass. car fast charging vs. private charging)
Consumption	- 10%	+ 10%	Consumption figures based on energy at wheel using Diesel as a base – While the energy need at wheel will remain, other factors could change the overall consumption, e.g. higher efficiency of electric drive (-10%), powertrain weight and payload impact (+10%)
Driving pattern	Fully homogenous	Fully heterogenous	The buffer included in the model for driving patterns determines the powertrain design to allow for stable (homogenous) or varying (heterogenous) daily ranges
Annual mileage	- 30,000 km	+ 30,000 km	Annual mileages are dependent on individual operations, with most mileages ranging between 110,000-170,000 km/year for the investigated use case (information from RB expert interviews)
Road toll	Diesel – 100% ZEV – 0%	Diesel – 125% ZEV – 75%	Road toll exemptions or prices linked to CO_2 performance are discussed as a short-term levers for ZEV, as observed with CNG/LNG trucks

1) Selection of parameters is based on main cost drivers and Advisory Board input

Source: Advisory Board; Expert interviews; Roland Berger

With the sensitivity analyses, the model assumptions can be tested and potential upsides and risks of TCO influences are identified

Introduction to the sensitivity analyses illustrations



Consideration on time and weight-related factors

1

The **direct comparison of technologies in 2023 and 2030** shows the impact of the sensitivity variations over the years – This way, **changes in the TCO** can be observed in the **short-term niche scenario and at scale in 2030**

2023 **2030**

The sensitivity analyses also consider the **weight/payload-corrected perspective** to test whether further insights need to be considered regarding potential **payload restrictions**.

10kEUR/truck **EUR cent/tonne-km**

Comparison of different technologies

3

3.1 The sensitivity analyses focus on the **comparison of diesel (reference case) with selected zero-emission technologies**:

- > **FCEV – all storage technologies, and**
- > **BEV**

Diesel e-fuels and catenary are excluded due to the limited competitiveness of the technologies even with the sensitised assumptions

3.2 The difference arrow indicates the comparison between the 'worse' performance of FCEV and the 'better' performance of BEV

Modelled variations in relation to technology base case

2

The three bars represent the **different variations modelled in the analysis** per technology (see graph legend above):

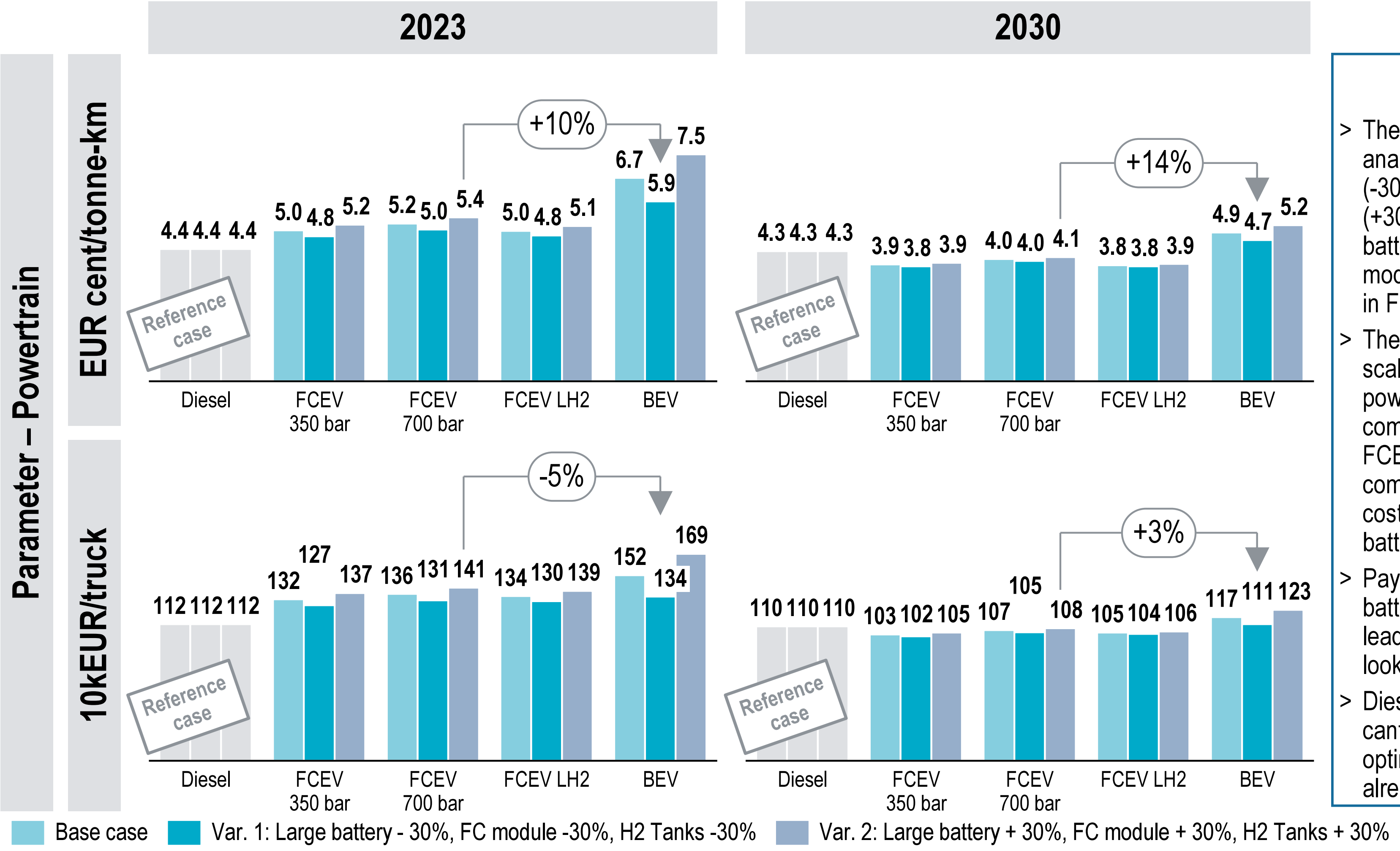
- **'Base case'** refers to the TCO result based on the base case assumption
- **'Variation 1'** shows the TCO result when decreasing the input variable of the base case assumption by -10%
- **'Variation 2'** shows the TCO result when increasing the input variable of the base case assumption by +10%

The variation values were selected to test realistic and maximum scenarios within the certain parameter

Source: Roland Berger

Comparing a cost reduction for large batteries but higher costs for FC module and H_2 tanks demonstrates the TCO potential of FCEV

TCO sensitivity – Cost of powertrain [Use case I; 1st & 2nd life]

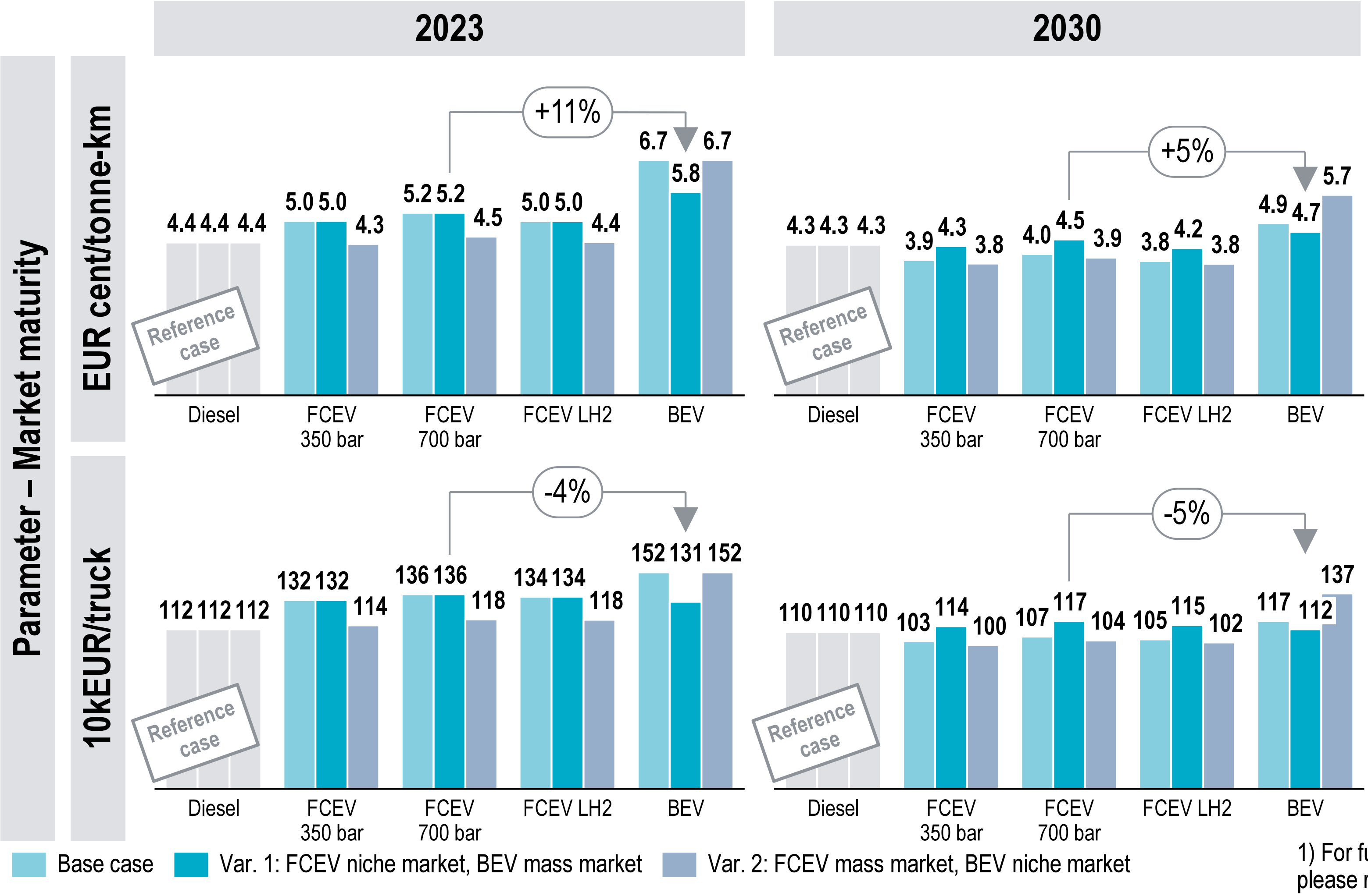


- The variation in this analysis looks at lower (-30%) vs. increased (+30%) costs for the large battery in BEV and the FC module and hydrogen tanks in FCEV in 2023 and 2030
- The analysis shows that at scale in 2030, the FCEV powertrain will reach competitive cost levels – FCEV TCO is lower compared with BEV even if costs are increased and the battery costs lowered
- Payload effects of the large battery (payload reduction) lead to a better FCEV outlook on a tonne-km basis
- Diesel will not see significant cost changes for the optimised diesel engine already mass produced

Source: Roland Berger

If FCEV remains a niche technology and a mass market develops for BEV, FCEV would only be an alternative if payload is a constraint

TCO sensitivity – Market maturity [Use case I; 1st & 2nd life]



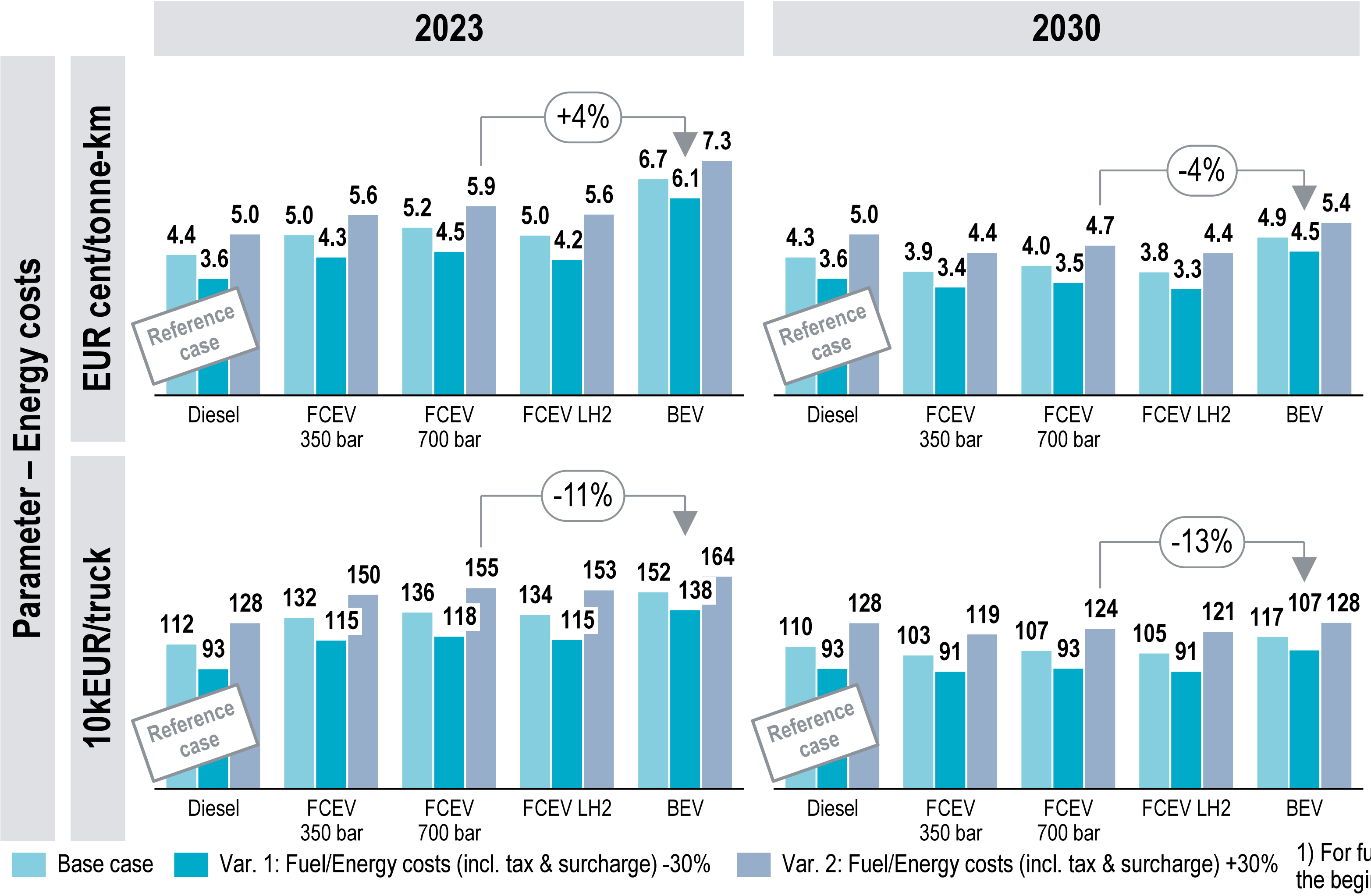
- The comparison of market maturity levels[1] investigates the TCO results if the technology development will not materialise as assumed
- In a niche market, production volumes remain low which in turn translates into higher component costs; in the mass markets, volumes are high with lower costs as a result
- The analysis shows that assuming a mass market for BEV and a niche market for FCEV, the absolute TCO for FCEV is higher
- It shows that if FCEV will not be produced at scale in the near term, costs will not get down and the market uptake will not materialise

1) For further details on the assumptions, please refer to the Annex

Source: Roland Berger

Assuming higher H_2 costs for FCEV would benefit BEV in a direct TCO comparison – However, payload effects to be considered

TCO sensitivity – Energy/fuel cost [Use case I; 1st & 2nd life]



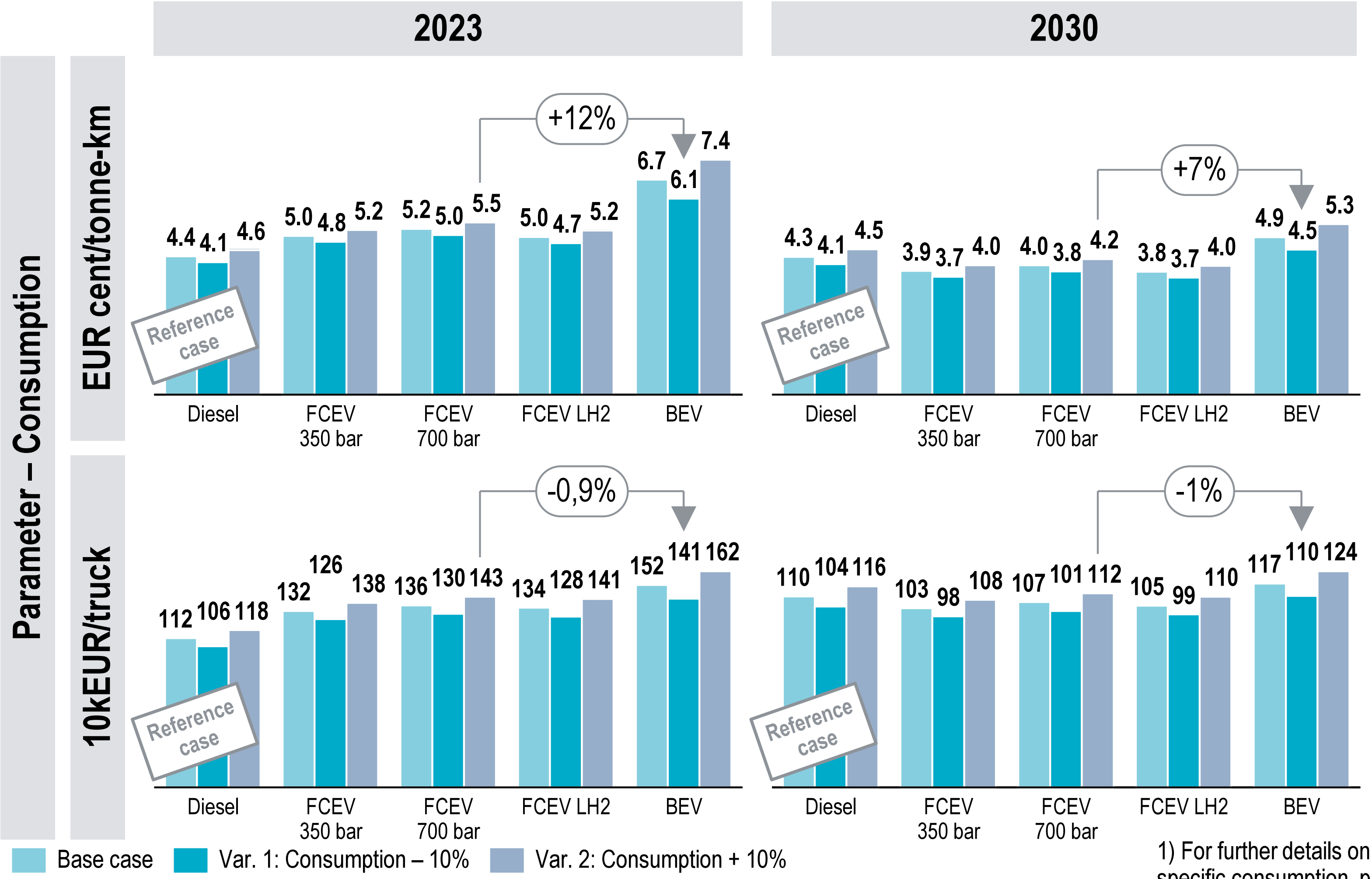
- Energy and fuel costs underlie different effects regarding, e.g. price and tax levels across geographies, electricity grid and infrastructure conditions, energy prices at peak hours, availability of renewable energy
- H_2 production and supply are still in development – Potential upsides can be observed, but costs still remain uncertain[1]
- Analysis shows that the FCEV TCO could still compete with BEV if energy/fuel costs increase for both technologies
- Lower energy price at such extent is not expected in practice as it is improbable due to grid and infrastructure build-out, peak prices

[1] For further explanations, please refer to the beginning of chapter C.2.2

Source: Roland Berger

In a 'energy at the wheel' consumption comparison with BEV, FCH trucks provide a good TCO outlook even with a higher consumption

TCO sensitivity – Consumption [Use case I; 1st & 2nd life]



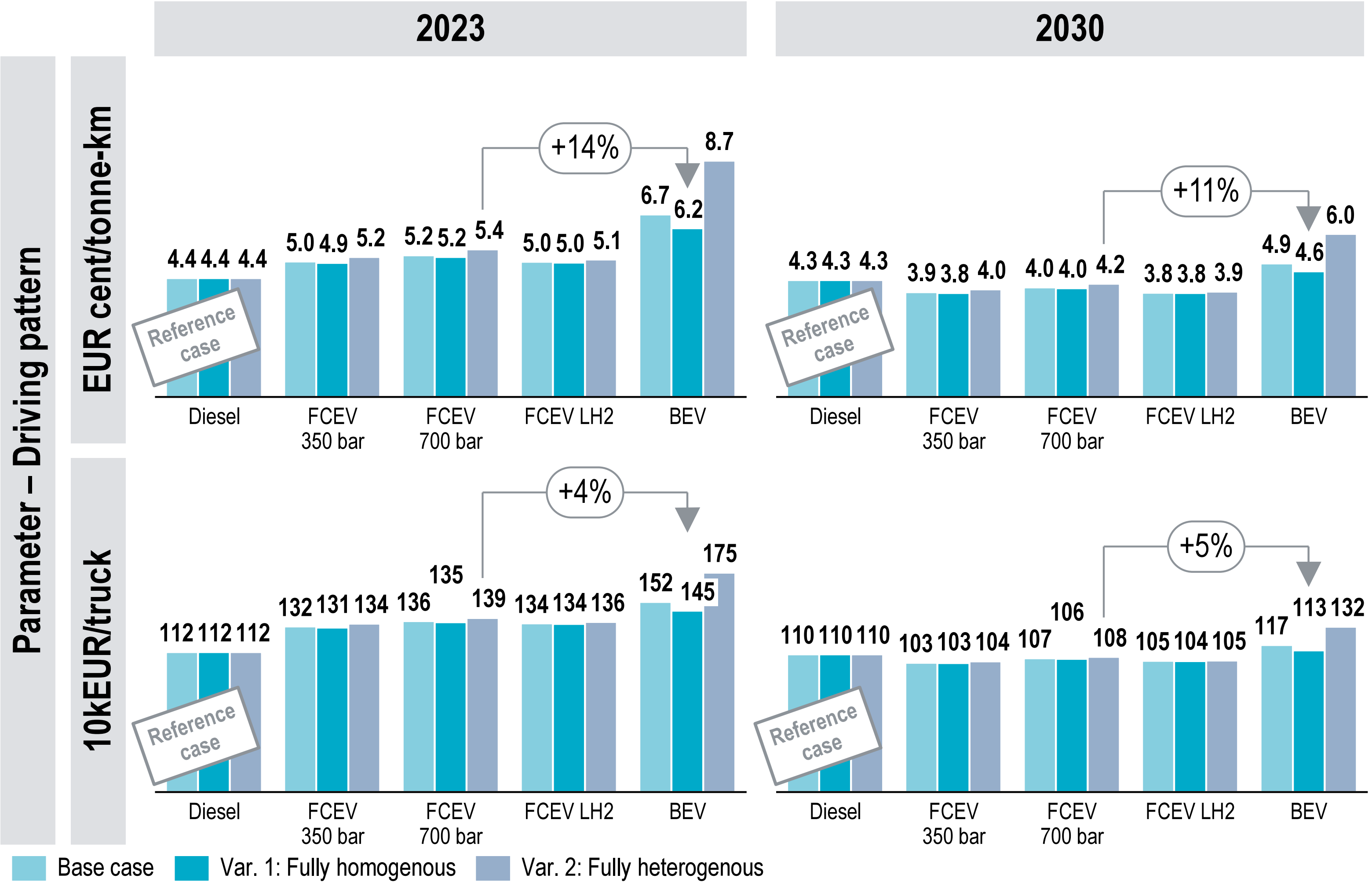
- > Currently, limited field data for HD trucks with zero-emission powertrains leads to uncertainties for assumptions on consumption
- > The sensitivity analysis accounts for views that alternative powertrains should have a better consumption performance due to a higher efficiency of electric energy conversion (building on the 'energy at the wheel' calculation with a Diesel truck benchmark[1])
- > Assuming a consumption reduction for BEV and an increase for FCEV, the analysis shows that the TCO of both technologies would be at par, allowing some margin for higher FCEV consumption

[1] For further details on the assumptions on use case specific consumption, please refer to the Annex

Source: Roland Berger

FCEV are well-suited for the requirements of flexible operations – TCO results are less affected by heterogenous driving patterns

TCO sensitivity – Driving pattern [Use case I; 1st & 2nd life]

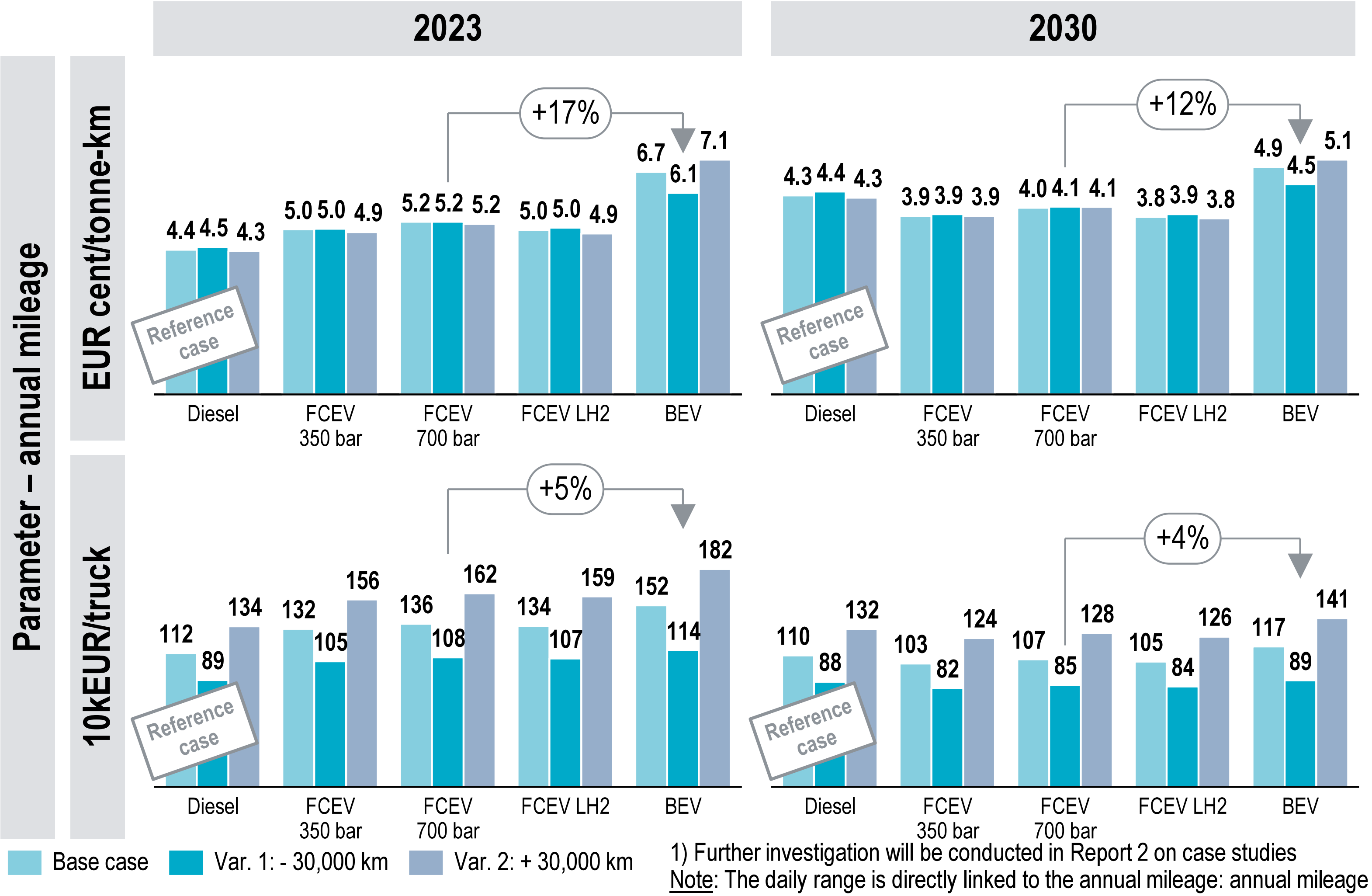


- The TCO model accounts for different driving profiles (standard routes vs. varying ranges) including an additional 'buffer' on the daily range set in the model (additional % put on km)
- The daily range determines the powertrain performance requirements (battery size, H_2 tanks) and is a decisive factor for the powertrain costs – The larger the buffer due to the driving pattern, the higher the costs
- The analysis shows that with more range flexibility (= higher buffer for heterogenous driving profile), the TCO increases – Compared to BEV, FCEV offer a higher flexibility and thus better TCO results

Source: Roland Berger

Testing the results for annual mileage robustness, it shows that the TCO of BEV benefits relatively more from lower mileage than FCEV

TCO sensitivity – Annual mileage [Use case I; 1st & 2nd life]



- The TCO analysis is based on use cases representing the average of annual mileage across the selected HD market segments, while the sensitivity analysis tests the robustness of TCO results for a range of annual mileages
- The sensitivity analysis shows that the lower the annual mileage, the lower the TCO in all cases
- When directly comparing FCEV and BEV, it becomes clear that in particular the TCO of BEV benefits from a lower mileage – FCEV on the other hand would provide more flexibility
- Further analysis of different mileages is conducted in specific case studies[1]

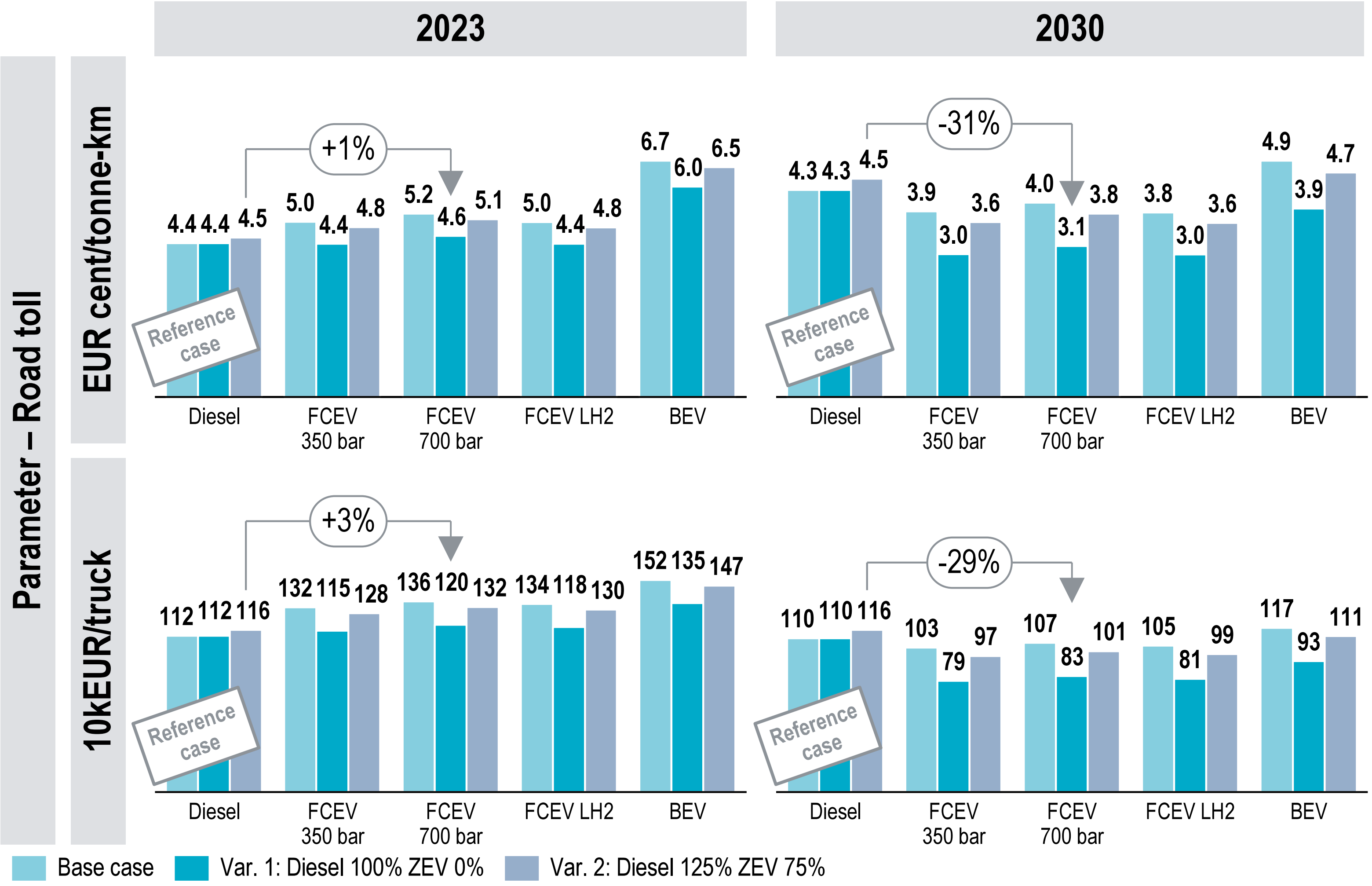
[1] Further investigation will be conducted in Report 2 on case studies

Note: The daily range is directly linked to the annual mileage: annual mileage / days of operation

Source: Roland Berger

Linking road toll to an emission-based mechanism benefitting ZEV, the TCO of FCEV could become close to diesel already in 2023

TCO sensitivity – Road toll [Use case I; 1st & 2nd life]



- Road toll exemptions are already considered as a lever to support low- and zero-emission vehicles in some European countries (e.g. CNG/LNG trucks)
- The sensitivity analysis shows that both a full exemption and a targeted approach (increase for Diesel, reduction for ZEV) have an impact on the TCO results at the advantage of FCEV and BEV
- The largest impact in the short-term could be reached if road-toll for diesel was increased while ZEV are exempt – This could bring the TCO of FCEV in the range of diesel already in 2023

Source: Roland Berger

C.2.3 Market potential analysis

The market potential analysis investigates the possible market development in terms of sales of new trucks until 2030

Insights on the market potential analysis

Analysis of market segments

The **market potential of FCH HD trucks** in Europe is **analysed along three use cases**, representing **different road transport segments**, **operating patterns** and **truck types**

Reference to technology acceptance

Technology acceptance factors reflect that despite **specific TCO results,** only a certain **number of FCH trucks would enter the market** (e.g. first movers) – Three uptake scenarios are identified

Link to 2050 climate goals

Truck **sales from 2035 onwards will determine the fleet composition by 2050** – In order to **reach** the **CO_2 emission reduction targets**, the identified **growth rate of zero emission technology until 2030** needs to materialise

Long-haul market segment (Use case I)

In the long-haul use case, a clear potential of FCEV market uptake is indicated – This market segment has the highest CO_2 reduction potential

Mid-haul market segment (Use case II)

For the mid-range use case, the market uptake scenarios show a high potential for FCH trucks; being the smallest market segment, numbers of trucks are limited

Short-haul market segment (Use case III)

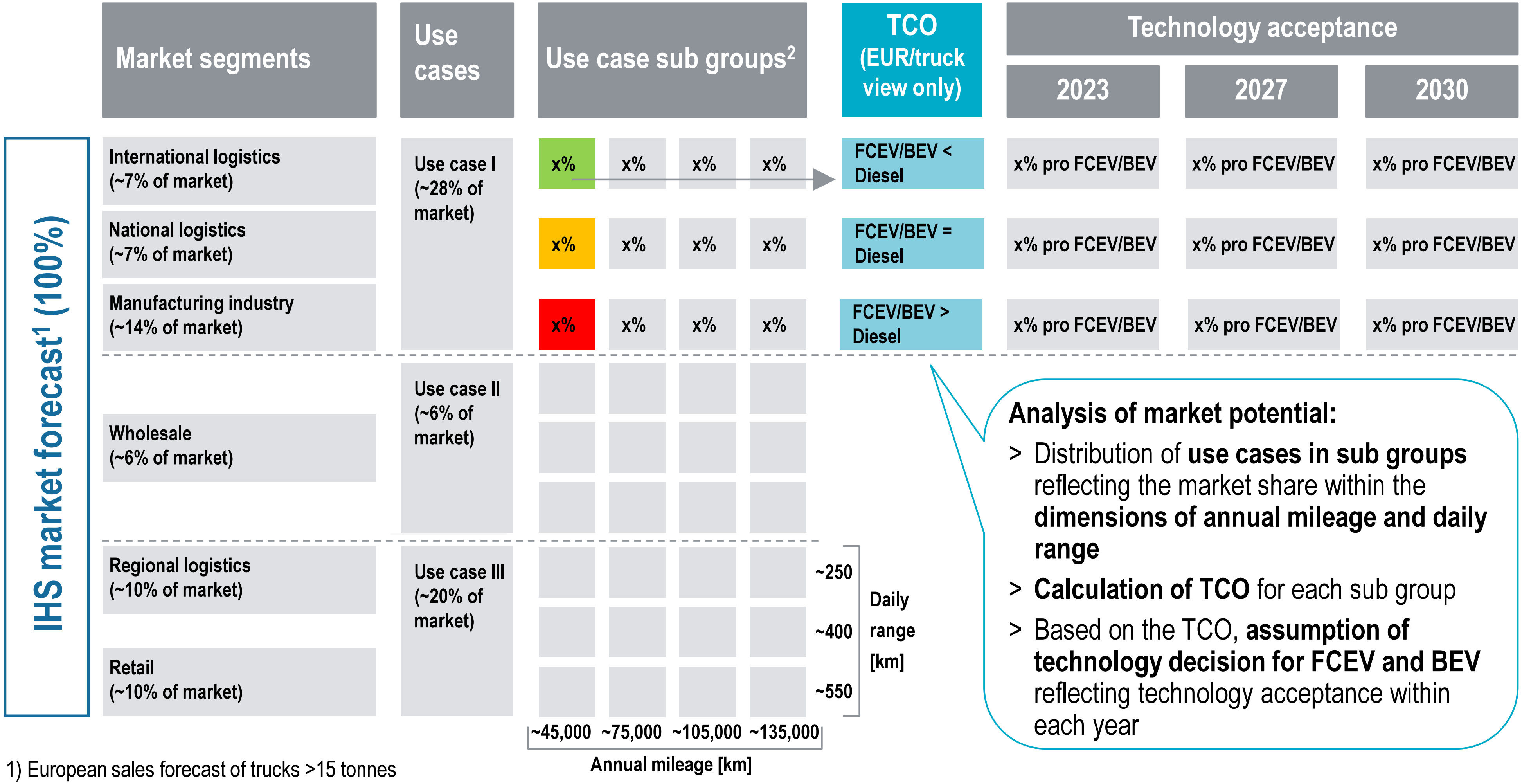
The short-haul market segments are a good fit for the alternative powertrain technologies – FCEV and BEV both have potential, with a higher share for FCH technology

Overall, FCH technology has a high potential within the investigated truck market – The analysis predicts that 17 % of new truck sales in 2030 could be FCEV

Source: Roland Berger

The market model builds on the developed TCO model and truck market forecast – Level of new technology acceptance considered

Market model structure



IHS market forecast[1] (100%)

Market segments	Use cases	Use case sub groups[2]				TCO (EUR/truck view only)	Technology acceptance 2023	Technology acceptance 2027	Technology acceptance 2030
International logistics (~7% of market)	Use case I (~28% of market)	x%	x%	x%	x%	FCEV/BEV < Diesel	x% pro FCEV/BEV	x% pro FCEV/BEV	x% pro FCEV/BEV
National logistics (~7% of market)		x%	x%	x%	x%	FCEV/BEV = Diesel	x% pro FCEV/BEV	x% pro FCEV/BEV	x% pro FCEV/BEV
Manufacturing industry (~14% of market)		x%	x%	x%	x%	FCEV/BEV > Diesel	x% pro FCEV/BEV	x% pro FCEV/BEV	x% pro FCEV/BEV
Wholesale (~6% of market)	Use case II (~6% of market)								
Regional logistics (~10% of market)	Use case III (~20% of market)								
Retail (~10% of market)									

Analysis of market potential:

- > Distribution of **use cases in sub groups** reflecting the market share within the **dimensions of annual mileage and daily range**
- > **Calculation of TCO** for each sub group
- > Based on the TCO, **assumption of technology decision for FCEV and BEV** reflecting technology acceptance within each year

---

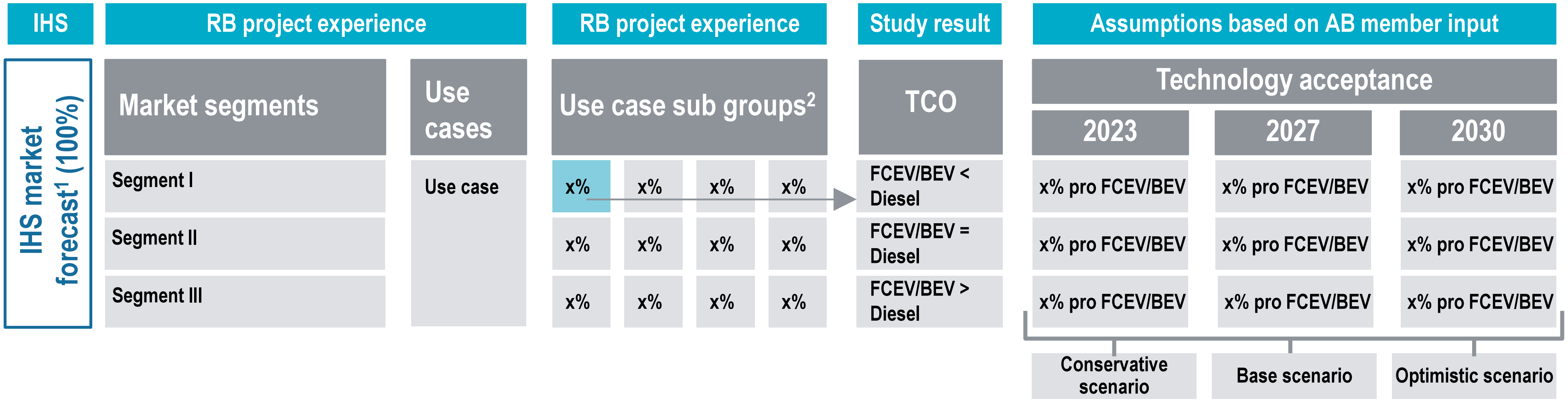
1) European sales forecast of trucks >15 tonnes

2) Sales share per use case sub group is calculated based on known annual mileage and daily range group distribution

Source: Roland Berger

The calculation builds on the TCO results and market size of the use case breakdown, corrected by the technology uptake factors

Detailed approach for the market model



IHS	RB project experience		RB project experience				Study result	Assumptions based on AB member input		
IHS market forecast[1] (100%)	Market segments	Use cases	Use case sub groups[2]				TCO	Technology acceptance		
								2023	2027	2030
	Segment I	Use case	x%	x%	x%	x%	FCEV/BEV < Diesel	x% pro FCEV/BEV	x% pro FCEV/BEV	x% pro FCEV/BEV
	Segment II		x%	x%	x%	x%	FCEV/BEV = Diesel	x% pro FCEV/BEV	x% pro FCEV/BEV	x% pro FCEV/BEV
	Segment III		x%	x%	x%	x%	FCEV/BEV > Diesel	x% pro FCEV/BEV	x% pro FCEV/BEV	x% pro FCEV/BEV

Conservative scenario

Base scenario

Optimistic scenario

1 **IHS forecast data on truck sales** >15 tonnes in Europe from 2023 until 2030 is used as a starting point

2 **Truck sales per use case** are calculated **based on the truck sales and size of market segments**

Use case market sizes are derived from a **market segmentation** based on RB project experience

3 **Use cases are further divided in sub groups** along the **dimension annual mileage and daily range,** building **on distribution shares** per sub group based on RB project experience

4 **TCO** is calculated for **use case sub group combinations** on annual mileage and daily range

3 options possible:

> FCEV/BEV < Diesel

> FCEV/BEV = Diesel

> FCEV/BEV > Diesel

5 **For each TCO option** and each year, **technology acceptance factors** (based on logistics expert opinion) are introduced for three scenarios to **reflect potential uptake scenarios of new technologies**

XX Source of model input

1) European sales forecast of trucks >15 tonnes

2) Sales share per use case sub group is calculated based on known annual mileage and daily range group distribution

Source: Roland Berger

In order to reflect that technology acceptance depends on a range of external factors, three uptake scenarios are introduced

Market uptake scenarios [% of FCEV/BEV uptake]

Parameters based on AB expert input

	Conservative scenario			Base scenario			Optimistic scenario		
TCO	**2023**	**2027**	**2030**	**2023**	**2027**	**2030**	**2023**	**2027**	**2030**
FCEV/BEV < Diesel	**2%**	**10%**	**25%**	**2%**	**15%**	**50%**	**10%**	**30%**	**80%**
FCEV/BEV = Diesel	**1%**	**3%**	**15**	**1%**	**5%**	**30%**	**5%**	**15%**	**60%**
FCEV/BEV > Diesel	**0.5%**	**0.5%**	**2%**	**0.5%**	**1%**	**5%**	**1.5%**	**5%**	**20%**

Potential external factors (selected)

- Widespread risk aversion towards new technologies when business risks taken by truck operators (only)
- Remaining short-term subcontracting ("until further notice")
- Reduction of initial incentives / subsidies as market develops
- Price and reliability emphasised as top priorities by logistic service customers

- Subsidies / incentives to reach costs at scale
- Some acceptance of business risks by other parties (e.g. OEMs, fuel provider [e.g. H_2 'floaters'])
- Long(er)-term contracts ensuring plannability
- Significant hydrogen infrastructure developments on main routes
- Development of secondary market

- Acceptance of business risks by other parties besides truck operators
- H_2 'floater' as part of contracts
- Increasing buy-back options offered by OEMs
- Strong policy push for the whole transport chain (e.g. OEMs, logistics users, truck operators, fuel & infrastructure providers)

Source: Advisory Board; Roland Berger

The uptake scenarios reflect that – besides the TCO result – there are also other decisive factors when considering FCH trucks

Key assumptions per uptake scenario

- **Three uptake scenarios** are developed that reflect that **truck adoption rates in the future market** are **estimated based on clear criteria**
- Also, **technology acceptance** of a new technology is not always the result of a straight-forward TCO calculation – **Market dynamics and infrastructure considerations** play an important role
- **Political, technological and vehicle availability parameters** are considered

Conservative scenario

- FCH and battery electric trucks mainly remain niche solutions, in selected leading market segments
- Widespread risk aversion towards new technologies continues to hamper technology uptake
- Incentives and subsidies will be reduced as the market develops

Base scenario

- FCH and battery electric trucks achieve increasing market shares in market segments
- Involved stakeholders show a higher degree of acceptance of business risks
- Subsidies and incentives are put in place to ensure cost reductions at scale
- Significant hydrogen infrastructure is being developed along main routes and near logistics & trade hubs

Optimistic scenario

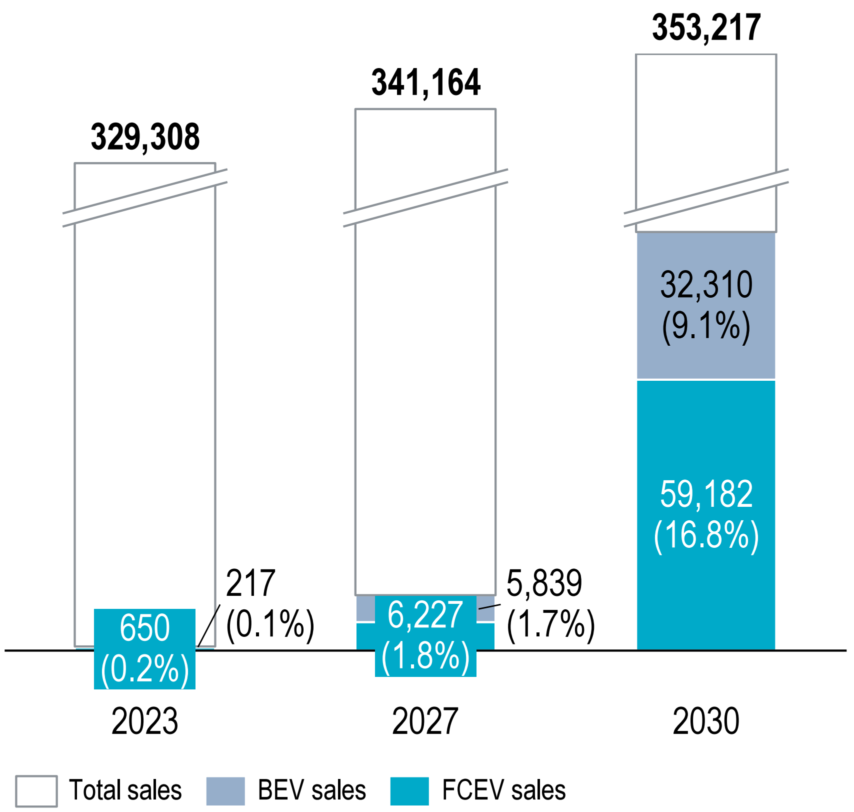
- FCH and battery electric trucks see robust adoption across all considered market segments
- Acceptance of business risks by other parties besides truck operators
- Strong policy push for the entire transport chain, including OEMs, hydrogen and infrastructure providers, truck operators and logistics users

Source: Advisory Board; Roland Berger

The market potential analysis shows a clear potential for alternative technologies and an increasing sales share until 2030

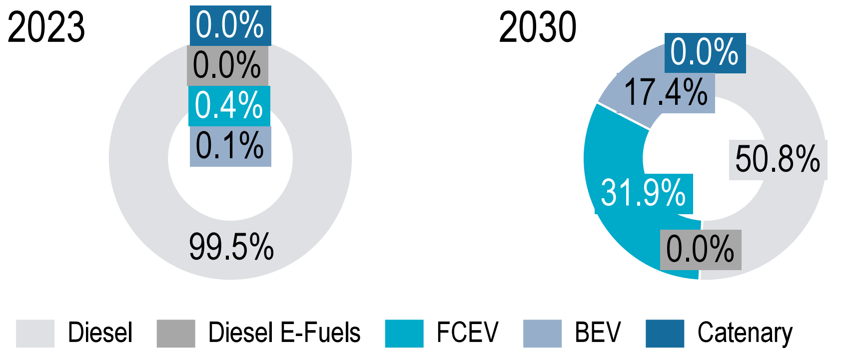
Overview of results (base scenario)

European market potential of FCEV [# of truck sales][1]



- The **market potential** analysis focuses on **selected market segments**[2] with a sales share of ~53%
- Overall, **FCEV have a high potential** within the whole truck market – **steep increase in sales share** from 0.2% in 2023 to **16.8% in 2030**
- Within the selected market segments, the **technology split** shows **dynamic changes between 2023 and 2030**: FCEV technology represents ~32% in 2030

Selected market segments' technology split [%]



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1) Results based on absolute EUR/truck results, not payload corrected

2) The market potential analysis refers to specific market segments: international logistics, national logistics, manufacturing industry, wholesale, retail and regional logistics

Source: IHS market forecast; Roland Berger

It also shows that even with the predicted market ramp-up of electric vehicles, decarbonisation efforts need to be increased

View on FCEV potential in the overall European market

Current outlook

Road transport volumes and the **number of trucks** on the road **increased over the last years** – Yet, a **90% CO_2 emission reduction by 2050** is set as the EU Green Deal target for transport

The **heavy-duty segment** is **responsible for 27% of road transport CO_2 emissions** → **HD vehicles** emit to up to **220 million tonnes CO_2** annually[1]

Up to **70% of total transport heavy-duty vehicle CO_2 emissions**[2] are caused by four vehicle types (4x2 rigid; 4x2 tractor; 6x2 rigid; 6x2 tractor)

FCEV market potential

~110,000 FCEV heavy-duty trucks by 2030 (accumulated total)

17% of annual new heavy-duty truck sales in 2030

Yet only **1.7% trucks market share**[3]

Impact

The **heavy-duty transport** sector can **fulfil its part in achieving the EU Green Deal target** for transport – Yet **only if all new sales of heavy-duty trucks** are **zero-emission vehicles** from 2035 onwards

With the projected market ramp-up, **up to 11 million tonnes CO_2 emissions** could be **avoided in 2030** with FCEV in the investigated market segments[4]

Long-haul trucks are in **focus for FCH technology** – **Highest market potential** in these segments demonstrated, **especially with increasing volumes of road transport**

> **Despite a significant predicted market growth**, the trajectory shows that **by 2030, only a very small percentage of the overall trucks driving on European roads would be zero-emission** vehicles

> To allow for the **transition in vehicle fleets** until 2050, **policy and industry efforts** must be **directed towards ensuring the zero-emission potential** for all new truck sales **from 2035**

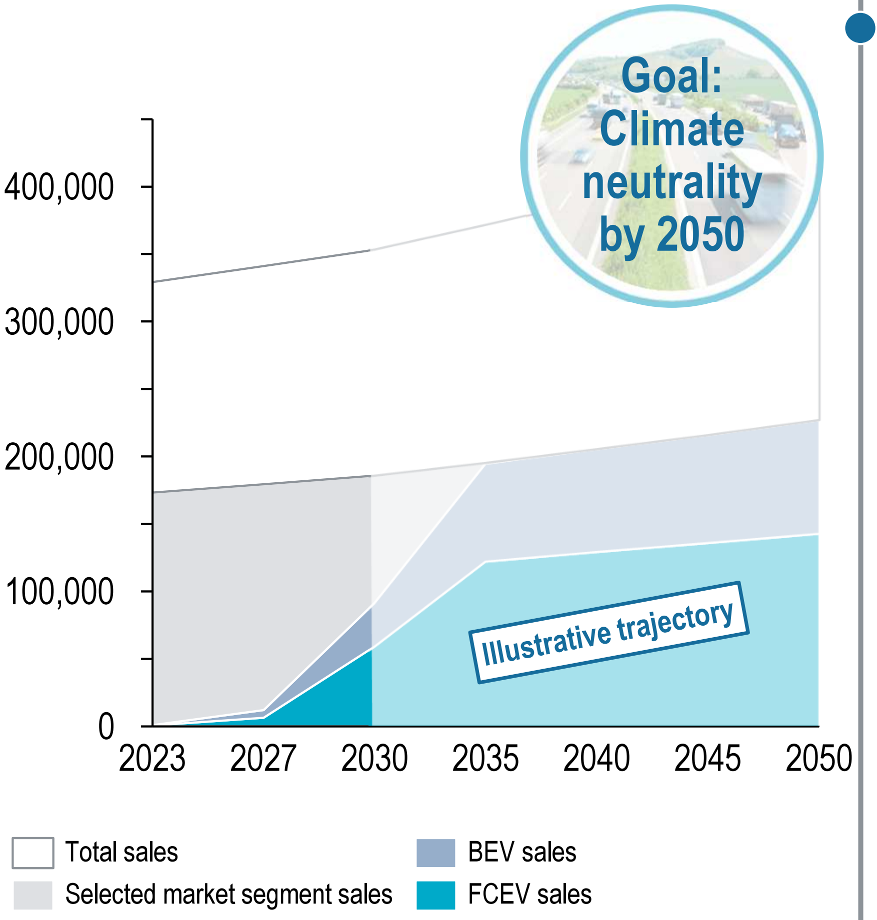
---

1) This figure is calculated based on publicly available information from the European Environment Agency for 2017 and might vary depending on the source and underlying calculation
2) Also considering 6x2 tractor vehicles not investigated in this study 3) Based on a total of 6.6 million medium and heavy-duty trucks in Europe 4) Market potential base scenario

Source: European Commission; EEA; ACEA; Desk research; Roland Berger

A fast market ramp-up over the next ten years is crucial for achieving the 2050 climate goals – Fleet replacement required

Assessment of 2050 market potential

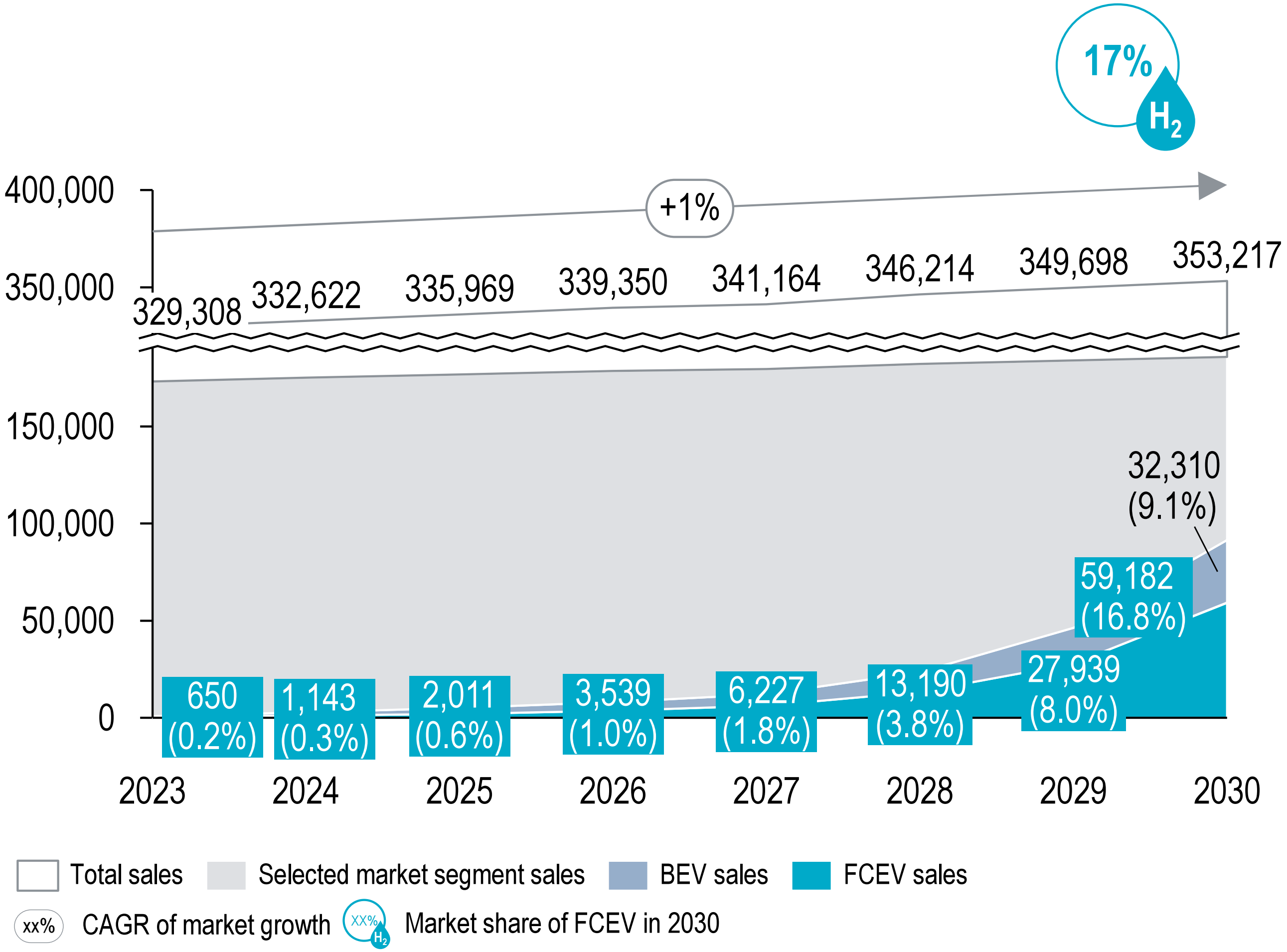


- > The CO_2 **emission reduction targets for 2050 in transport can be reached** for the heavy-duty truck segment – if the **growth rate of zero emission technology until 2030** materialises
- > As **zero-emission trucks become cost-competitive,** new sales of diesel trucks and other **CO_2-intensive technologies** could be **replaced from 2035** onwards – this is necessary to replace the majority of the fleet of diesel trucks until 2050
- > Critical factors:
  - **Push to market** for zero-emission trucks to ensure **scaling effects for cost competitiveness** and market uptake
  - **Enable infrastructure availability** to allow for widespread deployment
  - **Change within fleets** and **diesel phase-out** until 2035 as diesel trucks have a total lifetime of 10+ years
  - **Specific mandatory targets for all market actors** – OEMs in scope of HDT legislation, yet contribution across the whole sector necessary

Source: IHS market forecast; Roland Berger

The market potential of FCEV increases to an overall sales share of 17% in 2030 – Strong uptake from 2027 until 2030

European market potential of FCEV [# of truck sales] – Total base scenario[1]



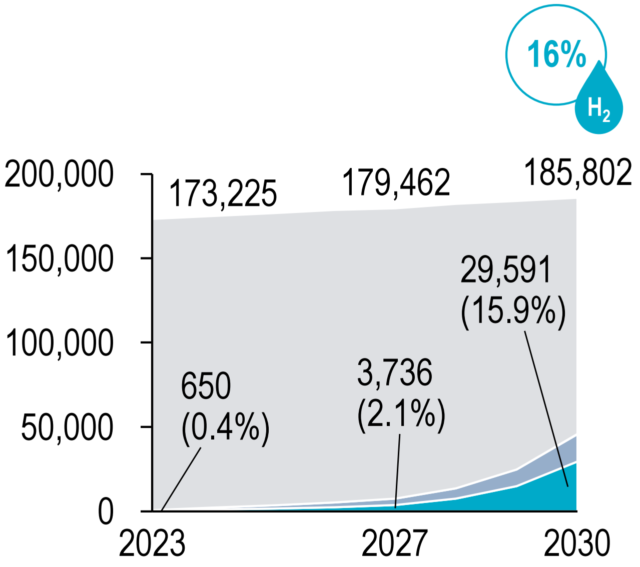
- The **market potential** analysis focuses on **selected market segments** that represent the most **relevant logistics industry** segments[2] (sales share of ~53% in the base year)
- In **2023,** the **sales share of FCEV is at 0.2%** due to assumptions made for **limited market maturity**, yet **increasing uptake opportunities**
- In **2027**, **a 1.8% sales share** is expected for FCEV
- In **2030**, the **FCEV sales share increases to ~17%**
- The **BEV sales share is increasing** overall and **establishes a market share of 9%** until 2030

1) The relative development of ZEV is based on the total number of truck sales in Europe, including the market segments selected for the market potential analysis (53% of total)
2) The market potential analysis refers to specific market segments: international logistics, national logistics, manufacturing industry, wholesale, retail and regional logistics
Source: IHS market forecast; Roland Berger

The comparison for the specific market segments shows a strong FCEV potential ranging between a sales share of 16 to 51% in 2030

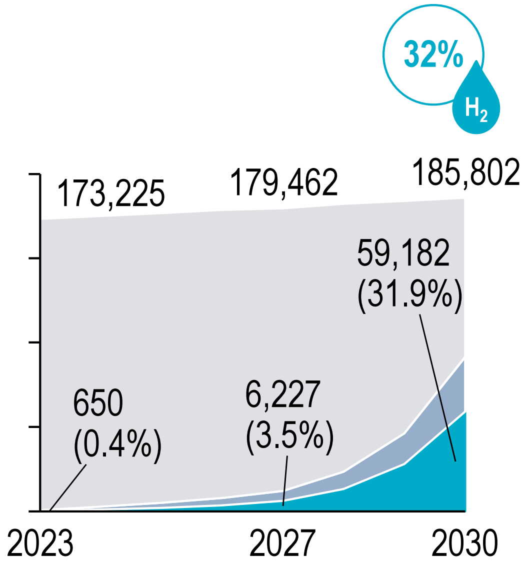
European market potential of FCEV [# of truck sales][1] – Market segment scenarios[2]

Conservative scenario



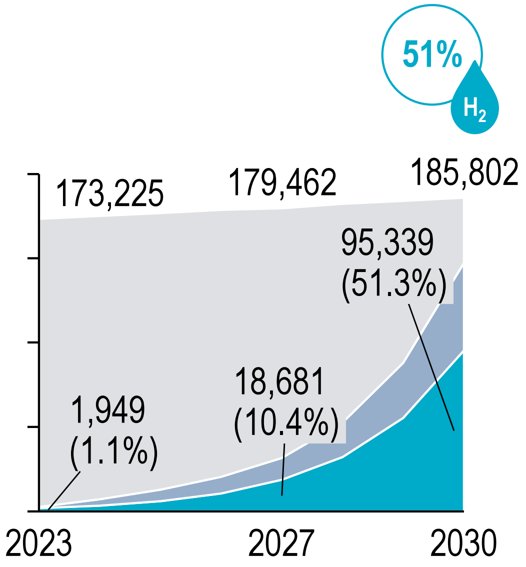
- > The conservative scenario shows a high growth rate of the FCEV sales share from 2027 until 2030; the development for BEV overall is predicted as slower (due to the large long-haul segment being a generally good fit for FCEV)

Base scenario



- > The base scenario shows a higher uptake already for 2027 with a steep increase until 2030 – FCEV sales surpass BEV sales share already after 2023, yet BEV still remain a relevant technology

Optimistic scenario



- > The optimistic scenario assumes a faster market development for zero-emission technologies from 2023 onwards
- > FCEV is predicted to take over >50% of the diesel sales share, with BEV assuming another significant share

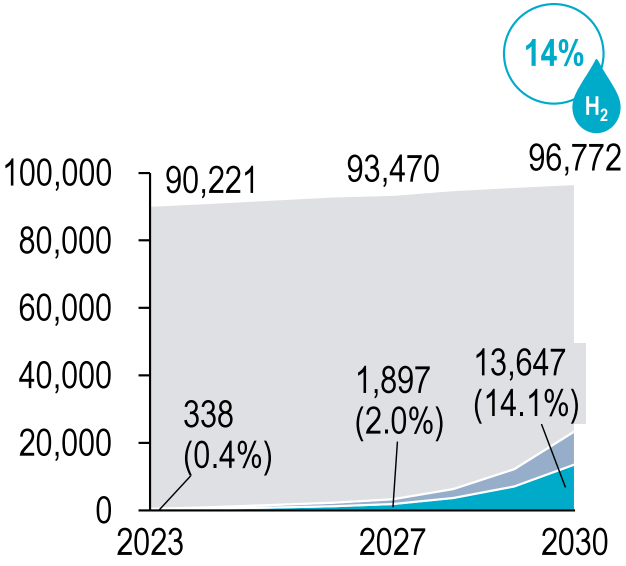
▨ Selected market segment sales ▨ BEV sales ▨ FCEV sales ○ Market share of FCEV in 2030

1) The market potential analysis refers to specific market segments: international logistics, national logistics, manufacturing industry, wholesale, retail and regional logistics
2) The relative development of ZEV is based on the market segments selected for the market potential analysis only (53% of total)
Source: IHS market forecast; Roland Berger

The comparison across uptake scenarios for Use case I shows that FCEV will see a promising market development for long-range cases

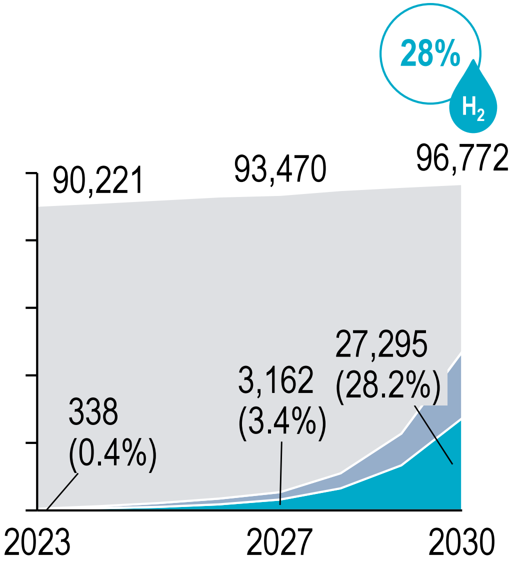
European market potential of FCEV [# of truck sales] – Use case I[1]

Conservative scenario



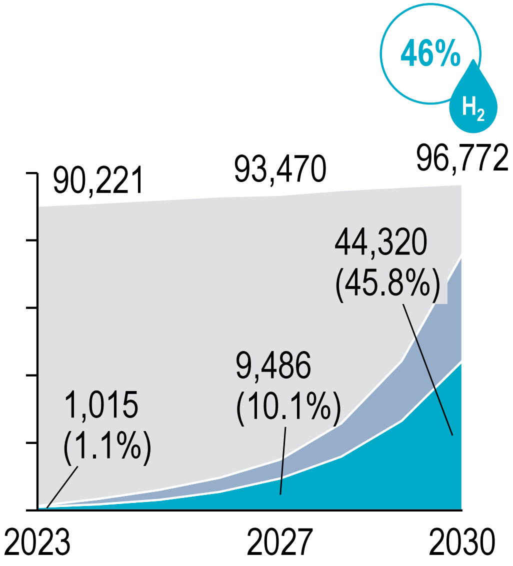
- The potential of zero-emission technology for long-haul operations is investigated
- The corresponding market segments represent the largest share in the analysis

Base scenario



- The high truck utilisation in the long-haul case leads to higher costs of powertrain and energy and fuel costs – Hence, the TCO of ZEV is generally higher than diesel

Optimistic scenario



- Despite the optimised cost/performance ratio of diesel, FCH technology at scale sees a positive development and reaches higher market shares from 2027 onwards

Note: Results are not payload corrected; a higher requirement for payload flexibility could shift the BEV results further towards FCEV

▨ Use case I market segment sales ▨ BEV sales ▨ FCEV sales ○ Market share of FCEV in 2030

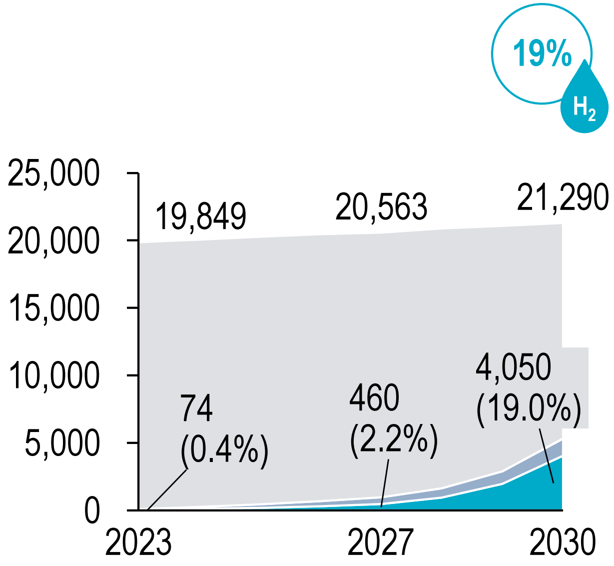
[1] The market potential analysis refers to specific market segments: international logistics, national logistics, manufacturing industry

Source: IHS market forecast; Roland Berger

For the wholesale market segment represented in Use case II, a clear uptake potential is shown even in the conservative scenario

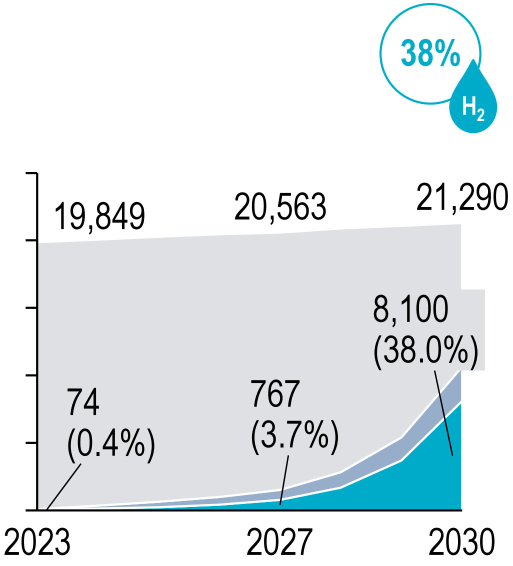
European market potential of FCEV [# of truck sales] – Use case II[1]

Conservative scenario



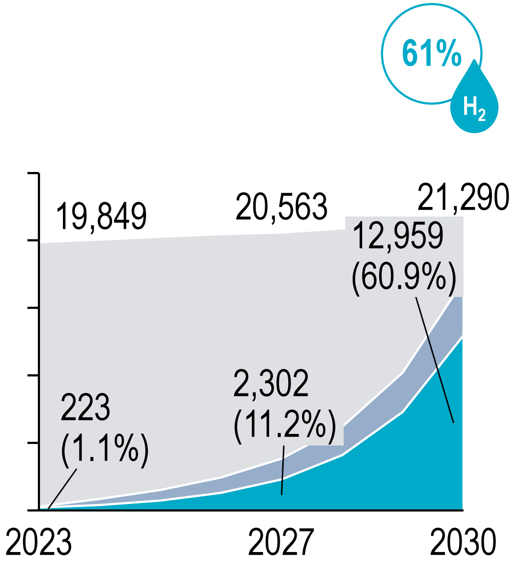
> Due to the overall medium mileage, the cost delta between the TCO of diesel and FCEV/BEV is not as high – With decreasing costs at scale, FCEV take over a larger part of the diesel market

Base scenario



> Despite higher BEV sales in the short-term due to the fact of technology availability (and corresponding costs), FCEV sales catch up from 2027

Optimistic scenario



> The clear increase in uptake of FCEV shows that this use case is (generally) better suited for FCEV due to the medium mileage/necessary reach; some exceptions show good fit for BEV, esp. concerning lower mileage combinations

▨ Use case II market segment sales ▨ BEV sales ▨ FCEV sales ○ Market share of FCEV in 2030

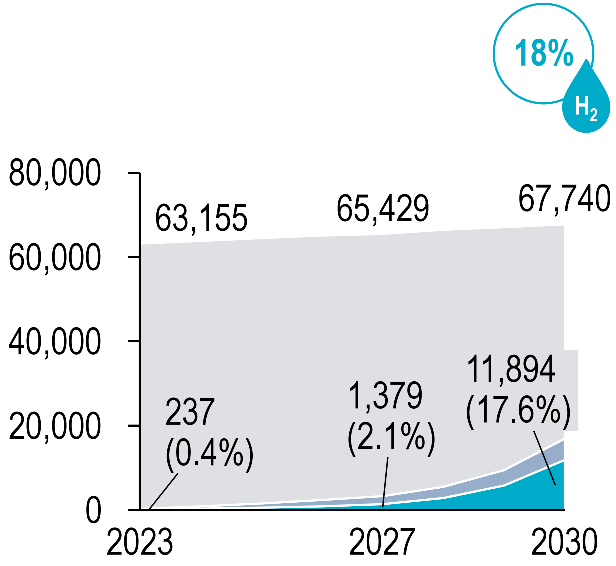
1) The market potential analysis refers to specific market segments: wholesale

Source: IHS market forecast; Roland Berger

The Use case III market segments are well suited for alternat. power-train technology – High to very high FCEV sales share in 2030

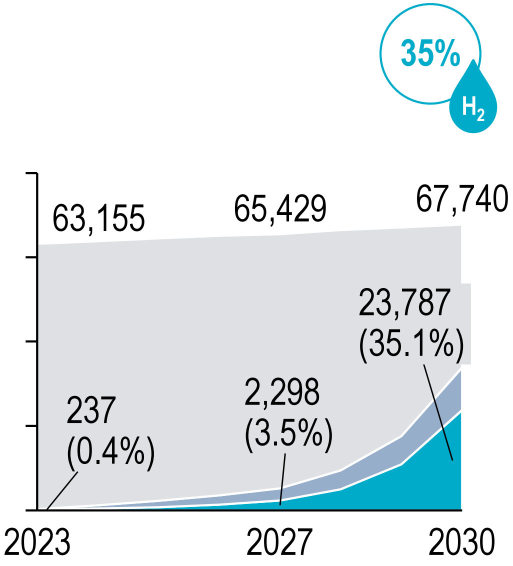
European market potential of FCEV [# of truck sales] – Use case III[1]

Conservative scenario



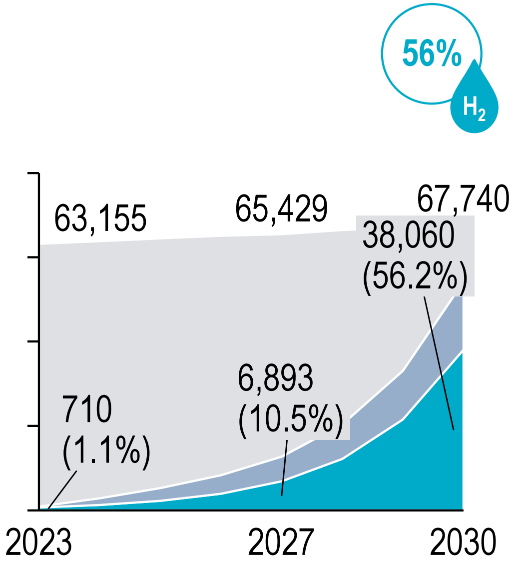
- The market growth rates illustrate the suitability of both FCEV and BEV for regional transport operations
- Lower mileages are usually a good fit for BEV due to the required smaller battery size and low energy costs

Base scenario



- FCEV have the advantage of providing higher flexibility regarding, e.g. payload, mileage and fast refuelling
- As a result, FCEV are better suited for multiple-shift operations than BEV

Optimistic scenario



- Assuming the existence of infrastructure and a strong policy support for hydrogen and FCH technology, key factors push the market rather towards FCEV than BEV

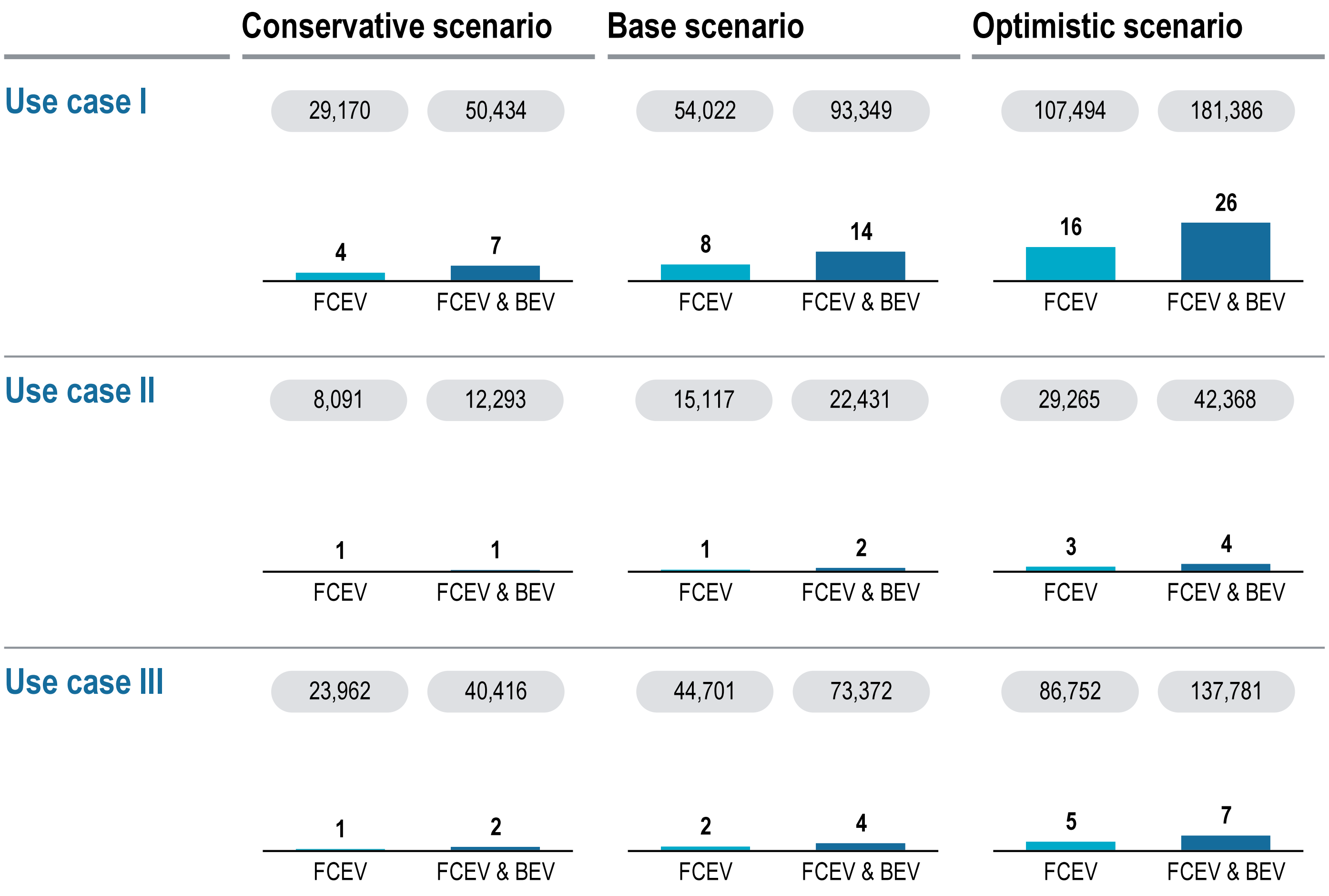
⬜ Use case III market segment sales 🟦 BEV sales 🟦 FCEV sales XX% H_2 Market share of FCEV in 2030

[1] The market potential analysis refers to specific market segments: retail and regional logistics

Source: IHS market forecast; Roland Berger

Realising the predicted number of FCEV (and BEV) in deployment in European fleets can lead to significant CO_2 savings by 2030

Estimated CO_2 savings potential 2030 [million tonnes CO_2e/year][1]



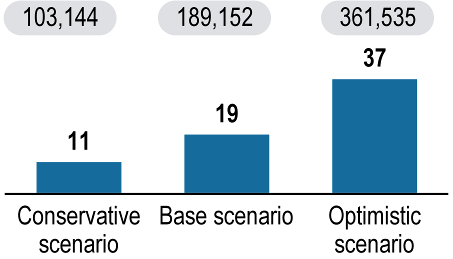
Total number of trucks predicted by 2030

"Big picture"

Overall, the predicted number of **zero-emission trucks to enter the European market from 2023 until 2030** will have a **significant CO_2 emission savings potential**

The analysis shows that FCEV make up the largest share of the deployed trucks, yet **decarbonisation efforts** also **benefit from other zero-emission vehicles** such as BEV

Overall potential for FCEV & BEV



Source: IHS market forecast; Roland Berger

D. Case studies

Case studies provide insights to real life operating conditions and make the large scale application of heavy-duty FCEV tangible

Key aspects of case studies

Key aspects

1. Explore **potential opportunities of FCH technology** and assess the economic and technological feasibility
2. Build on **real life operations in order to provide a realistic view for readers** based on actual industry expert insights
3. Provide **easy-to-grasp narrative** to facilitate the understanding of (selected) logistics processes, requirements and constraints for industry-external parties
4. Support discussions on 'applications first vs. infrastructure first' (chicken and egg) with **tangible illustration of the implications of FCEV uptake** on a specific route
5. Offer a **case specific perspective for Advisory Board members** on business cases and identify technological and non-technological barriers for FCEV

Source: Roland Berger

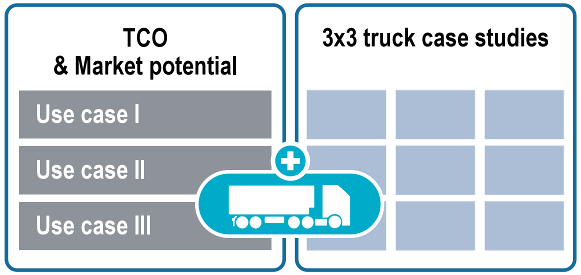
The analysis of case studies considers the European road transport sector and builds on the use cases specified in the study

Case study set-up

Relevant European logistics routes

- Major transport corridors typically along South-North and West-East
- Transport hubs which have emerged in proximity to consumption centres, freight ports and corridor crossroads
- Representative for EU logistics industry

Integration of use cases and routes


3 truck case studies for each of the 3 use cases[1]

- Technological concept and feasibility
- Infrastructure needs/changes
- TCO and qualitative conditions
- Environmental impact

Comparison with alternative technologies

➡ Transportation North-South
➡ Transportation East-West
Conurbations and logistics hubs
Scandinavia-Mediterranean-corridor
'Blue Banana'-corridor (UK-BE-NL-GE-CH-IT)
'Golden Banana'-corridor (Mediterranean cost)
New East-West corridors, e.g. Germany-Poland

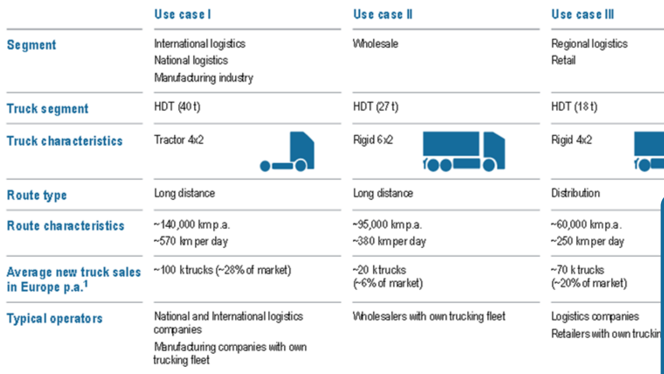
Source: Colliers, Savills, Roland Berger

For each defined use case, three case studies were identified that illustrate the differences of heavy-duty road transport in Europe

Case study selection process

Use cases[1]

Three use cases were developed to **represent six road transport segments** most relevant for heavy-duty operations



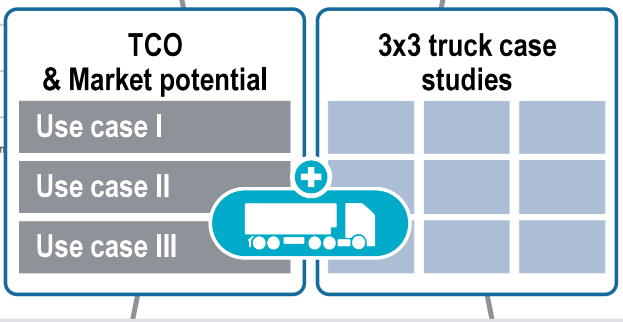
	Use case I	Use case II	Use case III
Segment	International logistics National logistics Manufacturing industry	Wholesale	Regional logistics Retail
Truck segment	HDT (40 t)	HDT (27 t)	HDT (18 t)
Truck characteristics	Tractor 4x2	Rigid 6x2	Rigid 4x2
Route type	Long distance	Long distance	Distribution
Route characteristics	~140,000 km p.a. ~570 km per day	~95,000 km p.a. ~380 km per day	~60,000 km p.a. ~250 km per day
Average new truck sales in Europe p.a.[1]	~100 ktrucks (~28% of market)	~20 ktrucks (~6% of market)	~70 k trucks (~20% of market)
Typical operators	National and International logistics companies Manufacturing companies with own trucking fleet	Wholesalers with own trucking fleet	Logistics companies Retailers with own truckin

Case studies

Truck operators and logistics users provided **case study suggestions** per use cases across Europe. These **suggestions were prioritised and the case studies selected** considering the use cases.

Selection criteria:

- Link to **real-life route and operations**
- Access to **specific local data** for differentiation of case studies
- Representation of a **concrete opportunity for roll-out but not in execution yet**
- Representation of a **fleet of vehicles**
- **Geographical spread** across Europe
- **Contact to AB member** for case develop.



The selection of case studies was carried out in alignment with the FCH JU project management and was based on Advisory Board suggestions and input.

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1) For more information, please refer to C.2.1

Source: Roland Berger

Nine case studies were selected for a detailed analysis considering a balance of technological and geographical perspectives

Overview of selected case studies

		Location	Truck type	Country	Company
Use case I	1	Košice-Bratislava	Tractor 4x2, 40 t	SK	Bioway
	2	Alsace region	Tractor 4x2, 40 t	FR	FM Logistic
	3	Zwickau-Emden	Tractor 4x2, 40 t	DE	Schnellecke
Use case II	4	Hof-Kladno	Rigid 6x2, 27 t	DE/ CZ	DACHSER
	5	Valencia region	Rigid 6x2, 27 t	ES	DISFRIMUR
	6	Bolzano-Munich	Rigid 6x2, 27 t	IT/ DE	FERCAM
Use case III	7	Hatfield	Rigid 4x2, 18 t	UK	DHL
	8	Leoben-Göss region	Rigid 4x2, 18 t	AT	Brau Union
	9	Flen-Stockholm	Rigid 4x2, 18 t	SE	Unilever

Tractor 4x2, 40 t
Rigid 6x2, 27 t
Rigid 4x2, 18 t

Source: Roland Berger

The case study business cases were calculated using the TCO model – Adjustments were made for available real-life data

Approach on case study assessment

Case study

The case studies selected per use case represent

- ☑ Link to **real-life route** and operations
- ☑ Specific **local data** for differentiation of case studies
- ☑ **Concrete opportunity** for roll-out, not yet in execution
- ☑ **Fleet of vehicles**

The case study was developed together with the participating Advisory Board member companies (logistics users / operators)

Developed case study

Total cost of ownership model[1]

TCO model identified the economic competitiveness of a FCH truck compared to a like-for-like diesel truck (e.g. same performance)

The TCO model was adjusted to reflect real-life conditions of the specific case suggested as far as available

Case specific adjustments

Advisory Board members suggested the real-life route and provided data to develop the case study

Case specific data and information

Advisory Board member input

Advisory Board member companies served as 'sponsors' for a case study and provide specific real-life data and information related to a case

---

1) For further information on the total cost of ownership model, please refer to chapter C

Source: Roland Berger

D.1 Case study approach

For each case study, a 10-page dossier is developed that introduces route and operation and evaluates the potential for FCH technology

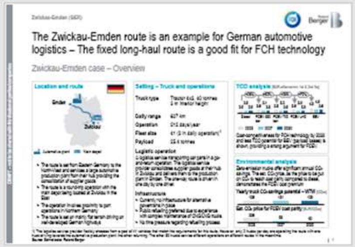
Overview of the case study concept design

Case study concept design

1 Route and operations
- > Background
- > Location and route
- > Truck type
- > Route specifications

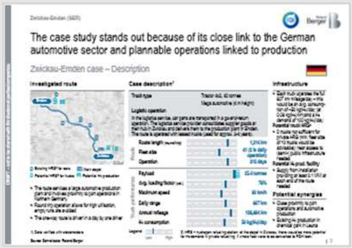
2 TCO analysis
- > Main changes to base assumptions
- > First and second life TCO analysis
- > Cost breakdown (EUR ct/tonne-km and EUR/truck)

3 Evaluation
- > Environmental analysis
- > Analysis of enablers and constraints
- > Synthesis


The Zwickau-Emden route is an example for German automotive logistics – The fixed long-haul route is a good fit for FCH technology

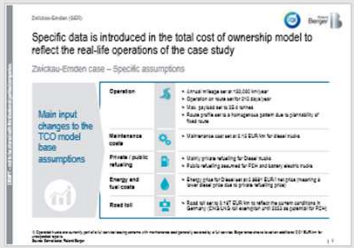
Zwickau-Emden case – Overview

1


The case study stands out because of its close link to the German automotive sector and plannable operations linked to production

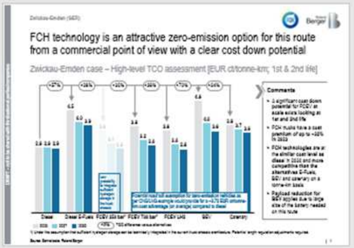
Zwickau-Emden case – Description

2


Specific data is introduced in the total cost of ownership model to reflect the real-life operations of the case study

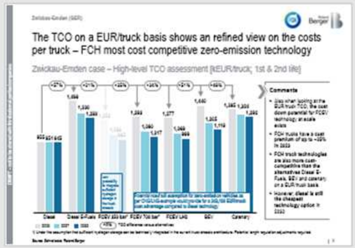
Zwickau-Emden case – Specific assumptions

3


FCH technology is an attractive zero-emission option for this route from a commercial point of view with a clear cost down potential

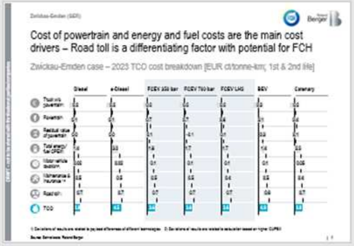
Zwickau-Emden case – High-level TCO assessment [EUR ct/tonne-km; 1st & 2nd life]

4


The TCO on a EUR/truck basis shows an refined view on the costs per truck – FCH most cost competitive zero-emission technology

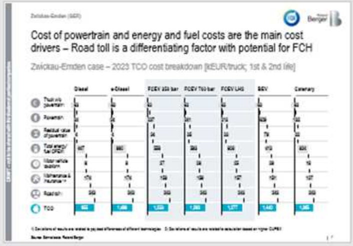
Zwickau-Emden case – High-level TCO assessment [kEUR/truck; 1st & 2nd life]

5


Cost of powertrain and energy and fuel costs are the main cost drivers – Road toll is a differentiating factor with potential for FCH

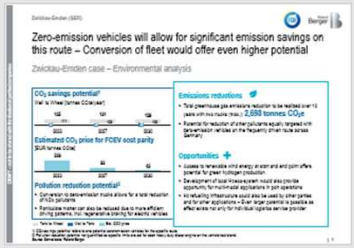
Zwickau-Emden case – 2023 TCO cost breakdown [EUR ct/tonne-km; 1st & 2nd life]

6


Cost of powertrain and energy and fuel costs are the main cost drivers – Road toll is a differentiating factor with potential for FCH

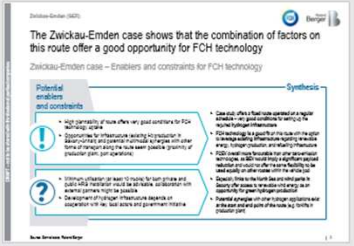
Zwickau-Emden case – 2023 TCO cost breakdown [kEUR/truck; 1st & 2nd life]

7


Zero-emission vehicles will allow for significant emission savings on this route – Conversion of fleet would offer even higher potential

Zwickau-Emden case – Environmental analysis

8


The Zwickau-Emden case shows that the combination of factors on this route offer a good opportunity for FCH technology

Zwickau-Emden case – Enablers and constraints for FCH technology

9


The case study on the route Zwickau-Emden in Germany was supported by specific information and data from Schnellecke

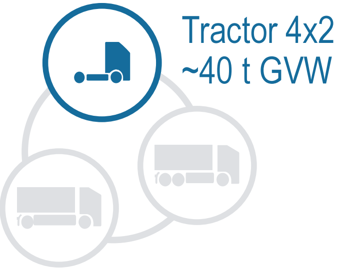
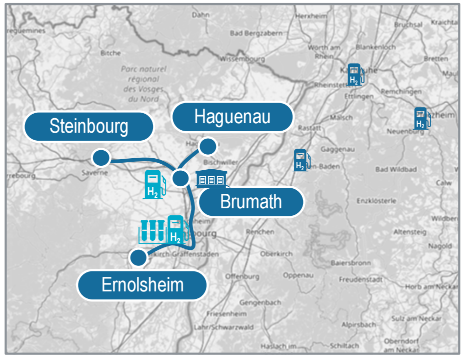
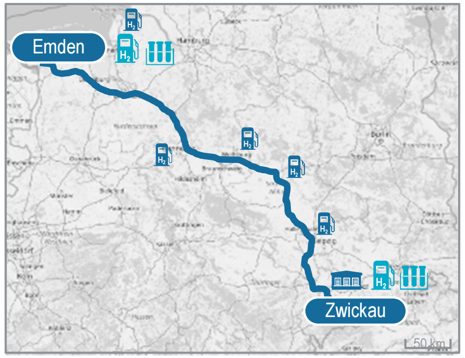
Zwickau-Emden case – Background

10

Source: Roland Berger

Use case I case studies include long-haul routes in different forms: cross-border, cross-country and regional distribution operations

Overview of case studies for Use case I

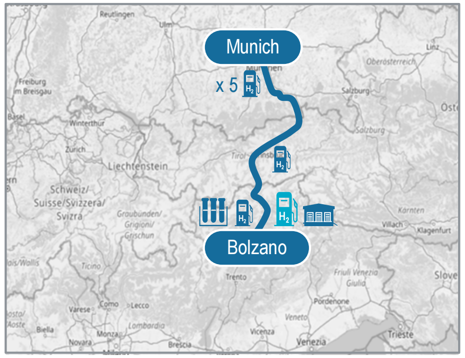
Use case I – Case Studies	***Košice-Bratislava (SK)***	***Alsace region (FR)***	***Zwickau-Emden (DE)***
 Tractor 4x2 ~40 t GVW			
Daily range	406 km	~270 km	607 km
Annual mileage	~130,000 km	~100,000 km	~130,000 km
Fleet size	15	8	2
H_2 consumption	0,08 kg/km	0,083 kg/km	0,08 kg/km
of fleet	500 kg/day	180 kg/day	100 kg/day
Route characteristics	Transport of various goods to the capital (with further operation to other EU countries)	24h operation with refrigerated trailers between three factories and a regional warehouse	Automotive logistics service transporting car parts in a go-and-return operation

Main depot Production plant Main distribution center Stores Existing & planned HRS[2] for cars Potential HRS for trucks Potential H_2 production

Source: Roland Berger

The case studies of Use case II involve different shift operations with swap bodies, refrigerated equipment and night routes

Overview of case studies for Use case II

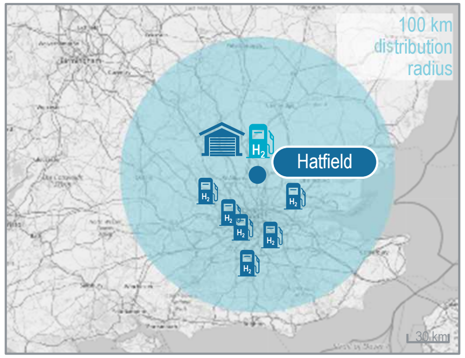
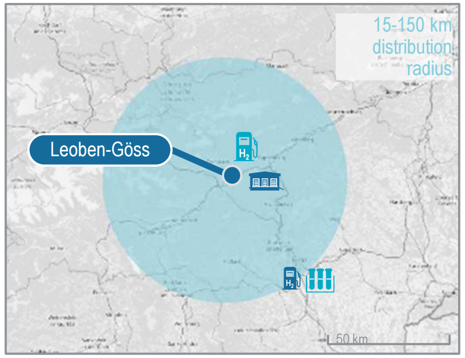
Use case II – Case Studies	***Hof (DE) – Kladno (CZ)***	***Valencia region (ES)***	***Bolzano (IT) – Munich (DE)***
 Rigid 6x2 ~27 t GVW			
Daily range	424 + 233 km	~300 km	582 + 175 km
Annual mileage	~160,000 km	~90,000 km	~180,000 km
Fleet size	5	4	10
H_2 consumption	0,071 kg/km	0,074 kg/km	0,071 kg/km
of fleet	233 kg/day	90 kg/day	537 kg/day
Route characteristics	Two shift operation to transport two swap bodies with industrial groupage goods across Europe	Regional three shift food delivery route with trucks with refrigerated equipment	Cross-border, go-and-return route driven at night with regional distribution in a second shift

Main depot · Production plant · Main distribution center · Stores · Existing & planned HRS[2] for cars · Potential HRS for trucks · Potential H_2 production

Source: Roland Berger

Use case III routes include regional delivery operations in different geographies of rural and urban areas for varying daily ranges

Overview of case studies for Use case III

Use case III – Case Studies	***Hatfield (UK)***	***Leoben-Göss region (AT)***	***Flen-Stockholm (SE)***
 Rigid 4x2 ~18 t GVW			
Daily range	200 km	~76 km (on average)	260 km
Annual mileage	~75,000 km	5,000-25,000 km	65,000 km
Fleet size	6	10	10
H_2 consumption	0,066 kg/km	0,066 kg/km	0,069 kg/km
of fleet	80 kg/day	50 kg/day	18 kg/day
Route characteristics	Closed loop multi-drop transport delivering clothing and home goods to the client stores	Milk run distribution from a regional brewery to outlets in the same district	Refrigerated trucks transport food from the production site to the capital (secondary outbound)

Main depot Production plant Main distribution center Stores Existing & planned HRS[2] for cars Potential HRS for trucks Potential H_2 production

Source: Roland Berger

D.2 Case study findings

Case studies show that supporting factors of FCH trucks outbalance constraints in theory, yet these need to be overcome first for uptake

Main learnings from case studies

- > **Long ranges, fast refuelling** and **payload capacity** comparable to diesel vehicles
- > Clear **cost-down potential** over the years
- > Additional potential in cases of **high energy needs** (e.g. for refrigerated equipment, in winter)
- > **Environmental potential beyond CO_2** reduction (e.g. on pollution reduction)

Enablers

- > **Plannable conditions** of the route to enable set-up of infrastructure
- > **Existing H_2 infrastructure** (e.g. adjusted from cars) incl. supply network and local know-how
- > Strong **company interest** to fast-track uptake of trucks and set-up of infrastructure
- > **Experience with battery and/or LNG trucks** and handling of new technologies
- > **Ongoing/planned FCH projects** in the area of the route incl. stakeholder coalitions

Opportunities

- > **Favourable regulation** for low-emission vehicles (e.g. road toll exemption, high diesel prices)
- > **Mid-to-long-term contracts / collaborations** that ensure plannability of investments
- > **Proximity to renewable energy** with direct potential for **green hydrogen production or existing low-cost industrial sources** (e.g. wind / solar parks)
- > **Local/regional HRS infrastructure partnerships** (higher utilisation by multiple users)
- > **Multi-modal use** of hydrogen infrastructure for synergies with other applications (e.g. cars, forklifts)
- > **Aligned cross-border rollout with EU standards** to have a concerted uptake and no interoperability problems

Constraints / barriers

- > **Dependence on local hydrogen refuelling infrastructure**
- > High **cost of powertrain** for FCH trucks in the short-term and **uncertainty on second life use** and **value today**
- > **Cost of hydrogen** – High fuel costs (OPEX) at current market prices
- > **Limited flexibility of utilisation patterns** (e.g. possibilities to allow for intra-day refuelling)
- > **HRS minimum utilisation requirements** for both private and public stations (assumption of at least 10 trucks on a regular basis to allow positive business case for infrastructure provider)

Source: Roland Berger

The TCO analysis shows that the powertrain costs and operational pattern make a case for FCEV vs. BEV for high mileage routes

Comparison of FCEV and BEV technology

	FCEV	**BEV**
TCO	Higher TCO in cases of low mileage due to the cost of powertrain and comparatively high costs of H_2	Lower TCO in case studies with lower mileage – Smaller size of the battery needed and low energy costs
Operations	High flexibility also on routes with higher mileage. Fast refuelling process enables multiple shifts – No payload losses, yet not all H_2 tank sizes pot. possible for all storage technologies due to limitations of the truck chassis (further R&D needed)	Good fit for plannable, low-to-medium range routes in ideally back-to-base operations. Slower charging process requires longer stops (at night). For long ranges, the weight of the required battery would likely imply payload losses
Favourable use cases	Long-range use cases with a relatively similar operational pattern as diesel	Regional (distribution) routes of a rather limited range and very plannable schedules

! **FCEV offer higher operational flexibility regarding range, refuelling time and payload capacity.**

Source: Roland Berger

For Use case I and II, FCEV would be the best suited zero-emission technology - Use case III routes with potential for FCEV and BEV

Main findings on use cases (1/2)

	Use case I	**Use case II**	**Use case III**
Route characteristics	Trucks are used on **long ranges** in a **large variety of operations**, e.g. cross-country, 24h multiple shift operations, fixed-contract transport linked to supply and production cycles.	Trucks are deployed for **high utilisation on mostly fixed routes**, with multiple shifts and high mileage; the trucks partially also operate across borders.	Trucks are used in **regional distribution/delivery operations** with routes leading **into inner cities**; the operation perimeter is defined around the depot with a lower mileage.
Suitability for FCH technology	**FCH technology** is found to be the **best-suited zero-emission option for the case studies**. If it is not for the **TCO result**, it is indicated by **operational requirements**, e.g. of 24h operation that won't allow the necessary charging time for BEV. However, in all case studies, Diesel is still the cheapest technology in 2023.	The case studies have very **different utilisation profiles**. For the routes with a **high daily range, FCEV are the most cost-attractive zero-emission technology** – due to the long-haul transport profile. For the **regional delivery route battery technology is shown as a potential option** – however, payload restrictions point towards a better fit of FCH tech.	For a **lower daily range** (and annual mileage), **both FCH and battery technology have potential**, with a **slight cost-advantage of BEV**. In cases of very low mileage, battery electric trucks could already become more cost competitive with diesel in 2023. However, **FCEV advantages regarding flexibility and refuelling could be more favourable**.

In all use cases, one case study with **refrigerated equipment** was considered. **FCH technology was the best suited zero-emission technology regarding operational flexibility**, yet not always for TCO.

Source: Roland Berger

For Use case I and II, FCEV would be the best suited zero-emission technology - Use case III routes with potential for FCEV and BEV

Main findings on use cases (2/2)

	Use case I	Use case II	Use case III
CO_2 emissions reduction potential	**CO_2 emissions are linked to fuel consumption** – For the **long-haul routes** on which many kilometres are driven, the **CO_2 emissions are highest, as is the reduction potential**. As these routes are mostly carried out on highly utilised European transport corridors, the **positive environmental impact of zero-emission vehicles will be significant.**	Similar to the long-haul use case, the case studies in this use case also showed a **high CO_2 reduction potential due to the high mileage** driven. Similarly, the **positive environmental impact of zero-emission vehicles will be significant** in this use case, as well.	For the regional distribution/ delivery routes, the **CO_2 emissions reduction potential is lower** in terms of magnitude **due to the lower mileage.** Yet **more frequent starts and stops can cause higher CO_2 emissions**. As operations often **drive in urban areas**, truck emissions directly **affect the citizens' health** and **emissions reduction is critical**.
Infrastructure requirements	**Private refuelling stations** would only be commercially viable (similar to diesel) if **vehicle fleets are of a sufficient size to fulfil minimum requirements regarding hydrogen demand** – Industry experts consider the threshold around 0.5 tonnes H_2/day. As a result, **for the first FCEV within a fleet, access to public infrastructure is required**. Such access is **more likely to be provided in industrial hubs** (e.g. production facilities, port operations) **and close to larger cities** due to higher utilisation potential.		
Synergies[1]	Across the case studies, **concrete synergies for FCH trucks were identified in real-life transport** operations, e.g. existing **HRS upgrading** for trucks, **multi-partner collaborations**, knowledge exchange in **H_2 eco-systems** & hydrogen valleys, **access to renewable energy and H_2 production.**		

1) For further elaboration on potential and investigated synergies, please refer to chapter E.2

Source: Expert interviews; Roland Berger

D.3 Case study concept designs

The case studies demonstrate the wide spectrum of deployment for FCH trucks – TCO model of study as starting point for all cases

Underlying assumptions in case study evaluation

- The case study TCO analyses were mostly conducted looking at the combined **first and second life** (5 vs. 10 years) – However, in cases of very high annual mileage, the calculation was based on the first life only. This is due to the **high utilisation of the vehicles that would reach the end of their lifetime within the second life**. This was indicated in the respective case studies. [As seen in case studies 4 and 6]
- A **dynamic capacity sizing of the powertrain for FCEV and BEV** is included to allow for the **like-for-like comparison** with the diesel truck currently carrying out the operation. This corresponds to the base assumption in the TCO model used for the calculation. [As seen in case study 8]
- The included **two perspectives on the TCO results** (kEUR/truck and EUR ct/tonne-km basis) illustrate the **potential weight-related constraints that could impact the truck payload** (especially with high mileages) and vary across the different technologies. [As seen in all case studies]
- Looking at potential blue-print business cases for the industry, it is important to reflect that **some uncertainty remains regarding the technological development of H_2 storage technology**. The **TCO results show the potential** of different storage technologies, but the **maturity status needs to be considered**, especially when comparing the TCO results of the different storage technologies against one another. For all case studies, the use of green hydrogen only was assumed. Further details can be found in the TCO introduction chapter C. [As seen in all case studies]
- The TCO model **assumptions on the residual value of a truck are based on the assumed scrap value of the powertrain and the mileage driven over lifetime**. If the mileage is much lower than 60,000 km, there are **some limitations on the representativeness of the modelled residual value**, which was made explicit in the respective case studies. This is due to the fact that a **very high residual value** (in comparison to the initial vehicle purchase price) **is unlikely to be achieved in a second market** for a technology from 10 years ago (uncertainty of results). At the same time, the strong impact of the residual value shows that uncertainties on market development can be a roadblock for FCEVs. [As seen in case study 8]
- For the sake of comparability across the case study environmental analyses, a **uniform CO_2 emissions value was assumed** that **reflects the CO_2 emissions of pure diesel** as a fuel. However, in multiple countries the **standard diesel is mixed with a share of biofuel with a lower emission factor**[1]. Therefore, the real emission values can vary from the environmental analysis, with variation also potentially being driven by real-life driving patterns, varying consumption figures, etc. [As seen in case study 8]

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1) For the analyses, CO_2e WtW emissions of 3,240 g/l are assumed for pure diesel, based on data from the German Freight Forwarding and Logistics Association DSLV

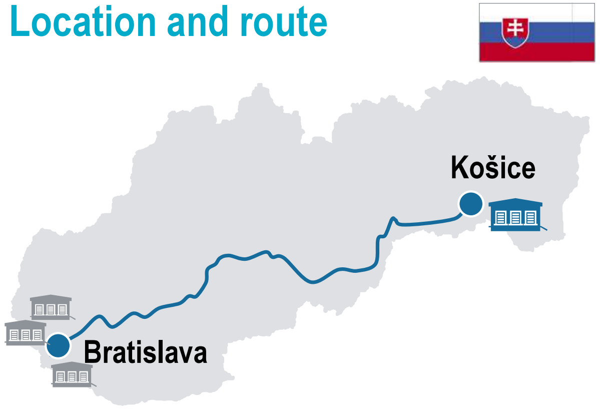
Source: Roland Berger

D.3.1 Košice - Bratislava case [Bioway]

The Košice-Bratislava route shows that FCH technology would be a good fit for a very frequent, plannable cross-country operation

Košice-Bratislava case – Overview

Location and route



Main depot — Customer locations

- > The route is set from the Eastern part of Slovakia in Košice to the capital Bratislava in the West
- > Some of the trucks continue further towards other European countries, others return
- > There is a high frequency on this route with trucks operating the route almost everyday
- > The route involves a combination of flat, hilly and mountainous terrain with cold and snowy winters

Setting – Truck and operations

Truck type	Tractor 4x2, 40 tonnes Low deck /mega truck
Daily range	406 km
Operation	320 days/year
Fleet size	15
Payload	10 tonnes

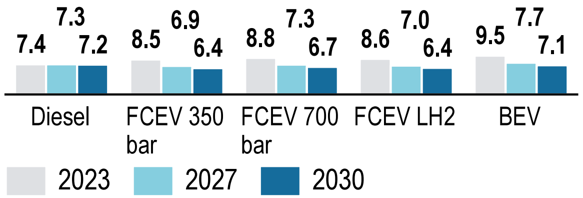
Logistic operation

The cross-country logistics route transports varying goods (car parts, beverages) from the regional hub to the capital. The route is currently operated with low-emission trucks (LNG). An increase of the number of LNG trucks is planned (150 vehicles until 2021) which shall be replaced by FCH technology in the future.

Infrastructure

- > Currently no infrastructure for alternative powertrains in place
- > 26 HRS are planned in Slovakia on important roads (main roads, TEN-T corridors)
- > No time pressure regarding refuelling process

TCO analysis [EUR ct/tonne-km; 1st & 2nd life]

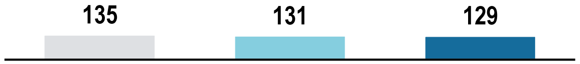


FCH technology with best TCO results of zero-emission technologies, yet BEV also close. As flexibility is required regarding potential payload restrictions, FCH tech. would be better suited.

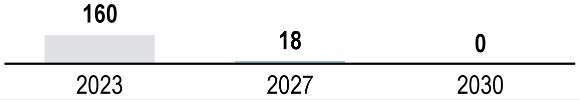
Environmental analysis

Zero-emission trucks offer significant annual CO_2 savings. The est. CO_2 price demonstrates the FCEV cost premium and the price to be put on CO_2 to reach cost parity compared to diesel

Yearly CO_2 savings potential – WTW [tCO_2e]



Est. CO_2 price for FCEV cost parity [EUR/tCO_2e]



Source: Bioway; Roland Berger

The case study stands out because of the clear ambition of involved parties to increase the number of low- and zero-emission trucks

Košice-Bratislava case – Description

Investigated route

Main depot HRS[2] planned for 'Black Horse' project (also for trucks)

- The route connects the regional city of Kosice in the Eastern part of Slovakia with the capital Bratislava
- Trucks on this route run almost every day – either driving to or returning from Bratislava
- The route involves a combination of flat, hilly and mountainous terrain with cold and snowy winters
- Road toll charges apply

Case description[1]

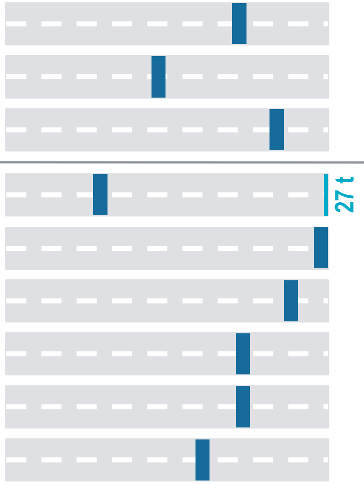
Truck type Tractor 4x2, 40 tonnes

Low deck /mega truck

Logistic operation

On this cross-country route, 15 trucks transport various light weight, high cubic goods (car parts, beverages) from the regional hub to the capital Bratislava where they unload the goods for different clients. The trucks then take up new load in Bratislava and carry the new freight further to other countries in the EU or back to Košice. The operation is volume restricted due to the heterogenous size of the load. Trucks are operated by one driver each. Currently, the route is carried out with low-emission trucks (LNG).

Route	**Route length**	406 km
	Fleet size	15
	Operation	320 days
Truck performance	**Payload** (average)	10 tonnes
	Avg. loading factor (vol.)	100%
	Maximum speed	90 km/h
	Daily range	406 km
	Annual mileage	129,920 km
	H_2 consumption	32 kg(H_2)/day



Legend Low High

Infrastructure

- Each truck operates min. 406 km/day – this would be an avg. consumption of ~32 kg(H_2)/day (at 0.08 kg(H_2) /km); fleet H_2 demand of ~500 kg(H_2)/day

Planned truck HRS[2]

- Installation of two public HRS near depot and Bratislava planned for passenger cars, buses, trucks (350 bar and 700 bar technology)

Planned H_2 prod. facility

- Supply with grey and (later) green hydrogen planned with production in Slovakia

Potential synergies

- Conversion of higher number of trucks planned
- Support for H_2 infrastructure in 'Black Horse' project to also benefit local and regional distribution

---

1) Data verified with stakeholders
2) HRS = hydrogen refuelling station
3) There will potentially be more H_2 demand at the depot in Košice as 150 trucks in the subcontractor fleets will be changed to LNG by mid 2021 and replaced by FCEV in the future

Source: Bioway; Roland Berger

Specific data is introduced in the total cost of ownership model to reflect the real-life operations of the case study

Košice-Bratislava case – Specific assumptions

Main input changes to the TCO model base assumptions

Operation	> Annual mileage set at 130,000 km > Operation on route set for 320 days/year > Route profile set to a homogenous pattern due to plannability of fixed route
Motor vehicle tax	> Motor vehicle tax set at 1.4 % of initial vehicle cost for 2023 and adjusted for 2027 and 2030 to reflect case specific data for diesel vehicles tax of 1,000 EUR/year[1]
Maintenance costs	> Maintenance cost set at 0.036 EUR/km for diesel, at 0.032 EUR/km for FCEV and at 0.029 EUR/km for BEV and catenary
Private / public refuelling	> Public refuelling assumed for all technologies
Energy and fuel costs	> No changes on energy and fuel costs as case specific average data indicated the diesel price at 1.259 EUR/l
Road toll	> Road toll set to 0.152 EUR/km

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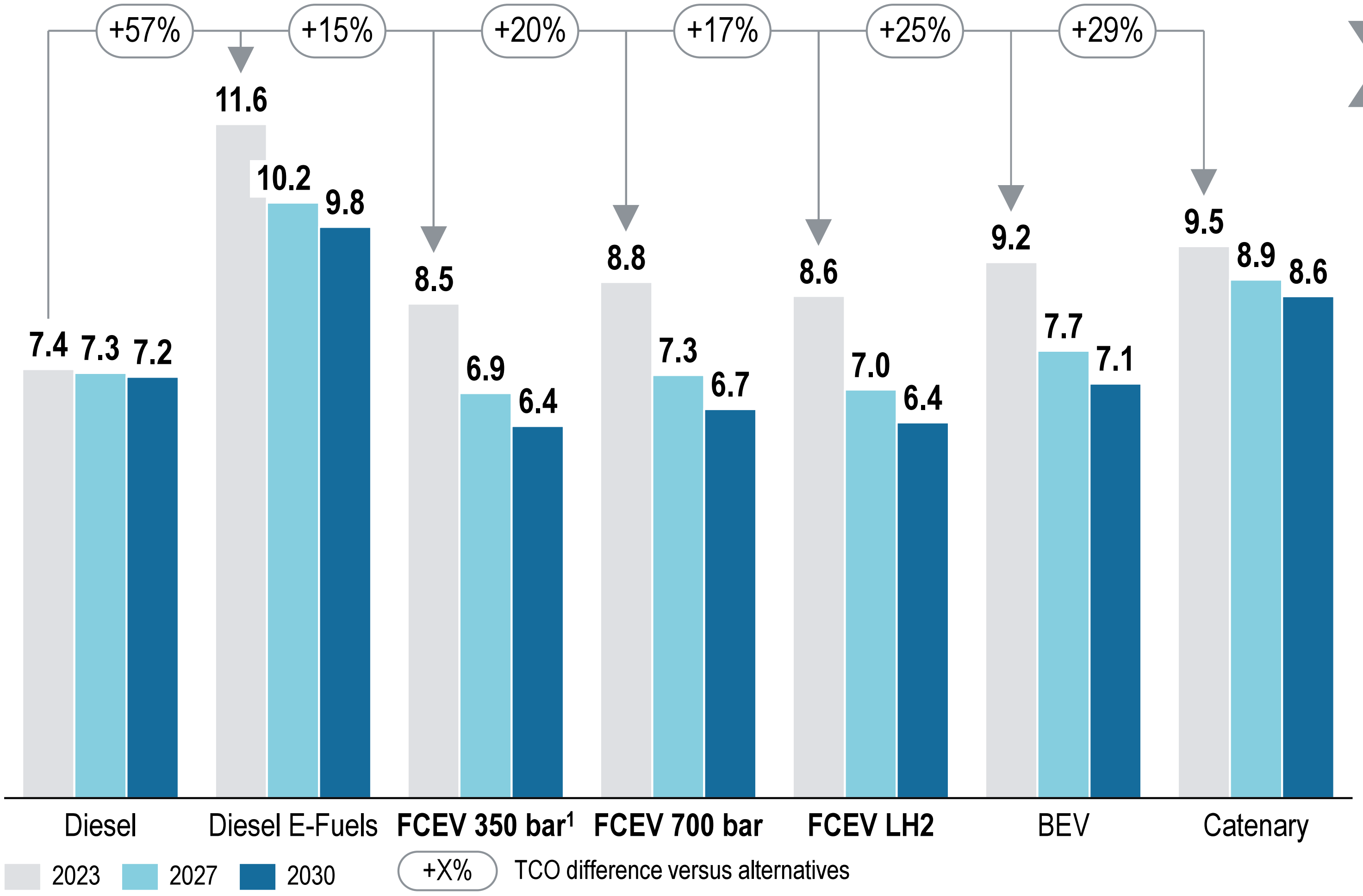
1) Motor vehicle tax refers to diesel vehicles; currently, LNG trucks are used that have a motor vehicle tax of 500 EUR/year (yet not considered in this study)

Source: Bioway; Roland Berger

FCH and BEV technology with very similar TCO results – Both technologies are cost-competitive with diesel from 2027

Košice-Bratislava case – High-level TCO assessment [EUR ct/tonne-km; 1st & 2nd life]



Comments

- A significant **cost down potential** for FCEV **at scale** exists **looking at 1st and 2nd life**
- FCH trucks have a **cost premium of up to ~20% in 2023**
- **FCH technologies** are at the **lower cost level than diesel** already in 2027
- **FCH and BEV tech.** are at a **very similar cost level** at tonne-km basis
- **As payload is relatively low,** there is **no payload reduction for BEV** which makes it a possible option despite the higher weight of the battery

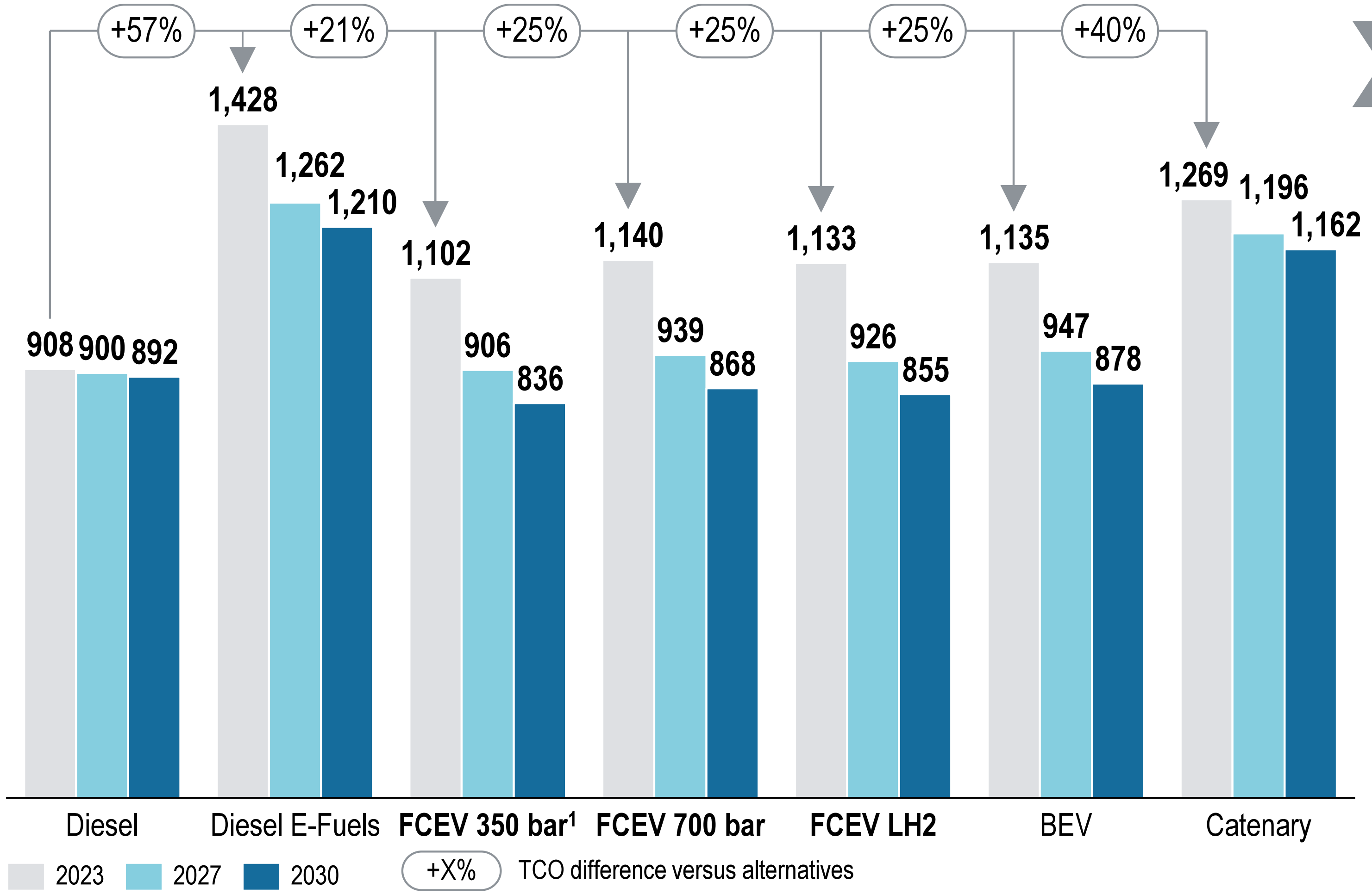
1) Under the assumption that sufficient hydrogen storage can be technically integrated in the current truck chassis architecture; Potential length regulation adjustments required

Source: Bioway; Roland Berger

1 Košice - Bratislava (SK)

On this route with its specific requirements, all FCH technologies have potential from a commercial and technical point of view

Košice-Bratislava case – High-level TCO assessment [kEUR/truck; 1st & 2nd life]



Comments

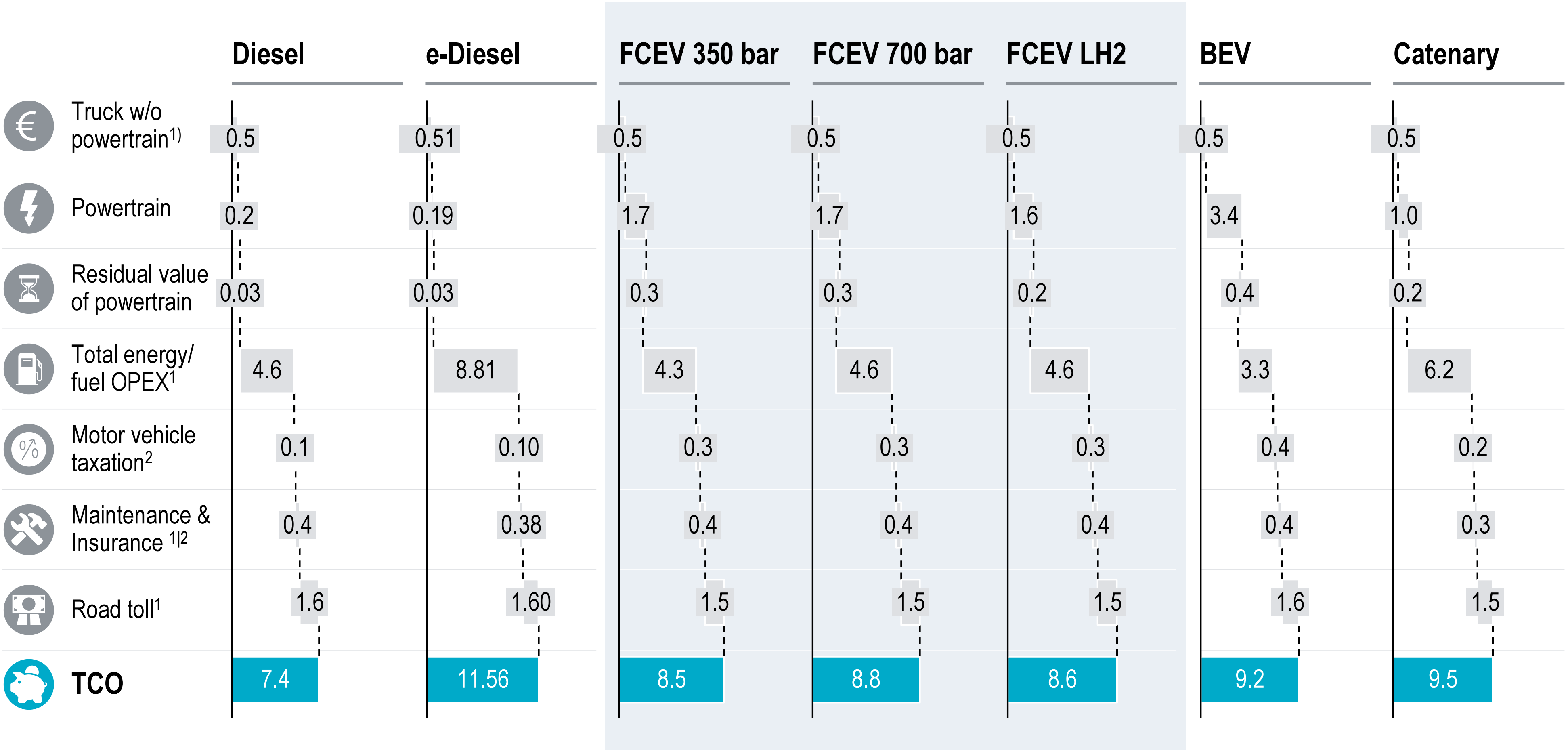
- Also when looking at the EUR/truck TCO costs, **the cost down potential** for FCEV technology **at scale** exists
- FCH trucks have a **cost premium of up to ~25% in 2023**
- **FCH and BEV tech.** show **very similar TCO results** on a EUR/truck basis - **Cost competitiveness** already **in 2027**
- Based on the **relatively low assumed payload, FCEV 350 bar could be an option** as more space for tank integration would be available

1) Under the assumption that sufficient hydrogen storage can be technically integrated in the current truck chassis architecture; Potential length regulation adjustments required

Source: Bioway; Roland Berger

At overall similar cost levels, FCEV and BEV see a trade-off for the main cost drivers: Either cost of powertrain or OPEX are lower

Košice-Bratislava case – 2023 TCO cost breakdown [EUR ct/tonne-km; 1st & 2nd life]



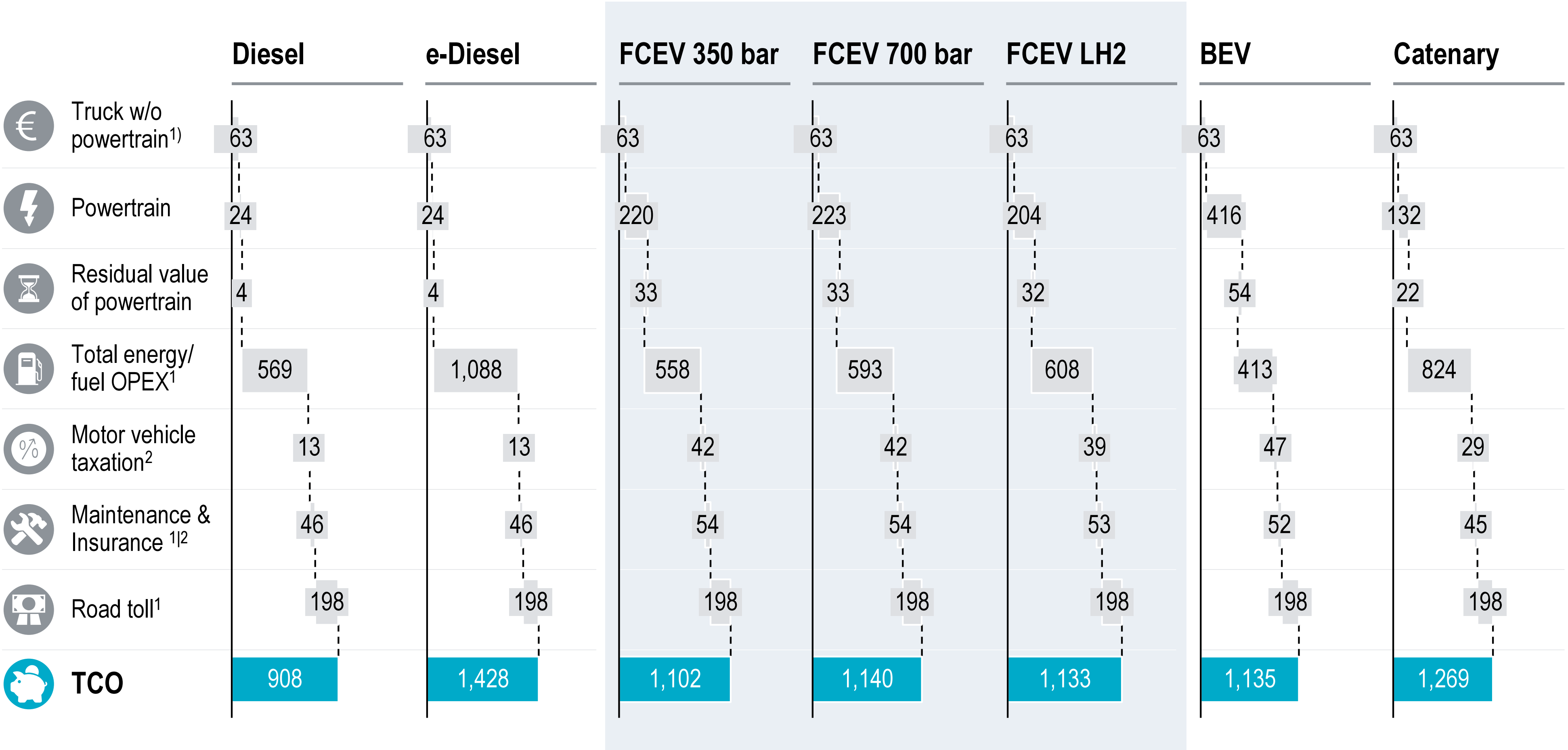
	Diesel	e-Diesel	FCEV 350 bar	FCEV 700 bar	FCEV LH2	BEV	Catenary
Truck w/o powertrain[1)]	0.5	0.51	0.5	0.5	0.5	0.5	0.5
Powertrain	0.2	0.19	1.7	1.7	1.6	3.4	1.0
Residual value of powertrain	0.03	0.03	0.3	0.3	0.2	0.4	0.2
Total energy/ fuel OPEX[1]	4.6	8.81	4.3	4.6	4.6	3.3	6.2
Motor vehicle taxation[2]	0.1	0.10	0.3	0.3	0.3	0.4	0.2
Maintenance & Insurance [1|2]	0.4	0.38	0.4	0.4	0.4	0.4	0.3
Road toll[1]	1.6	1.60	1.5	1.5	1.5	1.6	1.5
TCO	7.4	11.56	8.5	8.8	8.6	9.2	9.5

1) Deviations of results are related to payload differences of different technologies 2) Deviations of results are related to calculation based on higher CAPEX

Source: Bioway; Roland Berger

Looking at the EUR/truck comparison, cost of powertrain and energy/fuel costs are the main drivers for all technologies

Košice-Bratislava case – 2023 TCO cost breakdown [kEUR/truck; 1st & 2nd life]



	Diesel	e-Diesel	FCEV 350 bar	FCEV 700 bar	FCEV LH2	BEV	Catenary
Truck w/o powertrain[1)]	63	63	63	63	63	63	63
Powertrain	24	24	220	223	204	416	132
Residual value of powertrain	4	4	33	33	32	54	22
Total energy/ fuel OPEX[1]	569	1,088	558	593	608	413	824
Motor vehicle taxation[2]	13	13	42	42	39	47	29
Maintenance & Insurance [1|2]	46	46	54	54	53	52	45
Road toll[1]	198	198	198	198	198	198	198
TCO	908	1,428	1,102	1,140	1,133	1,135	1,269

1) Deviations of results are related to payload differences of different technologies 2) Deviations of results are related to calculation based on higher CAPEX

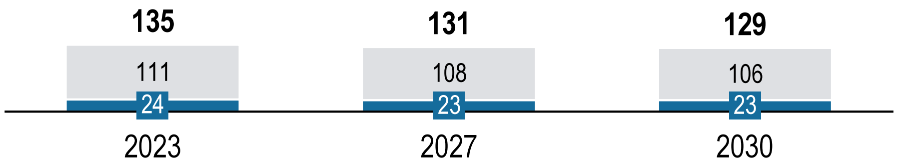
Source: Bioway; Roland Berger

Zero-emission vehicles will allow for significant emission savings on this route – Conversion of fleet would offer even higher potential

Košice-Bratislava case – Environmental analysis

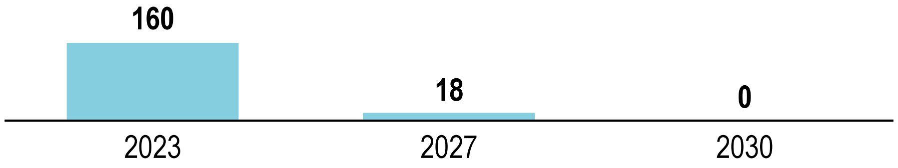
CO_2 savings potential[1]

Well to Wheel [tonnes CO_2e/year]



Estimated CO_2 price for FCEV cost parity

[EUR/tonnes CO_2e]



Pollution reduction potential[2]

- Conversion to zero-emission trucks allows for a total reduction of NOx pollutants
- Particulate matter can also be reduced due to more efficient driving patterns, incl. regenerative braking for electric vehicles

▨ Tank to Wheel ■ Well to Tank

Emissions reductions

- Total greenhouse gas emissions reduction to be realized over 10 years with fifteen trucks[1]: **20,233 tonnes CO_2e**
- Potential for reduction of other pollutants equally targeted with zero-emission vehicles on the frequently driven cross-country route

Opportunities

- The company's ambition for emission reduction are linked to activities to develop the H_2 eco-system in Slovakia – Good conditions to convert more vehicles to FCH technology and leverage the company's standing to also push subcontractors in this direction
- H_2 refuelling infrastructure will be set up on main transport corridors across the country to support the uptake of fuel cell and hydrogen vehicles – Proximity to main depot can be ensured

1) CO_2 savings potential refers to one potential zero-emission vehicle for the specific route

2) Pollution reduction potential not quantified as specific limits are set for each heavy duty diesel engine on the vehicle test stand

Source: Bioway; Roland Berger

Operating the cross-country route between Košice and Bratislava with FCH trucks could become a commercially attractive opportunity

Košice-Bratislava case – Enablers and constraints for FCH technology

Potential enablers and constraints

!

- > Fixed route on a almost daily schedule offers high plannability
- > Mixed terrain and cold winters are an advantage for FCH technology compared with other zero-emission options (e.g. cabin heating)
- > Strong company ambition and government support for hydrogen application and infrastructure (via the 'Black Horse' project) provide good prerequisites and will lead to increasing H_2 know-how within Slovakia
- > Stakeholders can build on current experience with LNG trucks
- > High concentricity of automotive industry with supplier transport can leverage technology also in regional and local transport

?

- > Planned setup of H_2 infrastructure until 2030 along main transport corridors does not offer immediate opportunities in Košice – Set up of (private) infrastructure would need to be initiated by the company
- > Build-up of hydrogen production in Slovakia (such as via the Black Horse project) will need to be set up; green source of hydrogen to be in focus

Synthesis

- > The case study shows a **long-haul route on a regular schedule** with a **significant number of trucks** – Combination of **important supporting factors** for FCEV adoption
- > **Payload considerations** between **FCEV and BEV** indicate that **despite similar TCO results**, BEV would not offer the **flexibility for a much higher payload** (e.g. heavier car parts) and **longer ranges** (e.g. cross-EU transport) which could restrict operations (e.g. not having the flexibility to carry heavy loads for specific clients) – Scenarios makes **FCH** technology the **favoured zero-emission option**
- > Current momentum of **support for H_2 application** in Slovakia will be **leveraged** to set up required **refuelling infrastructure in proximity of the depot**
- > **Expansion** of FCH technology **for the larger fleet** is a potential option – **company ambition acts as a push-factor** for partners and subcontractors

Source: Bioway; Roland Berger

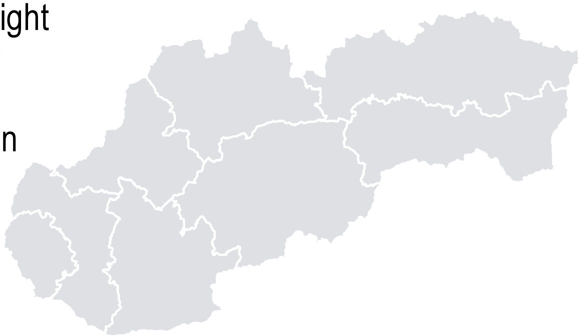
The case study on the Košice-Bratislava route in Slovakia was supported by specific information and data from Bioway

Košice-Bratislava case – Background

Road freight sector in Slovakia

Information on the road freight sector

- The road freight transport industry in Slovakia is the twelfth largest in the EU, despite the relatively small size
- Overall, the road freight industry revenue for transport by road in Slovakia is EUR 4 bn
- Currently, ~50,000 heavy duty vehicles are registered in Slovakia



Main transport corridors

- Slovakia has a central position in Central Europe with numerous motorways crossing through it
- Slovakia transport corridors offer access to Southern and South Eastern Europe, and also to the Austrian, German, Swiss and Italian markets

Information on company supporting the case

Company information

Name	Bioway s.r.o.
Industry	Logistics service provider
Headquarters	Košice, Slovakia
Zero-emission ambition	Company initiative of "green logistics" includes participation on EU-funded "Black Horse" project and push towards low-emission trucks for all subcontractors

Depot linked to route

Location	Košice
Description	Regional hub
Total number of trucks	700 (15 subcontractor companies)

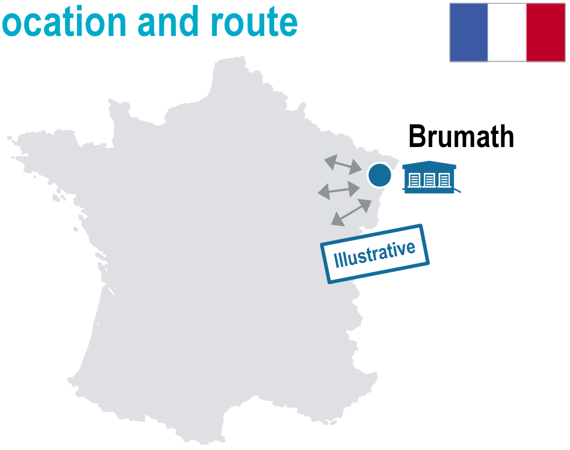
Source: Statista; Comité National Routier; Bioway; Roland Berger

D.3.2 Alsace region case [FM Logistic]

The Brumath case is an example for a short-haul, heavy load operation on a (almost) 24/7 schedule with high potential for FCEV

Alsace region case – Overview

Location and route



Main depot

- The operation is set in the Strasbourg area (Alsace, France) and services three local production sites by linking them to material supply and storage facilities in the logistics warehouse
- The three routes involve round trips, driven various times over the day
- The operation is mostly driven on a well-developed network of regional highways

Setting – Truck and operations

Truck type	Tractor 4x2, 40 tonnes Refrigerated trailers
Daily range	~270 km
Operation	360 days/year
Fleet size	8
Payload	avg. 26 tonnes

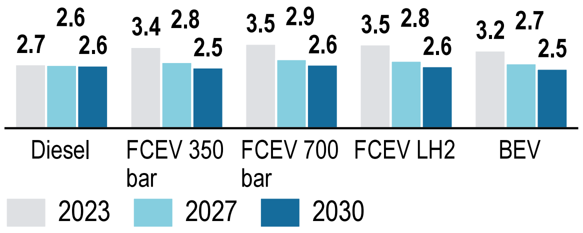
Logistic operation

The operation is composed of various flows, linking three factories in the Strasbourg area to the regional warehouse on a (almost) 24 h schedule. The refrigerated trailers transport chocolate, ice cream and pet food from the different factories.

Infrastructure

- Hydrogen refuelling infrastructure for trucks would need to be installed (private or public)
- Time-constraint operation would allow for (fast) refuelling of FCEV, yet no charging of BEV
- Current assessment of development of own hydrogen hub or collaboration with external partners in the region

TCO analysis [EUR ct/tonne-km; 1st & 2nd life]

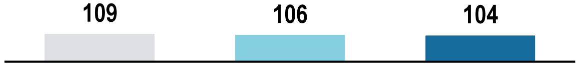


The TCO shows cost competitiveness for FCH technology with diesel by 2030. TCO results also indicate good potential for BEV, yet the 24 h operations would not allow the necessary charging time.

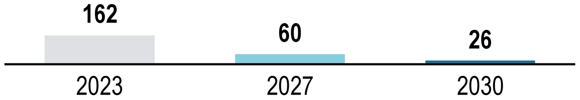
Environmental analysis

Zero-emission trucks offer significant annual CO_2 savings. The est. CO_2 price demonstrates the rather high FCEV cost premium in 2023, indicating the potential for environmental incentive schemes.

Yearly CO_2 savings potential – WTW [tCO_2e]



Est. CO_2 price for FCEV cost parity [EUR/tCO_2e]

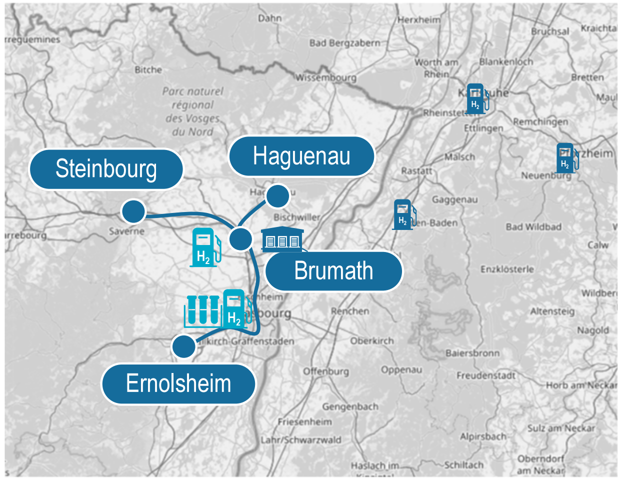


Source: FM Logistic; Roland Berger

The case study stands out because of around-the-clock operation on short distances between local factories and the warehouse

Alsace region case – Description

Investigated route



- Existing HRS[2] for cars
- Main depot
- Potential HRS[2] for trucks
- Potential H_2 production

> The operation is set in the Strasbourg area and services three local production sites by linking them to material supply and storage facilities in the logistics warehouse

> The three routes involve round trips, driven various times over the day

> The operation is mostly driven on a well-developed network of regional highways (road toll involved on one route)

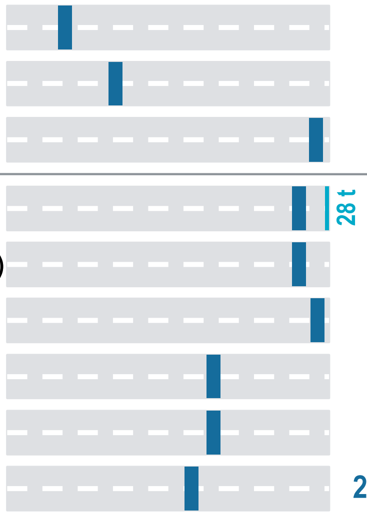
Case description[1]

Truck type Tractor 4x2, 40 tonnes

Refrigerated trailers

Logistic operation

Three main factories in the Strasbourg area are linked to the regional warehouse on a 24 h schedule (up to 3 shifts per day). The trailers going from the warehouse to the factories are loaded with raw materials, while the trailers loaded in the factories transport finished products to be stored in the warehouse (chocolate, ice cream and pet food). The operations follow seasonal patterns due to the transported goods.



Route	**Route length** (round trip)	30-88 km
	Fleet size	8
	Operation	360 days
Truck performance	**Payload**	26 tonnes
	Avg. loading factor (weight)	93%
	Maximum speed	110 km/h
	Daily range	~270 km
	Annual mileage	~96,546 km
	H_2 consumption	22 kg(H_2)/day

Legend Low High

Infrastructure

> Truck operate an avg. of ~270 km mileage/day – this would be an avg. consumption of ~22 kg(H_2)/day (at 0.083 kg(H_2)/km)and a H_2 demand of 180 kg(H_2)/day

Potential truck HRS

> Demand not sufficient for private HRS with external supply (min. of 500 kg(H_2)/day advisable for scale effects); in-house H_2 production potential option

Potential H_2 prod. facility

> Supply from electrolysis installation of > 0.5 MW needed at depot or close

Potential synergies

> Further operations linked to distribution of stored goods

> Potential build up of H_2 infrastructure and supply in Strasbourg area (contact with relevant parties)

---

1) Data verified with stakeholders

2) HRS = hydrogen refuelling station

Source: FM Logistic; Roland Berger

Specific data is introduced in the total cost of ownership model to reflect the real-life operations of the case study

Alsace region case – Specific assumptions

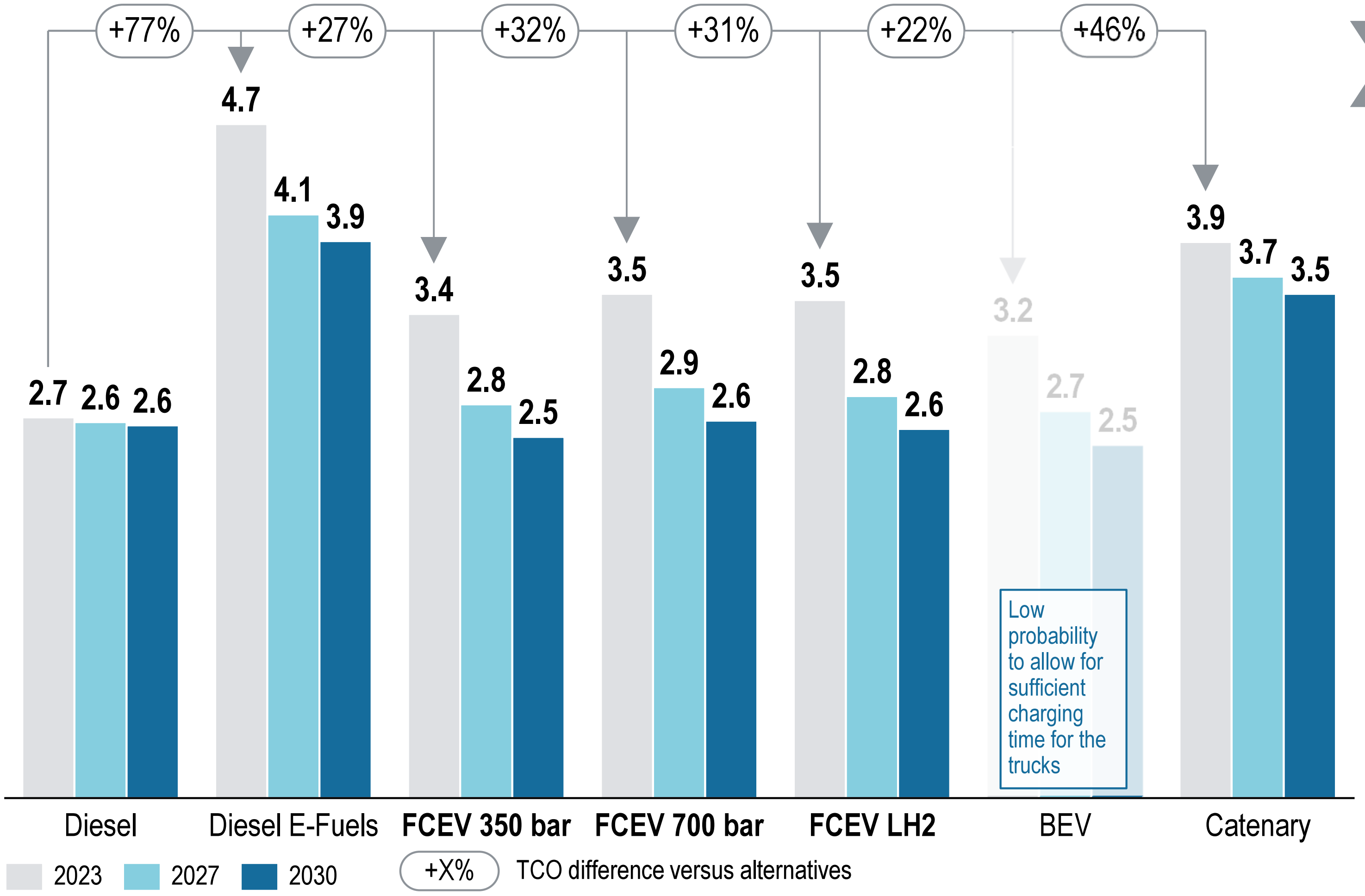
Main input changes to the TCO model base assumptions

Operation	> Annual mileage set at ~95,000 km/year > Operation on route set for 360 days/year > Max. payload set to 28 tonnes > Route profile set to a homogenous pattern due to plannability of fixed routes
Motor vehicle tax	> Motor vehicle tax set at 0.8% of initial vehicle cost for 2023 and adjusted for 2027 and 2030 to reflect case specific data for the French road transport vehicle tax
Maintenance costs	> Maintenance cost set at 0.072 EUR/km for diesel, at 0.064 EUR/km for FCEV and at 0.057 EUR/km for BEV and catenary
Energy and fuel	> Energy price for Diesel set at 1.02 EUR/l net price > AdBlue price set to 0.30 EUR/l net price > Consumption of diesel was increased by 11% to reflect the increased need of energy for the refrigeration equipment (additional consumption of ~3.5 l/100 km); principle of a consumption increase is also applied for BEV and catenary (4% due to the electric powertrain)
Fuel cell and H_2 technology	> Additional 2 kW of fuel cell size are assumed for higher energy needs > Consumption of H_2 was increased by 0.003 kg(H_2)/km to reflect the increased need of energy for the additional refrigeration equipment (Garde et al. 2012)
Private / public refuelling	> Public refuelling assumed for all technologies
Road toll	> Road toll set to 0.06 EUR/km to reflect that road toll only applies on 36 km of the routes

Source: FM Logistic; Garde et al. at World Hydrogen Energy Conference 2012; Roland Berger

FCH and battery technology both are attractive zero-emission options for this operation from a commercial point of view

Alsace region case – High-level TCO assessment [EUR ct/tonne-km; 1st & 2nd life]



1) At the current state of technology, the charging process could not be integrated into the 24 h operation

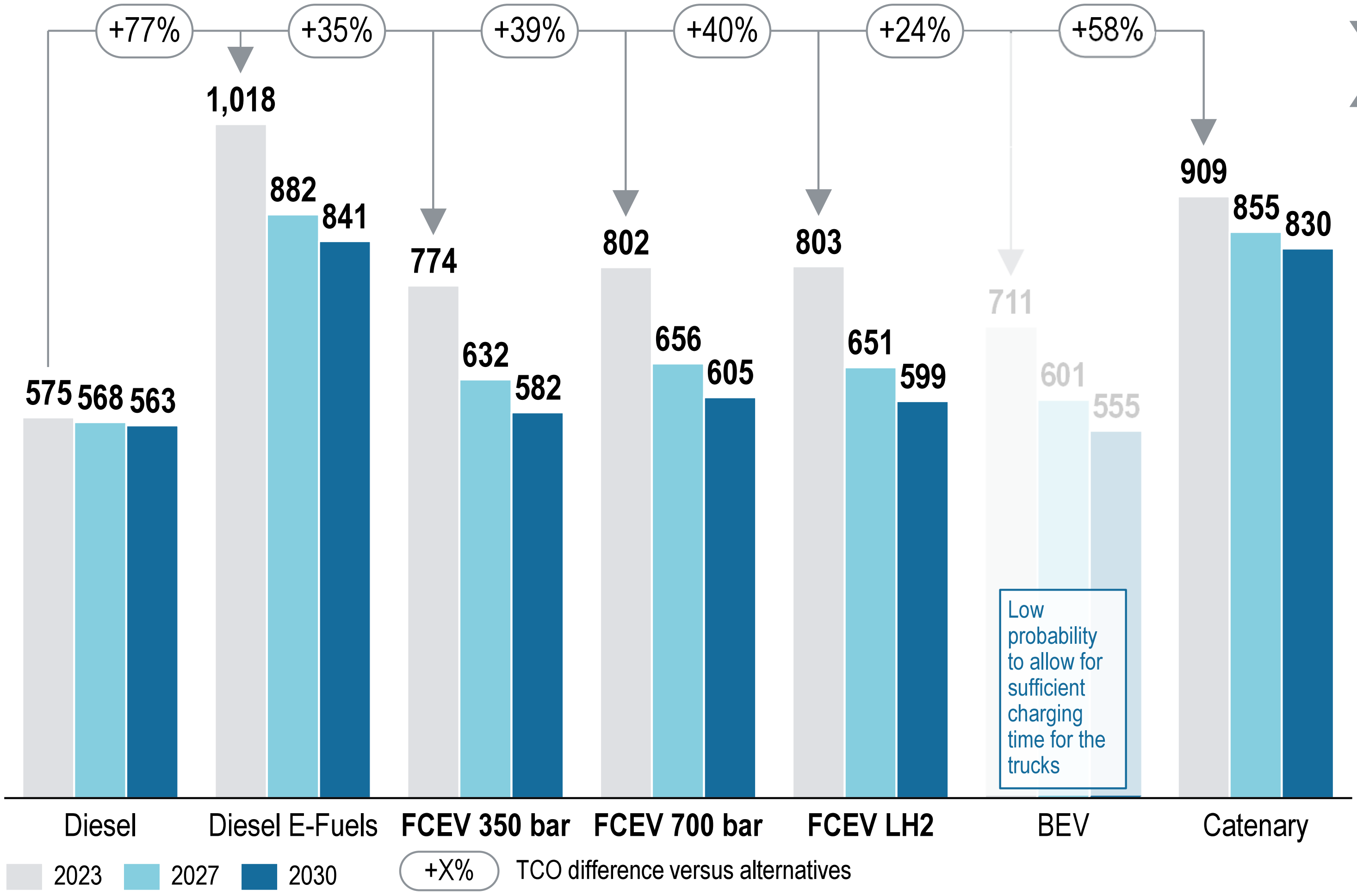
Comments

- > A significant **cost down potential** for FCEV **at scale** exists **looking at 1st and 2nd life**
- > FCH trucks have a **cost premium of up to ~32% in 2023** and are at the **similar cost level as diesel** in 2030 on a tonne-km basis
- > **BEV** is at the **same cost level as FCH technology** on a tonne-km basis with no payload reduction – However, the **almost 24 h operation** would **not offer the possibility** to **charge** the battery trucks[1]

Source: FM Logistic; Roland Berger

The TCO on a EUR/truck basis shows an refined view on the costs per truck – FCH is cost competitive, yet BEV slightly at advantage

Alsace region case – High-level TCO assessment [kEUR/truck; 1st & 2nd life]



Comments

- > Also when looking at the EUR/truck TCO, **the cost down potential** for FCEV techn. **at scale** exists
- > FCH trucks have a **cost premium of up to ~39% in 2023**
- > **FCH trucks and BEV** are at a similar level, yet BEV is **more cost-competitive than all alternatives** on a EUR/truck basis
- > **BEV[1]** results **include a replacement of the large battery** due to mileage over lifetime

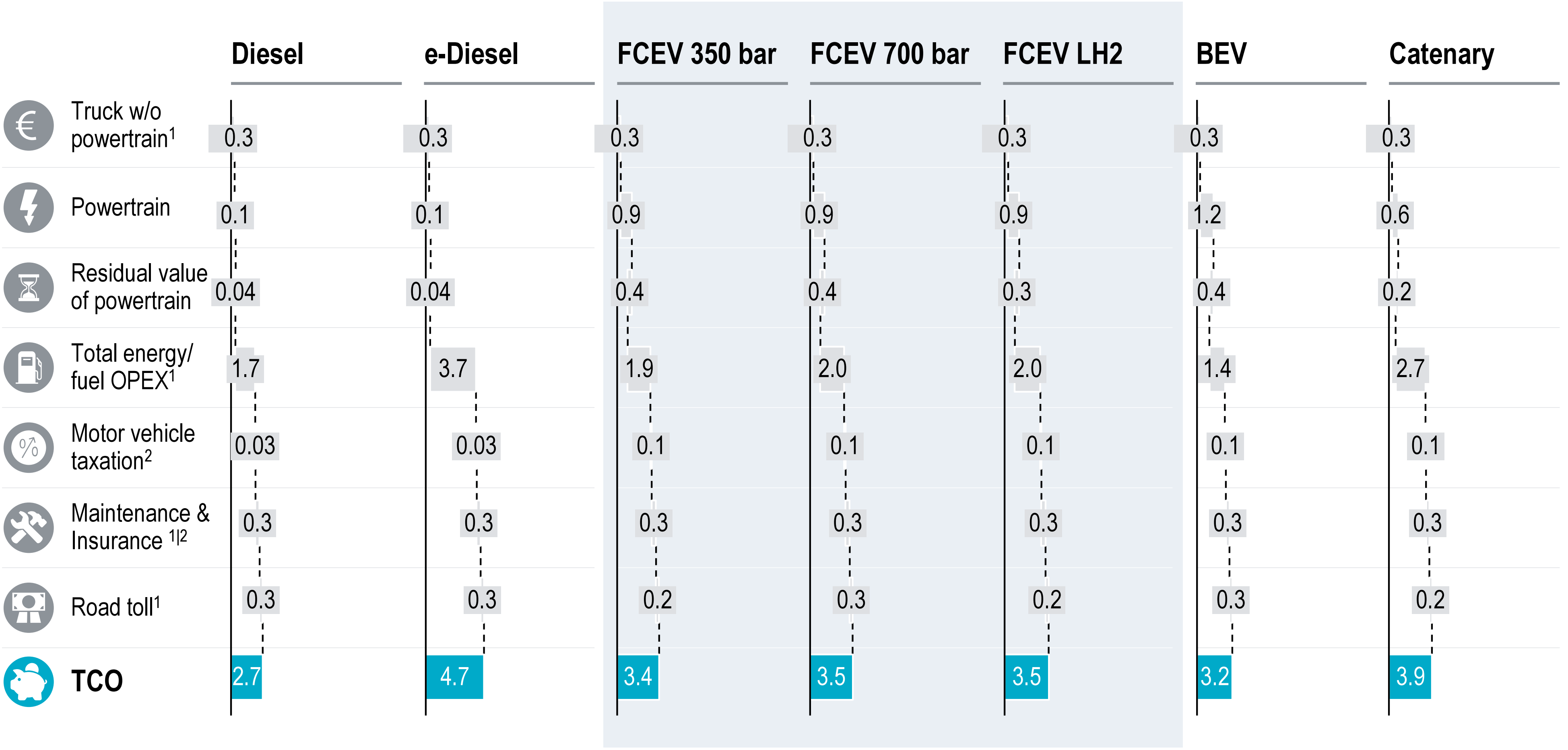
---

[1] At the current state of technology, the charging process could not be integrated into the 24 h operation

Source: FM Logistic; Roland Berger

FCEV have higher energy and fuel costs compared to battery electric trucks and diesel – Main cost driver for all technologies

Alsace region case – 2023 TCO cost breakdown [EUR ct/tonne-km; 1st & 2nd life]



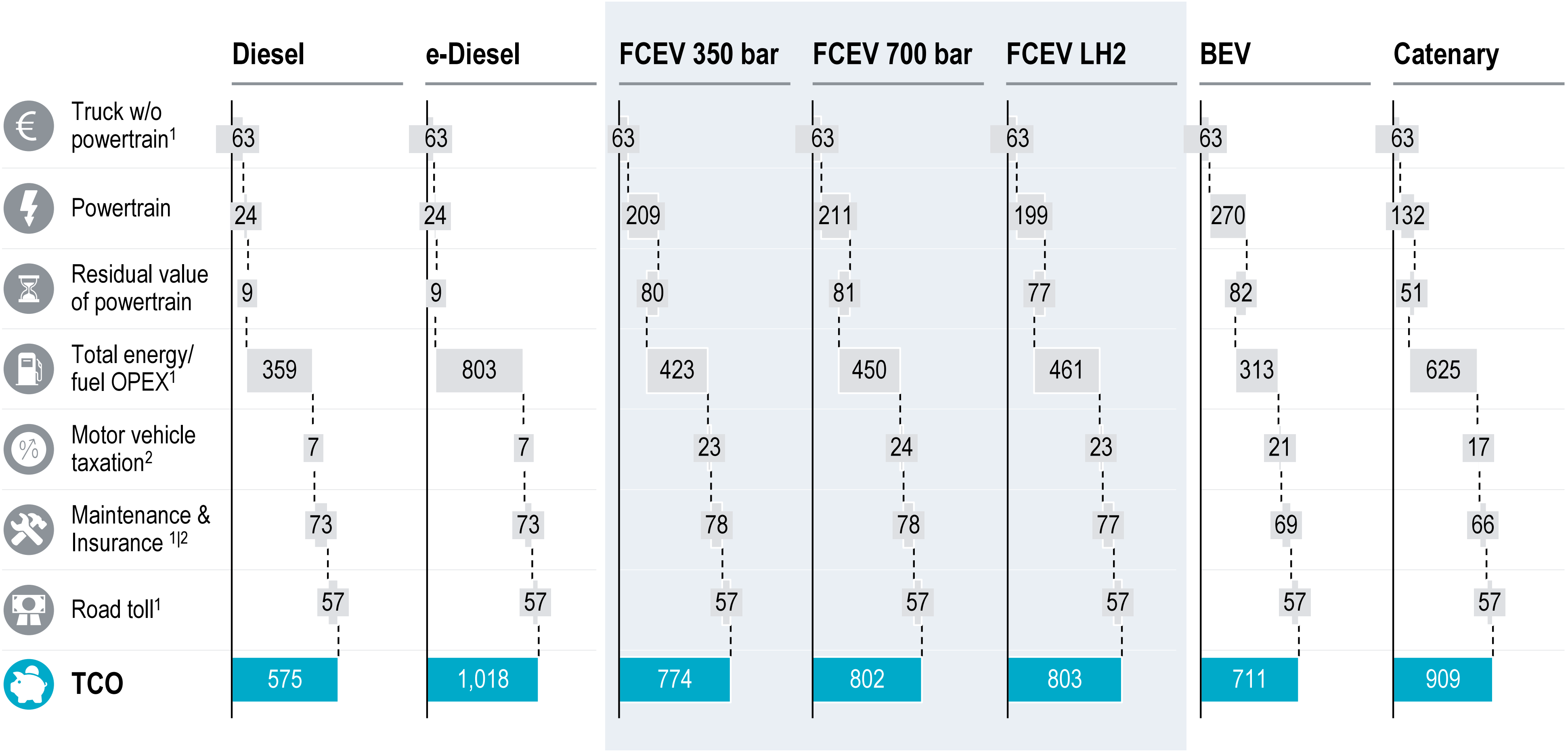
	Diesel	e-Diesel	FCEV 350 bar	FCEV 700 bar	FCEV LH2	BEV	Catenary
Truck w/o powertrain[1]	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Powertrain	0.1	0.1	0.9	0.9	0.9	1.2	0.6
Residual value of powertrain	0.04	0.04	0.4	0.4	0.3	0.4	0.2
Total energy/ fuel OPEX[1]	1.7	3.7	1.9	2.0	2.0	1.4	2.7
Motor vehicle taxation[2]	0.03	0.03	0.1	0.1	0.1	0.1	0.1
Maintenance & Insurance [1|2]	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Road toll[1]	0.3	0.3	0.2	0.3	0.2	0.3	0.2
TCO	2.7	4.7	3.4	3.5	3.5	3.2	3.9

1) Deviations of results are related to payload differences of different technologies 2) Deviations of results are related to calculation based on higher CAPEX

Source: FM Logistic; Roland Berger

The cost of powertrain for zero-emission trucks is another main cost driver – TCO results dependent on its residual value

Alsace region case – 2023 TCO cost breakdown [kEUR/truck; 1st & 2nd life]



	Diesel	e-Diesel	FCEV 350 bar	FCEV 700 bar	FCEV LH2	BEV	Catenary
Truck w/o powertrain[1]	63	63	63	63	63	63	63
Powertrain	24	24	209	211	199	270	132
Residual value of powertrain	9	9	80	81	77	82	51
Total energy/ fuel OPEX[1]	359	803	423	450	461	313	625
Motor vehicle taxation[2]	7	7	23	24	23	21	17
Maintenance & Insurance [1|2]	73	73	78	78	77	69	66
Road toll[1]	57	57	57	57	57	57	57
TCO	575	1,018	774	802	803	711	909

1) Deviations of results are related to payload differences of different technologies 2) Deviations of results are related to calculation based on higher CAPEX

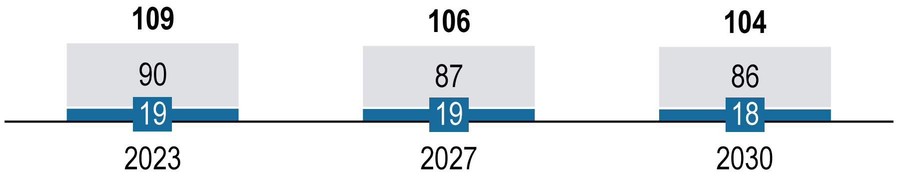
Source: FM Logistic; Roland Berger

Zero-emission vehicles will allow for significant emission savings on this route – Conversion of fleet would offer even higher potential

Alsace region case — Environmental analysis

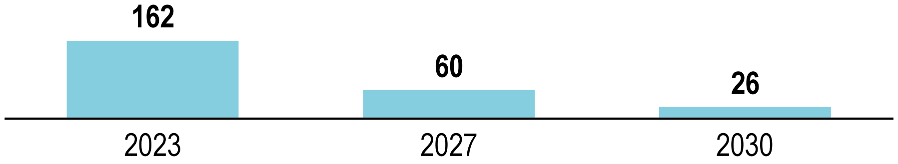
CO_2 savings potential[1]

Well to Wheel [tonnes CO_2e/year]



Estimated CO_2 price for FCEV cost parity

[EUR/tonnes CO_2e]



Pollution reduction potential[2]

- Conversion to zero-emission trucks allows for a total reduction of NOx pollutants
- Particulate matter can also be reduced due to more efficient driving patterns, incl. regenerative braking for electric vehicles

▨ Tank to Wheel ■ Well to Tank

Emissions reductions

- Total greenhouse gas emissions reduction to be realized over 10 years with eight trucks: **8,748 tonnes CO_2e**
- Potential for reduction of other pollutants equally targeted with zero-emission vehicles on the frequently driven route in the Strasbourg area

Opportunities

- Contact with regional H_2 production and supply structures already established for potential collaboration
- Assessment of development of own hydrogen hubs in France could be extended to Strasbourg area in the future, incl. solar panels on-site electrolysis and in-house supply of hydrogen
- Development of an on-site H_2 eco-system would provide the opportunity for multi-modal applications in warehouse operations, e.g. other trucks, forklifts, employee cars
- Recent government support for H_2 applications could leverage a faster development and increased investment support

---

1) CO_2 savings potential refers to one potential zero-emission vehicles for the specific route

2) Pollution reduction potential not quantified as specific limits are set for each heavy duty diesel engine on the vehicle test stand

Source: FM Logistic; Roland Berger

The case study linked to the Alsace warehouse offers a good fit for FCH technology and potential for in-house H_2 infrastructure

Alsace region case – Enablers and constraints for FCH technology

Potential enablers and constraints

!

- The high plannability of the very frequent operation (up to 24/7) to the same locations offers very good conditions for FCH technology uptake as infrastructure can be set up accordingly
- Company considerations of multi-modal applications, e.g. with H_2 trailers, forklifts, in France warehouse location can have leverage effects on the Strasbourg region operations
- Company ambition to potentially set up on-site electrolysis, strong government interest in hydrogen and potential investment support are supporting factors of (near) future deployment of FCH trucks / trailers

?

- H_2 demand of fleet investigated in the case study would not meet the advisable minimum utilisation (at least 10 trucks) for a private HRS with external H_2 supply; however, in-house hydrogen production to be investigated
- Set up of HRS could need cooperation with either hydrogen providers, key local actors and/or government initiative – Ongoing projects / plans to already being investigated in the area

Synthesis

- The case study with a relatively **low mileage but a heavy load** offers a **very plannable operation** on **fixed routes – good conditions** for setting up the required **hydrogen infrastructure**
- **FCH technology is a good fit** on this route as it is the identified zero-emission technology that would **enable the necessary reach, required payload capacity** and **short refuelling time** to allow for the almost 24 h operation schedule – **Battery electric trucks would not offer the same flexibility**, esp. with regard to charging time[1]
- Uptake of **hydrogen application already a near-term focus** of the company sustainability ambition, incl. use of **hydrogen trailers** and assessment of **development of own hydrogen hubs**, incl. solar panels, on-site electrolysis and in-house supply of hydrogen

---

1) Under the assumptions that, also in the coming years, very fast charging of the trucks (e.g. mega-chargers) would not provide a suitable solution, e.g. due to the high draw on the energy grid

Source: FM Logistic; Roland Berger

The case study on the Brumath routes in France is supported by specific information and data from FM Logistic

Alsace region case – Background

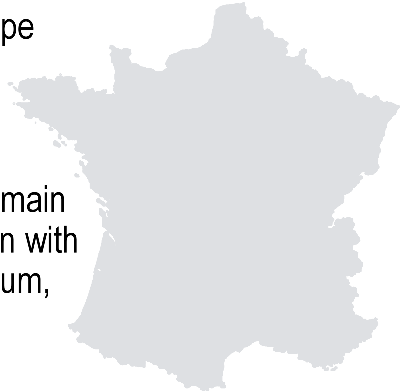
Road freight sector in France

Information on the road freight sector

> France has the second highest volume of road transport in Europe with approx. 2 billion tonnes of goods transported in 2018

> The largest part of freight is transported nationally, while the main country-to-country flows are seen with the neighbouring countries Belgium, Germany and Spain

> Overall, the road freight industry revenue for transport by road in France is approx. EUR 45 bn (2018)



Main transport corridors

> France has one of the densest networks of highways in Europe (both public and privately managed), with a higher density around the capital

Information on company supporting the case

Company information

Name	FM Logistic
Industry	Logistics company
Headquarters	Phalsbourg, France
Zero-emission ambition	Sustainability strategy to achieve sustainable growth, incl. target for carbon neutral warehouses by 2030

Depot linked to route

Location	Brumath
Description	Regional hub
Total number of trucks	8 owned trucks, with further trucks linked to the warehouse[1]

1) The Brumath warehouse is used as a hub for several clients; Further outbound operations by subcontractors or other logistics companies are linked to the location

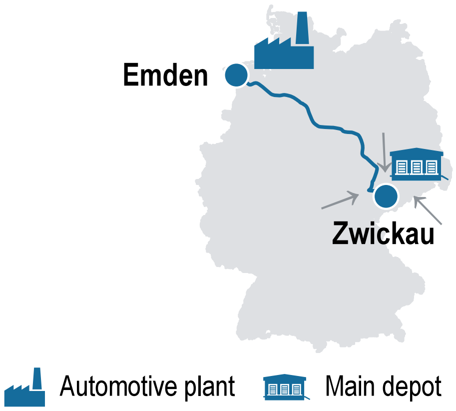
Source: FM Logistic; Statista; Eurostat; Roland Berger

D.3.3 Zwickau-Emden case [Schnellecke]

The Zwickau-Emden route is an example for German automotive logistics – The fixed long-haul route is a good fit for FCH technology

Zwickau-Emden case – Overview

Location and route



- > The route is set from Eastern Germany to the North-West and services a large automotive production plant from their hub providing the consolidation of supplier goods
- > The route is a round-trip operation with the main depot being located at Zwickau in the East
- > The operation involves proximity to port operations in Northern Germany
- > The route is set on mainly flat terrain driving on well-developed German highways

Setting – Truck and operations

Truck type	Tractor 4x2, 40 tonnes 3 m interior height
Daily range	607 km
Operation	212 days/year
Fleet size	41 (2 in daily operation)[1]
Payload	25.4 tonnes

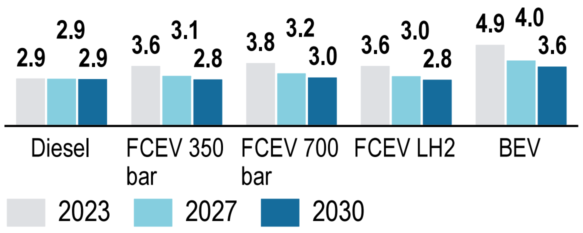
Logistic operation

A logistics service transporting car parts in a go-and-return operation. The logistics service provider consolidates supplier goods at their hub in Zwickau and delivers them to the production plant in Emden. The one-way route is driven in one day by one driver.

Infrastructure

- > Currently no infrastructure for alternative powertrains in place
- > Public refuelling preferred due to experience with complex maintenance of CNG/LNG trucks
- > No time pressure regarding refuelling process

TCO analysis [EUR ct/tonne-km; 1st & 2nd life]

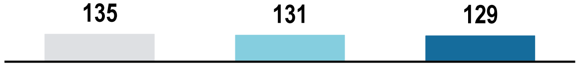


Cost-competitiveness for FCH technology by 2030 and less TCO potential for BEV (payload losses) is shown, providing a strong argument for FCEV.

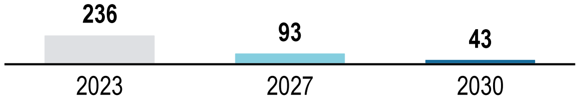
Environmental analysis

Zero-emission trucks offer significant annual CO_2 savings. The est. CO_2 price, as the price to be put on CO_2 to reach cost parity compared to diesel, demonstrates the FCEV cost premium

Yearly truck CO_2 savings potential – WTW [tCO_2e]



Est. CO_2 price for FCEV cost parity [EUR/tCO_2e]



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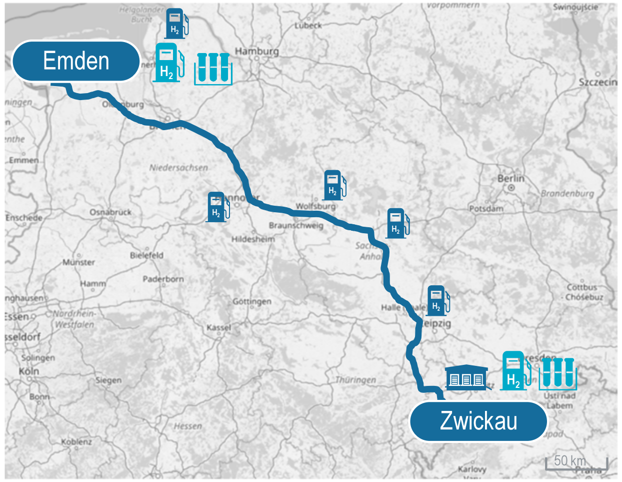
1) The logistics service provider flexibly chooses from a pool of 41 vehicles that match the requirements for this route – however, only 2 trucks per day are operating the route with one truck driving towards the automotive production plant, the other returning; The other 39 trucks service different operations on different routes in the meantime

Source: Schnellecke; Roland Berger

The case study stands out because of its close link to the German automotive sector and plannable operations linked to production

Zwickau-Emden case – Description

Investigated route



- Existing HRS[2] for cars
- Main depot
- Potential HRS[2] for trucks
- Potential H_2 production

> The route services a large automotive production plant and involves proximity to port operations in Northern Germany

> Round trip operation allows for high utilisation, empty runs are avoided

> The one-way route is driven in a day by one driver

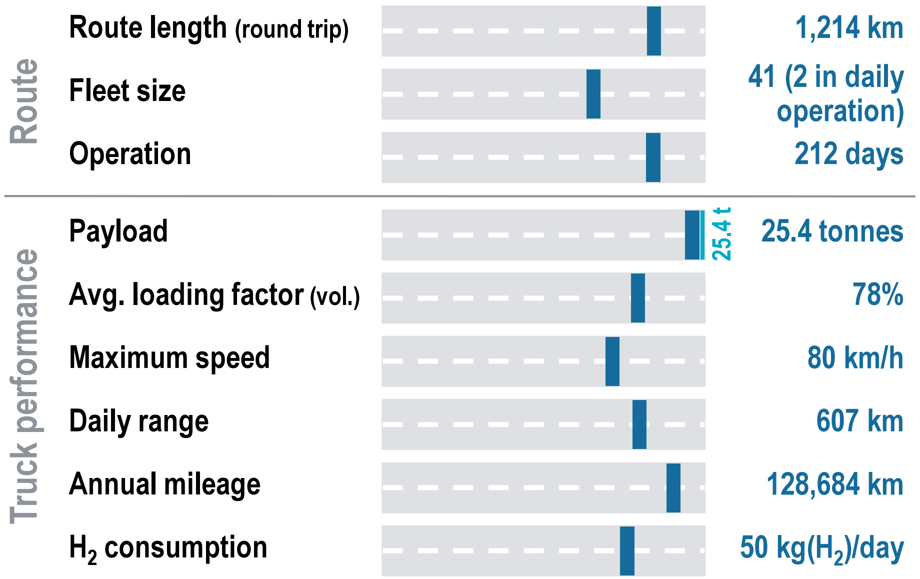
Case description[1]

Truck type Tractor 4x2, 40 tonnes

Mega automotive (4 m height)

Logistic operation

In the logistics service, car parts are transported in a go-and-return operation. The logistics service provider consolidates supplier goods at their hub in Zwickau and delivers them to the production plant in Emden. The route is operated with leased trucks (used for approx. 3-4 years).



Route	**Route length** (round trip)	1,214 km
	Fleet size	41 (2 in daily operation)
	Operation	212 days
Truck performance	**Payload**	25.4 tonnes
	Avg. loading factor (vol.)	78%
	Maximum speed	80 km/h
	Daily range	607 km
	Annual mileage	128,684 km
	H_2 consumption	50 kg(H_2)/day

Legend Low High

Infrastructure

> Each truck operates the full 607 km mileage/day – this would be an avg. consumption of ~50 kg(H_2)/day (at 0.08 kg(H_2)/km)and a H_2 demand of 100 kg(H_2)/day

Potential truck HRS[2]

> 2 trucks not sufficient for private HRS (min. fleet size of 10 trucks would be advisable); near access to (semi-) public infrastructure needed

Potential H_2 prod. facility

> Supply from electrolysis installation providing at least 0.1 MW at each end of the route needed

Potential synergies

> Close proximity to port operations and auto. ind.

> Existing H_2 production in chemical park in Leuna

[1] Data verified with stakeholders

Source: Schnellecke; Roland Berger

[2] HRS = hydrogen refuelling station; at the depot in Zwickau, there would be more potential for H_2 demand in private refuelling, if whole fleet were to be converted to FCH tech.

Specific data is introduced in the total cost of ownership model to reflect the real-life operations of the case study

Zwickau-Emden case – Specific assumptions

Main input changes to the TCO model base assumptions

Operation	> Annual mileage set at 130,000 km/year > Operation on route set for 212 days/year > Max. payload set to 25.4 tonnes > Route profile set to a homogenous pattern due to plannability of fixed route
Maintenance costs	> Maintenance cost set at 0.13 EUR/km for diesel trucks
Private / public refuelling	> Mainly private refuelling for Diesel trucks > Public refuelling assumed for FCH and battery electric trucks
Energy and fuel costs	> Energy price for Diesel set at 0.9681 EUR/l net price (meaning a lower diesel price due to private refuelling price)
Road toll	> Road toll set to 0.187 EUR/km to reflect the current conditions in Germany (CNG/LNG toll exemption until 2023 as potential for FCH)

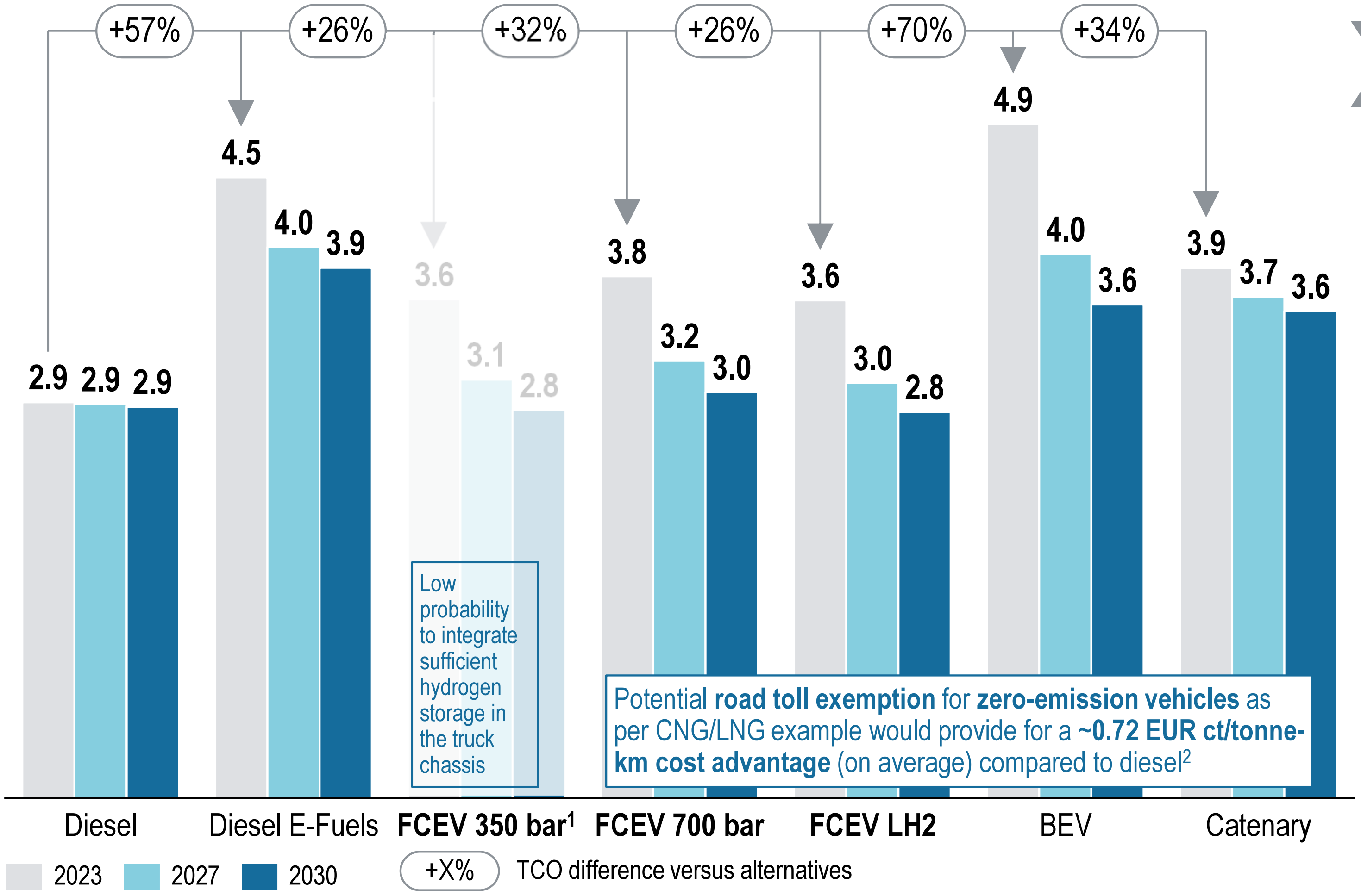
---

1) Operated trucks are currently part of a full service leasing scheme with maintenance cost generally covered by a full service; Experience shows to set an additional 0,01 EUR/km for unexpected repairs

Source: Schnellecke; Roland Berger

FCH technology is an attractive zero-emission option for this route from a commercial point of view with a clear cost down potential

Zwickau-Emden case – High-level TCO assessment [EUR ct/tonne-km; 1st & 2nd life]



	2023	2027	2030
Diesel	2.9	2.9	2.9
Diesel E-Fuels	4.5	4.0	3.9
FCEV 350 bar[1]	3.6	3.1	2.8
FCEV 700 bar	3.8	3.2	3.0
FCEV LH2	3.6	3.0	2.8
BEV	4.9	4.0	3.6
Catenary	3.9	3.7	3.6

Low probability to integrate sufficient hydrogen storage in the truck chassis

Potential **road toll exemption** for **zero-emission vehicles** as per CNG/LNG example would provide for a **~0.72 EUR ct/tonne-km cost advantage** (on average) compared to diesel[2]

Comments

- A significant **cost down potential** for FCEV **at scale** exists **looking at 1st and 2nd life**
- FCH trucks have a **cost premium of up to ~32% in 2023**
- **FCH technologies** are at the **similar cost level as diesel** in 2030 and **more competitive than the alternatives** E-Fuels, BEV and catenary on a tonne-km basis
- **Payload reduction for BEV** applies due to large size of the battery needed on this route

---

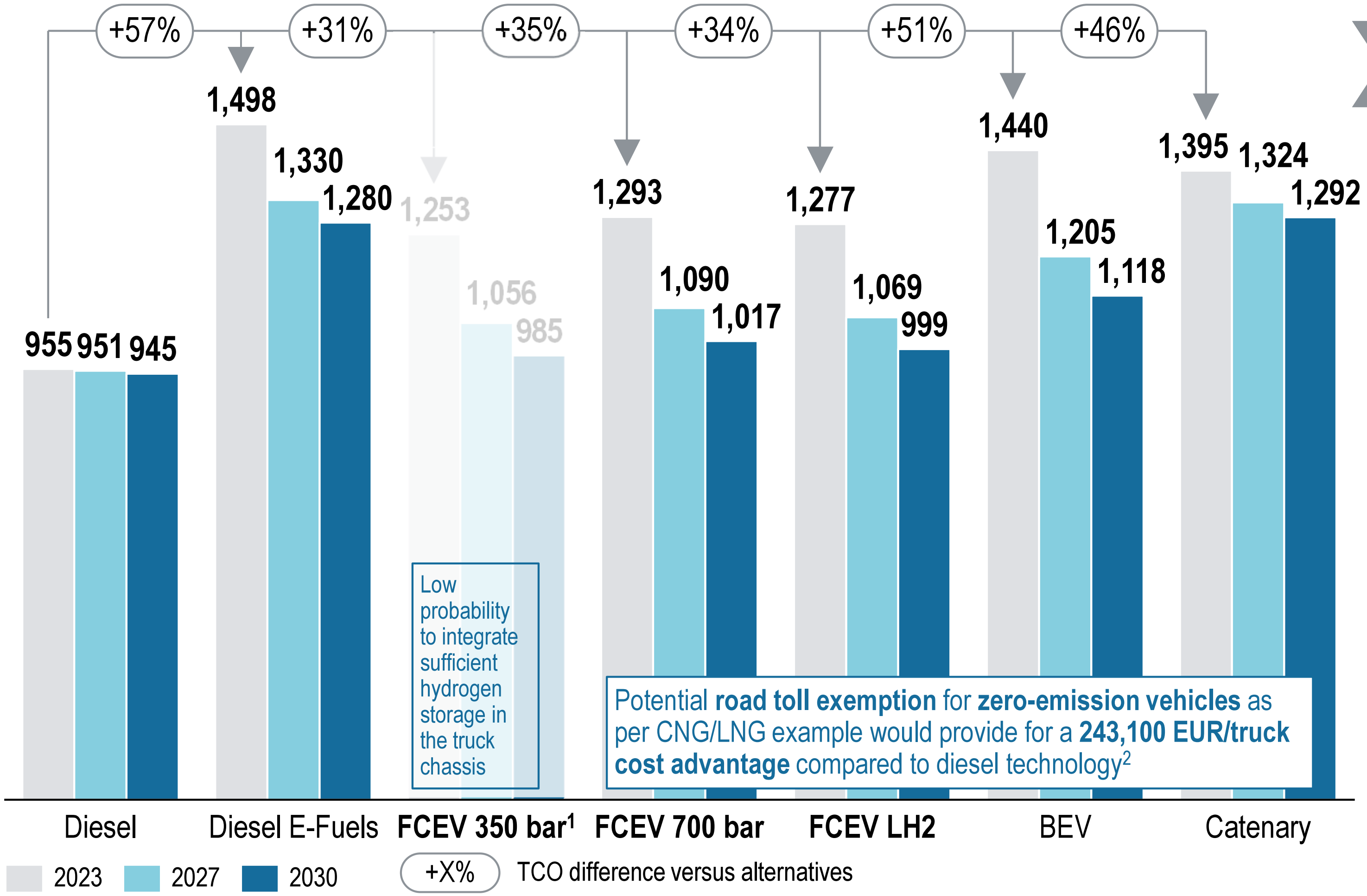
1) Under the assumption that sufficient hydrogen storage can be technically integrated in the current truck chassis architecture; Potential length regulation adjustments required

2) Potential not yet considered in the TCO calculation as there is not yet sufficient information on the long-term application for such legislation also for FCEV

Source: Schnellecke; Roland Berger

The TCO on a EUR/truck basis shows an refined view on the costs per truck – FCH most cost competitive zero-emission technology

Zwickau-Emden case – High-level TCO assessment [kEUR/truck; 1st & 2nd life]



Low probability to integrate sufficient hydrogen storage in the truck chassis

Potential **road toll exemption** for **zero-emission vehicles** as per CNG/LNG example would provide for a **243,100 EUR/truck cost advantage** compared to diesel technology[2]

Comments

- Also when looking at the EUR/truck TCO, **the cost down potential** for FCEV technology **at scale** exists
- FCH trucks have a **cost premium of up to ~35% in 2023**
- **FCH truck technologies** are also **more cost-competitive than the alternatives** Diesel E-Fuels, BEV and catenary on a EUR/truck basis
- However, **diesel is still the cheapest technology option** in 2030

---

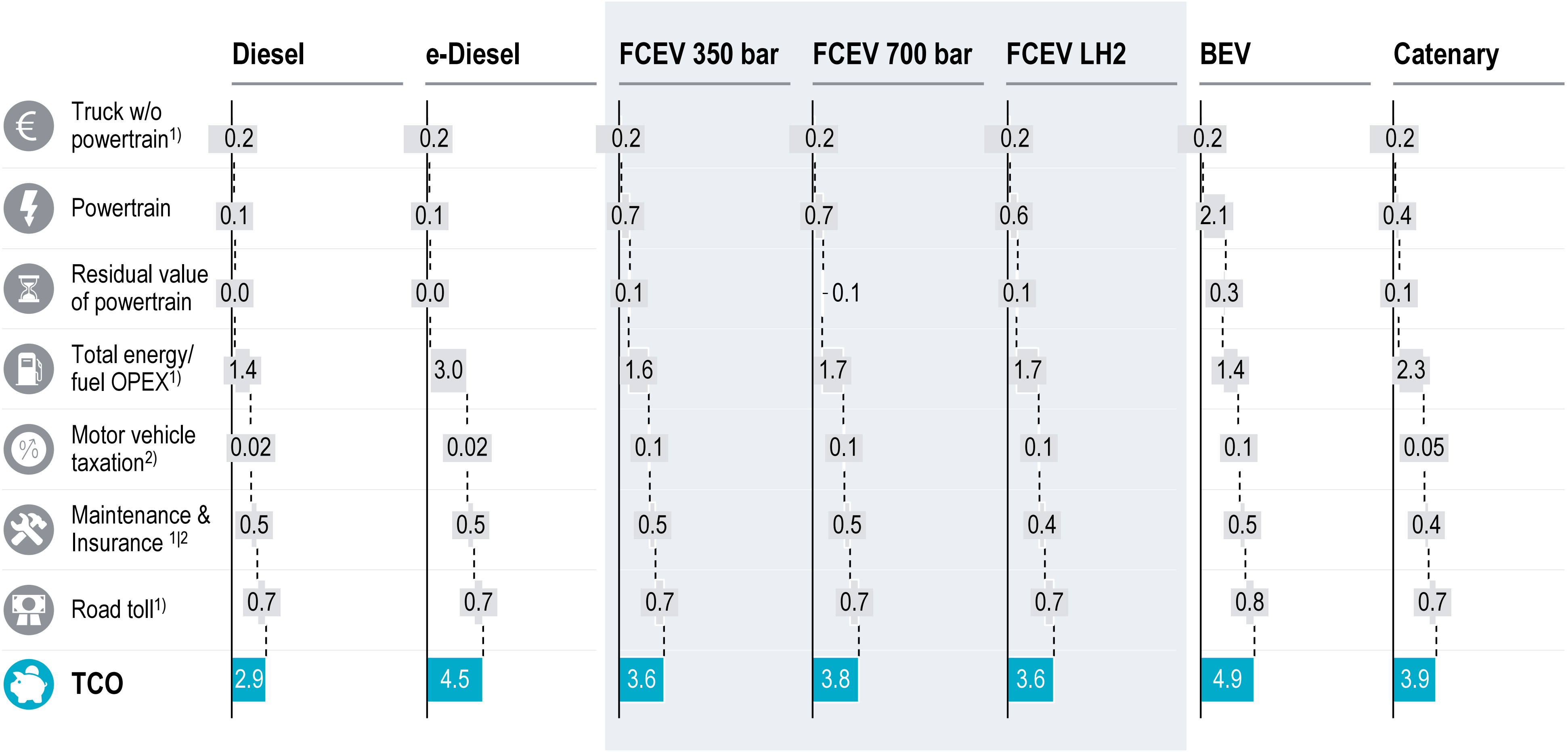
1) Under the assumption that sufficient hydrogen storage can be technically integrated in the current truck chassis architecture; Potential length regulation adjustments required

2) Potential not yet considered in the TCO calculation as there is not yet sufficient information on the long-term application for such legislation also for FCEV

Source: Schnellecke; Roland Berger

Cost of powertrain and energy and fuel costs are the main cost drivers – Road toll is a differentiating factor with potential for FCH

Zwickau-Emden case – 2023 TCO cost breakdown [EUR ct/tonne-km; 1st & 2nd life]

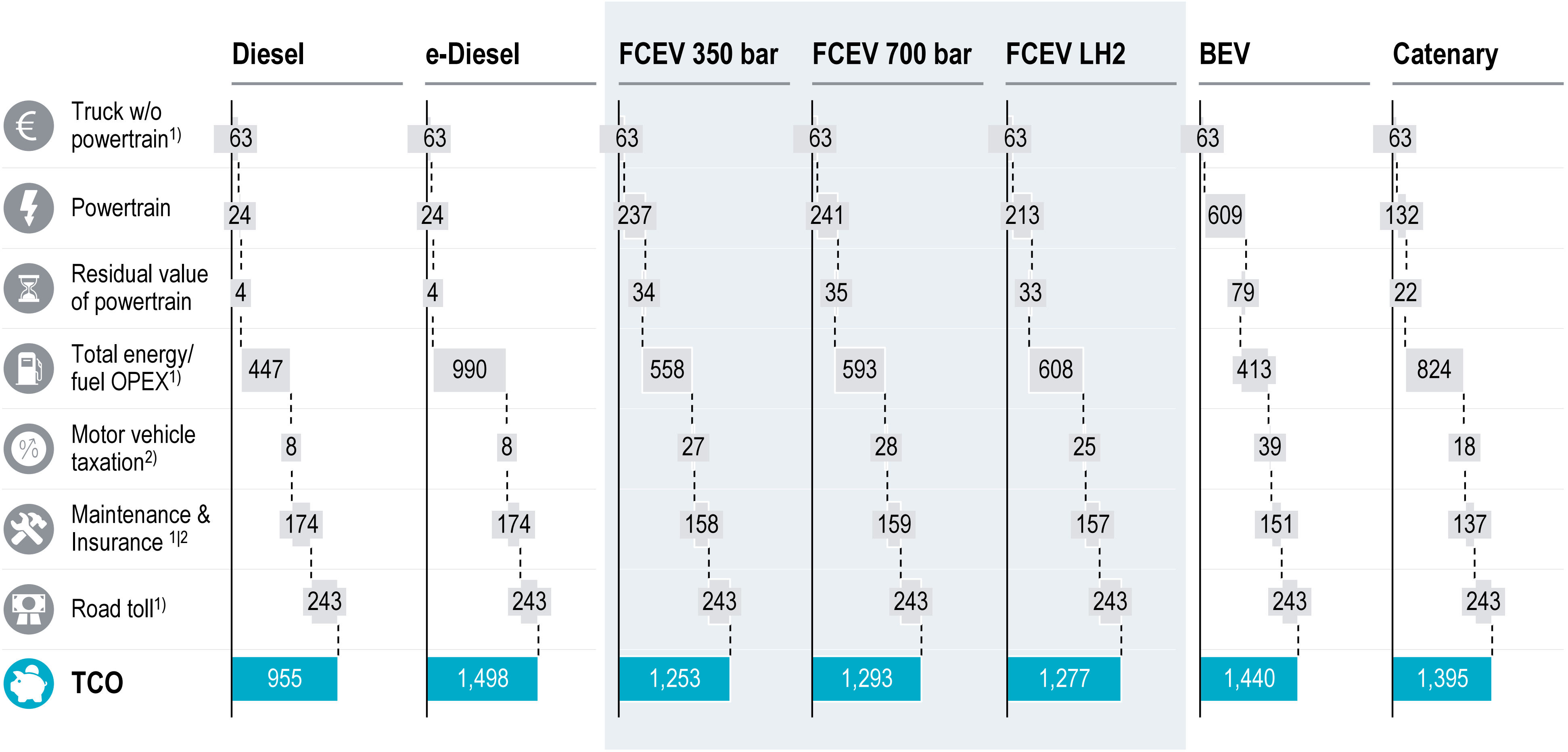


1) Deviations of results are related to payload differences of different technologies 2) Deviations of results are related to calculation based on higher CAPEX

Source: Schnellecke; Roland Berger

Cost of powertrain and energy and fuel costs are the main cost drivers – Road toll is a differentiating factor with potential for FCH

Zwickau-Emden case – 2023 TCO cost breakdown [kEUR/truck; 1st & 2nd life]



	Diesel	e-Diesel	FCEV 350 bar	FCEV 700 bar	FCEV LH2	BEV	Catenary
Truck w/o powertrain[1)]	63	63	63	63	63	63	63
Powertrain	24	24	237	241	213	609	132
Residual value of powertrain	4	4	34	35	33	79	22
Total energy/ fuel OPEX[1)]	447	990	558	593	608	413	824
Motor vehicle taxation[2)]	8	8	27	28	25	39	18
Maintenance & Insurance [1|2]	174	174	158	159	157	151	137
Road toll[1)]	243	243	243	243	243	243	243
TCO	955	1,498	1,253	1,293	1,277	1,440	1,395

1) Deviations of results are related to payload differences of different technologies 2) Deviations of results are related to calculation based on higher CAPEX

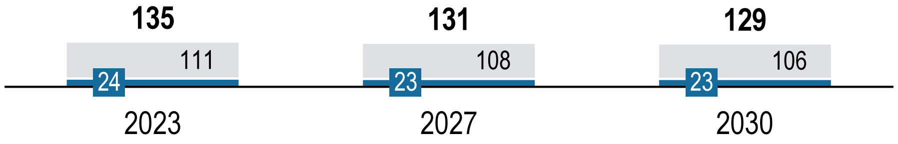
Source: Schnellecke; Roland Berger

Zero-emission vehicles will allow for significant emission savings on this route – Conversion of fleet would offer even higher potential

Zwickau-Emden case – Environmental analysis

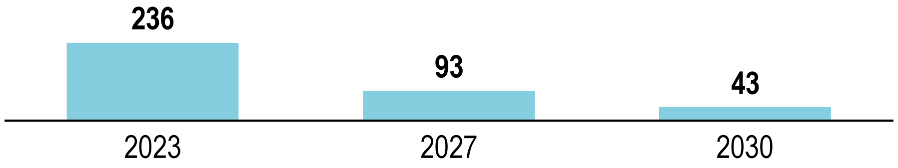
CO_2 savings potential[1]

Well to Wheel [tonnes CO_2e/year]



Estimated CO_2 price for FCEV cost parity

[EUR/tonnes CO_2e]



Pollution reduction potential[2]

> Conversion to zero-emission trucks allows for a total reduction of NOx pollutants

> Particulate matter can also be reduced due to more efficient driving patterns, incl. regenerative braking for electric vehicles

Emissions reductions

> Total greenhouse gas emissions reduction to be realized over 10 years with two trucks (max.): **2,698 tonnes CO_2e**

> Potential for reduction of other pollutants equally targeted with zero-emission vehicles on the frequently driven route across Germany

Opportunities

> Access to renewable wind energy at start and end point offers potential for green hydrogen production

> Development of local H_2 eco-system would also provide opportunity for multi-modal applications in port operations

> H_2 refuelling infrastructure could also be used by other parties and for other applications – Even larger potential is possible as effect exists not only for individual logistics service provider

▨ Tank to Wheel ■ Well to Tank ▨ Est. CO2 price

---

1) CO_2 savings potential refers to one potential zero-emission vehicles for the specific route

2) Pollution reduction potential not quantified as specific limits are set for each heavy duty diesel engine on the vehicle test stand

Source: Schnellecke; Roland Berger

The Zwickau-Emden case shows that the combination of factors on this route offer a good opportunity for FCH technology

Zwickau-Emden case – Enablers and constraints for FCH technology

Potential enablers and constraints

!

- High plannability of route offers very good conditions for FCH technology uptake
- Opportunities for infrastructure (existing H_2 production in Saxony-Anhalt) and potential multimodal synergies with other forms of transport along the route seem possible (proximity of production plant, port operations)

?

- Minimum utilisation (at least 10 trucks) for both private and public HRS installation would be advisable, collaboration with external partners might be possible
- Development of hydrogen infrastructure depends on cooperation with key local actors and government initiative

Synthesis

- Case study offers a **fixed route operated on a regular schedule** – very **good conditions** for setting up the required **hydrogen infrastructure**
- **FCH technology is a good fit** on this route with the option to **leverage existing infrastructure** regarding renewable energy, hydrogen production, and refuelling infrastructure
- **FCEV overall more favourable** than other zero-emission technologies, as **BEV would imply a significant payload reduction** and would not offer the same **flexibility to be used equally on other routes** within the vehicle pool
- Especially **links to the North Sea** and **wind parks in Saxony** offer access to renewable wind energy as an **opportunity for green hydrogen production**
- **Potential synergies** with other hydrogen applications exist **at the start and end point of the route** (e.g. forklifts in production plant)

Source: Schnellecke; Roland Berger

The case study on the route Zwickau-Emden in Germany was supported by specific information and data from Schnellecke

Zwickau-Emden case – Background

Road freight sector in Germany

Information on the road freight sector

- Germany sees the highest volume of road transport in Europe with approx. 3,2 billion tonnes of goods transported in 2018
- Due to its central position within Europe, Germany is a transit geography for (road) transport
- Overall, the road freight industry revenue for transport by road in Germany is EUR 35 bn (2018)

Main transport corridors

- Germany has a well-developed network of highways across the country with the main national transport links connecting North and South as well as East and West Germany

Information on company supporting the case

Company information

Name	Schnellecke Transportlogistik GmbH
Industry	Logistics service provider for the automotive sector
Headquarters	Braunschweig
Zero-emission ambition	Activities and projects with fully electric tractor units and CNG/LNG trucks (planned 2021)

Depot linked to route

Location	Zwickau
Description	Regional hub
Total number of trucks[1]	104 (incl. subcontractors)

---

[1] Overall, the depot premises offer room and infrastructure for up to 104 trucks, incl. those of subcontractors; For the specific case study route, a pool of 41 vehicles that match the requirements is considered

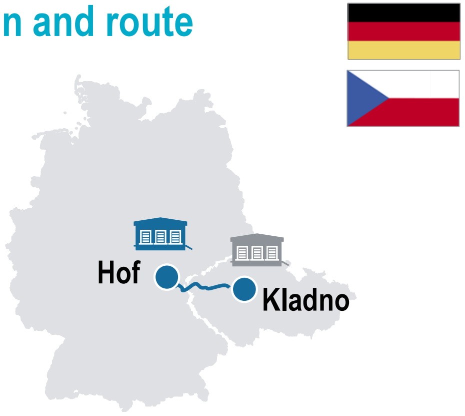
Source: Schnellecke; Statista; Destatis; Roland Berger

D.3.4 Hof-Kladno case [Dachser]

The cross-border line haulage route between Germany and Czech Republic shows some potential for FCEV in two-shift operations

Hof-Kladno case – Overview

Location and route



▦ German branch ▦ Czech branch

- The cross border route is set from Hof in Germany to Kladno in the Czech Republic. It is part of larger line haulage routes reaching Hof – Kladno – multiple branches in Central Eastern Europe
- Swap bodies are used for the line haulage: Two swap bodies are transported from Hof to Kladno and exchanged with swap bodies coming from multiple branches in Central Eastern Europe. Both trucks then return to their main depot with the new load.
- The route is set on mainly flat terrain driving on a well-developed network of highways.

Setting – Truck and operations

Truck type	Rigid 6x2, 26+14 tonnes Swap body truck + swap body trailer
Daily range	424 + 233 km
Operation	243 days/year
Fleet size	5
Payload	11.2 tonnes (for truck and trailer

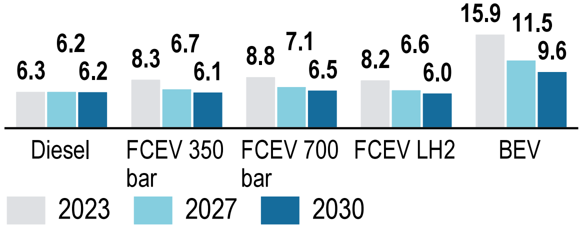
Logistic operation

Trucks on this route run in a two shift operation with swap bodies to transport industrial groupage goods across Europe. The trucks are operated at night between the branches of Hof and Kladno (round trip) in a line haulage system. During the day, a second shift in regional distribution route is driven by a different driver.

Infrastructure

- Hydrogen refuelling infrastructure for trucks would need to be installed (private or public)
- Time-constraint operation would allow for (fast) refuelling of FCEV, yet no charging of BEV

TCO analysis [EUR ct/tonne-km; 1st life]

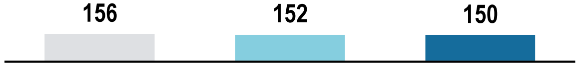


The analysis shows FCH technology as an increasingly cost-competitive alternative to diesel technology with a clear cost-down potential.

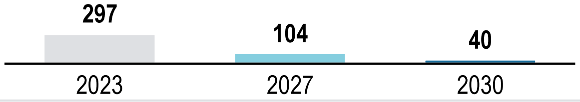
Environmental analysis

Zero-emission trucks offer significant annual CO_2 savings. The est. CO_2 price, as the price to be put on CO_2 to reach cost parity compared to diesel, demonstrates the FCEV cost premium

Yearly CO_2 savings potential – WTW [tCO_2e]



Est. CO_2 price for FCEV cost parity [EUR/tCO_2e]



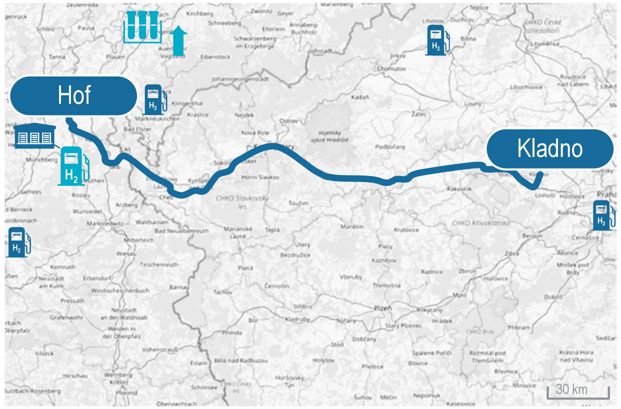
1) The operation includes a fixed line haulage route during the night (round trip 424 km) and the deployment of the trucks during the day in regional distribution (avg. of 233 km)

Source: Dachser; Roland Berger

The route with line haulage operations by night and regional distribution by day illustrates the industry demands for durable vehicles

Hof-Kladno case – Description

Investigated route



Existing & planned HRS[2] for cars; Main depot; Potential HRS[2] for trucks; Potential H_2 production

- The cross border route is set from Hof in Germany to Kladno in the Czech Republic; It is part of a larger line haulage route Hof – Kladno – multiple branches in Central Eastern Europe
- The route is set on mainly flat terrain driving on a well-developed network of highways
- In both countries, road toll charges apply, with higher prices in Germany and lower prices in the Czech Republic, where most of the route is driven

Case description[1]

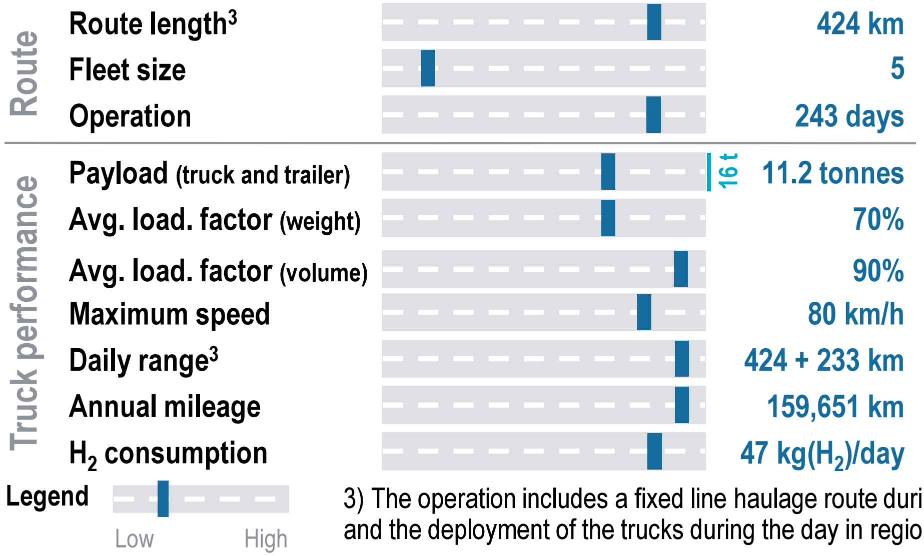
Truck type

Rigid 6x2, 26+14 tonnes

Swap body truck + swap body trailer

Logistic operation

Trucks on this route run in a two-shift operation to transport two swap bodies with industrial groupage goods across Europe. The first shift starts at night with a line haulage transport between the regional hubs of Hof and Kladno (round trip). The second shift with a different driver during the day is a regional distribution route with 5 stops (on average) for delivery and pick up back in Hof. The operation is volume restricted due to the heterogenous weights of groupage consignments in double deck loading.



Route	**Route length[3]**	424 km
	Fleet size	5
	Operation	243 days
Truck performance	**Payload** (truck and trailer)	11.2 tonnes
	Avg. load. factor (weight)	70%
	Avg. load. factor (volume)	90%
	Maximum speed	80 km/h
	Daily range[3]	424 + 233 km
	Annual mileage	159,651 km
	H_2 consumption	47 kg(H_2)/day

Infrastructure[2]

- Each truck operates on avg. 657 km per day – this would be an avg. consumption of ~47 kg(H_2)/day (at 0.071 kg(H_2)/km) and a H_2 demand of ~233 kg(H_2)/day for the whole fleet

Potential truck HRS

- Private station on site if conversion of further routes, min. 0.5 t(H2)/day, OR
- Public station if used together with further applications; min. 0.5 t(H_2)/day

Potential H_2 prod. facility

- Hydrogen supply from electrolysis installation of at least 1 MW needed

Potential synergies

- More trucks linked to depot could be replaced by FCEV
- Proximity to wind parks on Saxony and H_2 production in Saxony-Anhalt

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1) Data verified with stakeholders
2) HRS = hydrogen refuelling station
3) The operation includes a fixed line haulage route during the night (round trip 424 km) and the deployment of the trucks during the day in regional distribution (avg. of 233 km)

Source: Dachser; Roland Berger

Specific data is introduced in the total cost of ownership model to reflect the real-life operations of the case study

Hof-Kladno case – Specific assumptions

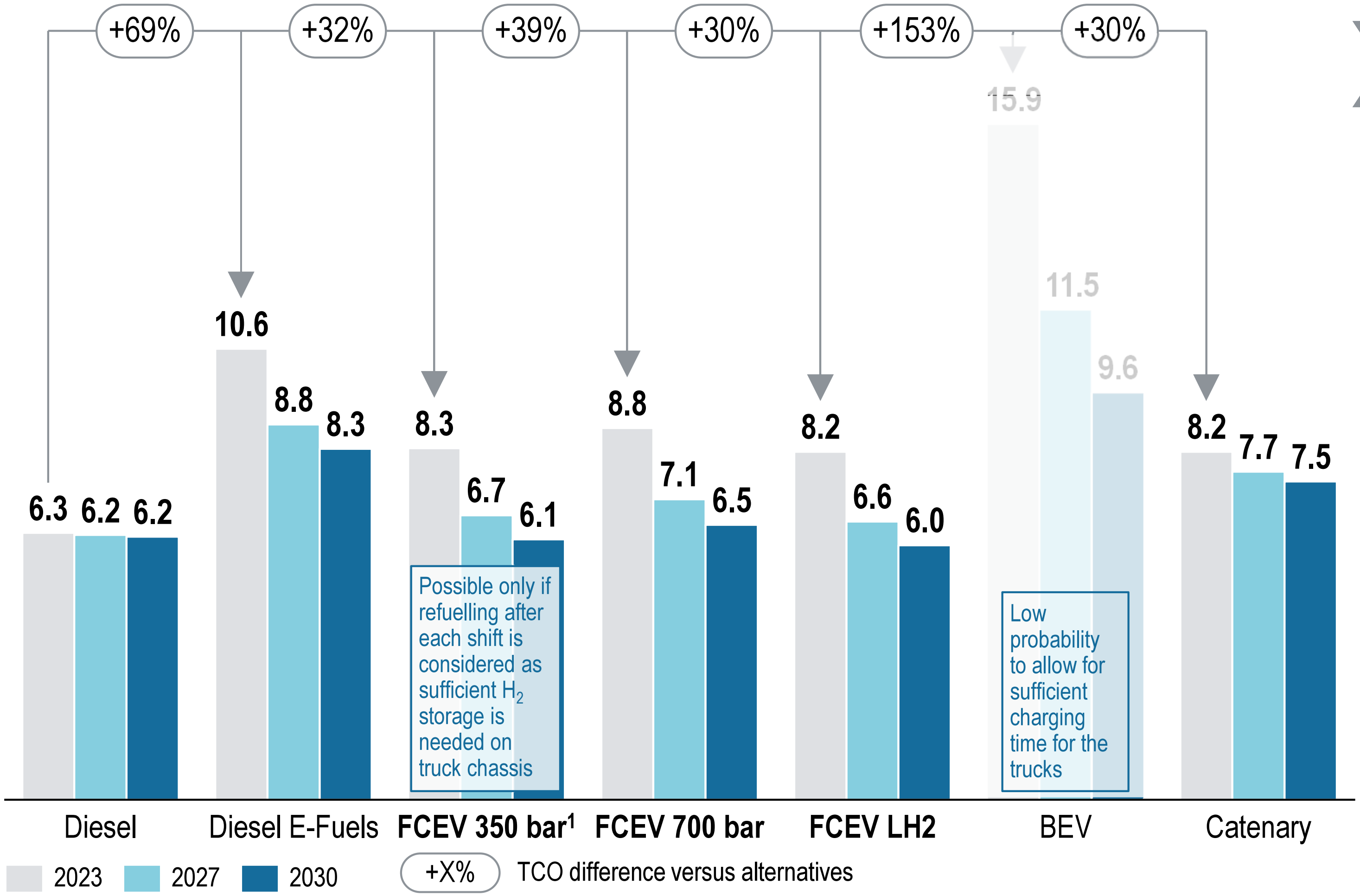
Main input changes on the TCO model base assumptions

Operation	> Only consideration of first life to very high annual mileage > Annual mileage set at 160,000 km/year > Operation on route set for 243 days/year > Max. payload set to 16 tonnes, reflecting the allowed GVW > Route profile set to a rather homogenous pattern due to plannability of fixed route by night and varying regional distribution by day
Maintenance costs	> Maintenance cost kept at 0.12 EUR/km for diesel trucks
Private / public refuelling	> Currently private refuelling used for diesel trucks > Public refuelling assumed for alternative powertrain technologies
Energy and fuel	> Diesel price kept at base assumption for private refuelling (1.00 EUR/l net price in 2023; surcharges for public refuelling not consid.) > Consumption figures set to the average of the base assumptions for the 6x2 rigid and 4x2 tractor vehicles to reflect the high mileage
Road toll	> Road toll set to 0.15 EUR/km to reflect an approx. average of the different costs of road toll in Germany and the Czech Republic and the related portion of the route

Source: Dachser; Roland Berger

FCH technology with a clear cost-down potential and a potential TCO advantage over diesel in 2030

Hof-Kladno case – High-level TCO assessment [EUR ct/tonne-km; 1st life]



Comments

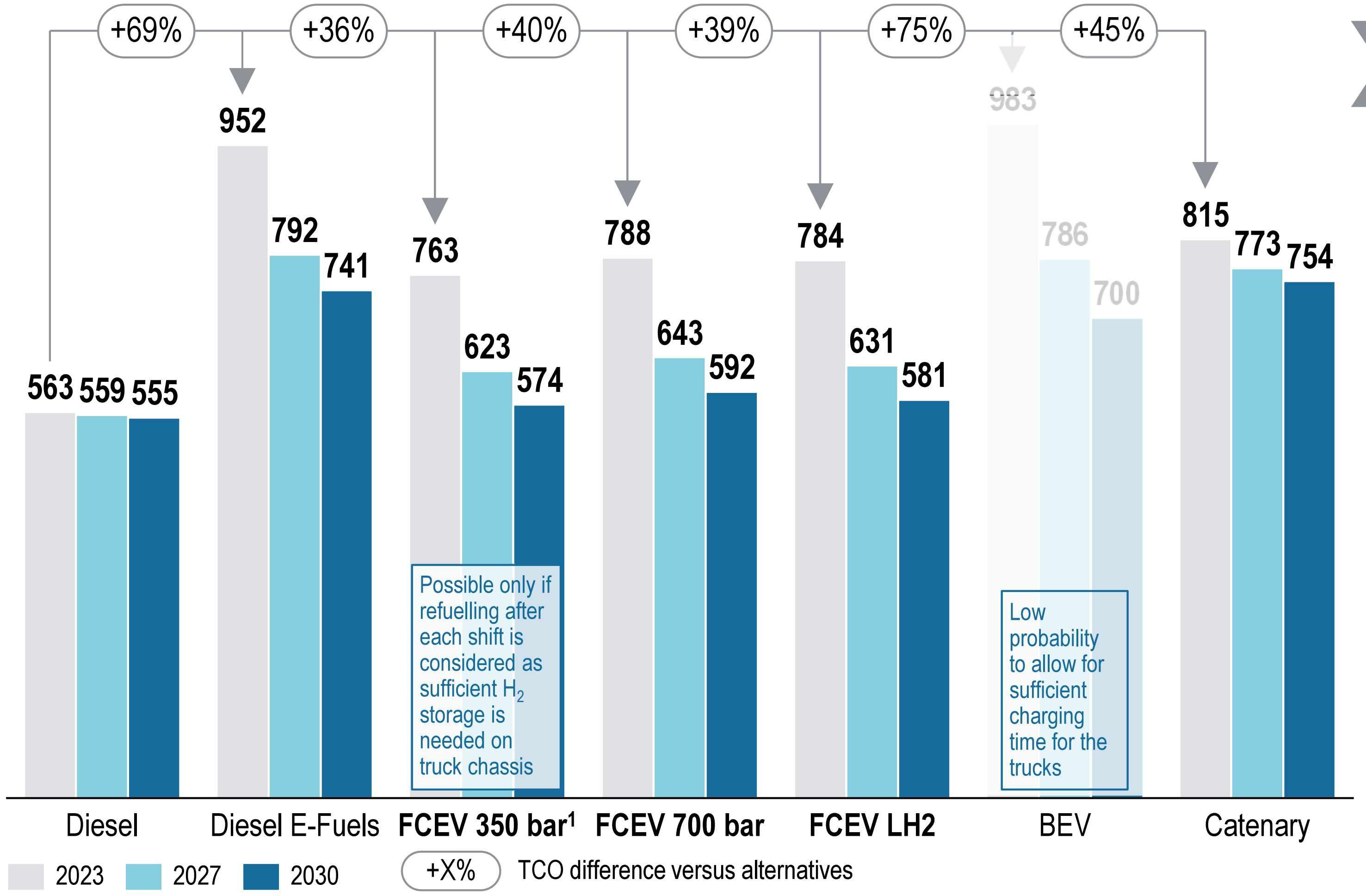
- A significant **cost down potential** for FCEV **at scale** exists **looking at 1st life**
- FCH trucks still have a **cost premium of up to ~39% in 2023** compared to diesel
- **FCH technologies** are the **most competitive zero-emission tech.** on a tonne-km basis
- **Payload reduction for BEV** due to large size of the battery needed on this route
- **BEV charging** would **not be possible** on shift-operation schedule

[1] Under the assumption that sufficient hydrogen storage can be technically integrated in the current truck chassis architecture; Potential length regulation adjustments required

Source: Dachser; Roland Berger

Also on a EUR/truck basis, the analysis shows the lowest TCO for diesel trucks – FCH technology increasingly cost-competitive

Hof-Kladno case – High-level TCO assessment [kEUR/truck; 1st life]



Comments

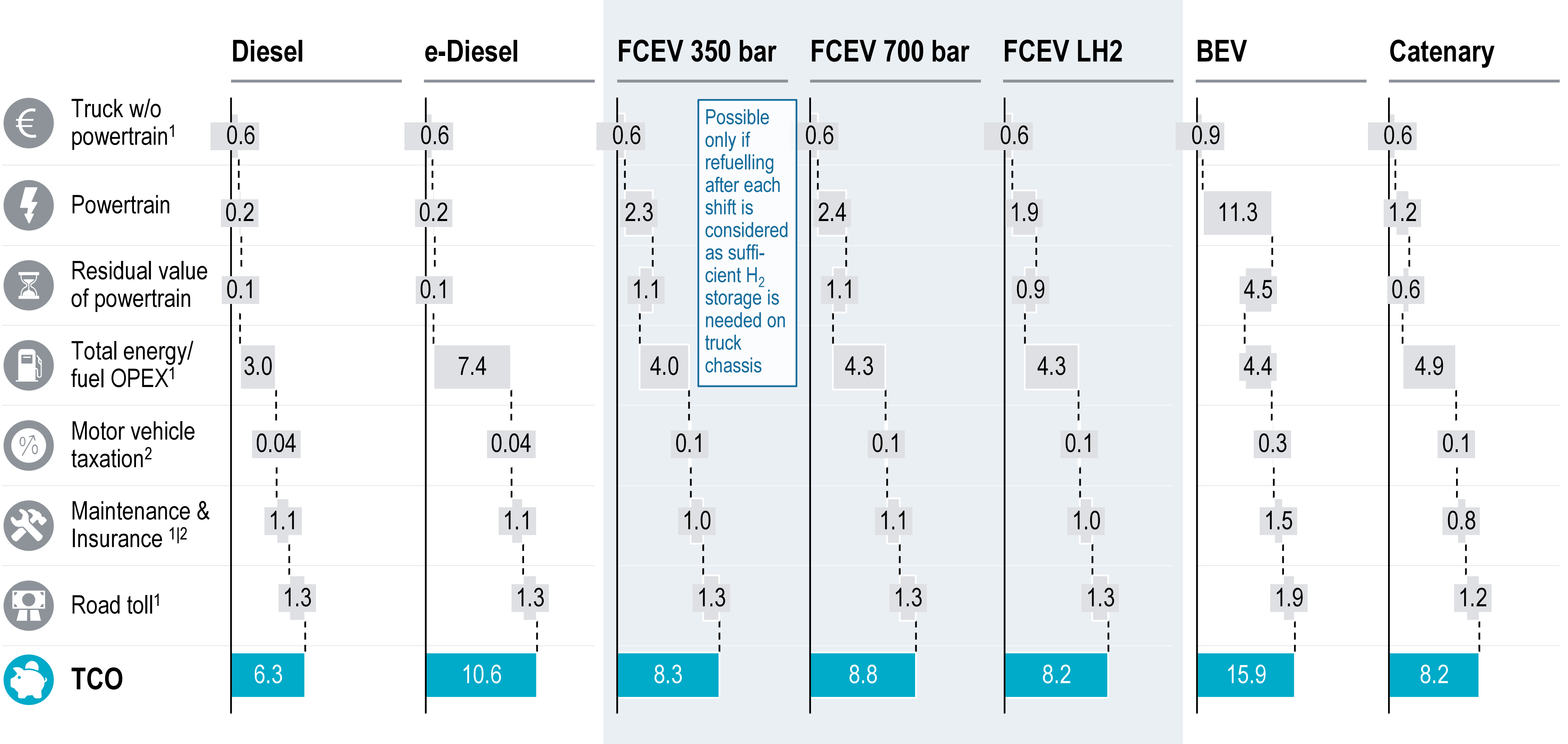
- Also when looking at the EUR/truck TCO, **the cost down potential** for FCEV technology **at scale** exists
- FCH trucks have a **cost premium of up to ~40% in 2023**
- **Diesel is the cheapest technology option** still in 2030 on a EUR/truck basis, but FCEV approach a comparable cost level
- TCO of **zero-emission technologies rely** on assumptions **on second life market**

1) Under the assumption that sufficient hydrogen storage can be technically integrated in the current truck chassis architecture; Potential length regulation adjustments required

Source: Dachser; Roland Berger

Residual value and energy and fuel costs are uncertain cost drivers - Battery replacement expected for BEV in 1st life due to high mileage

Hof-Kladno case – 2023 TCO cost breakdown [EUR ct/tonne-km; 1st life]



	Diesel	e-Diesel	FCEV 350 bar	FCEV 700 bar	FCEV LH2	BEV	Catenary
Truck w/o powertrain[1]	0.6	0.6	0.6	0.6	0.6	0.9	0.6
Powertrain	0.2	0.2	2.3	2.4	1.9	11.3	1.2
Residual value of powertrain	0.1	0.1	1.1	1.1	0.9	4.5	0.6
Total energy/ fuel OPEX[1]	3.0	7.4	4.0	4.3	4.3	4.4	4.9
Motor vehicle taxation[2]	0.04	0.04	0.1	0.1	0.1	0.3	0.1
Maintenance & Insurance [1|2]	1.1	1.1	1.0	1.1	1.0	1.5	0.8
Road toll[1]	1.3	1.3	1.3	1.3	1.3	1.9	1.2
TCO	6.3	10.6	8.3	8.8	8.2	15.9	8.2

Possible only if refuelling after each shift is considered as sufficient H_2 storage is needed on truck chassis

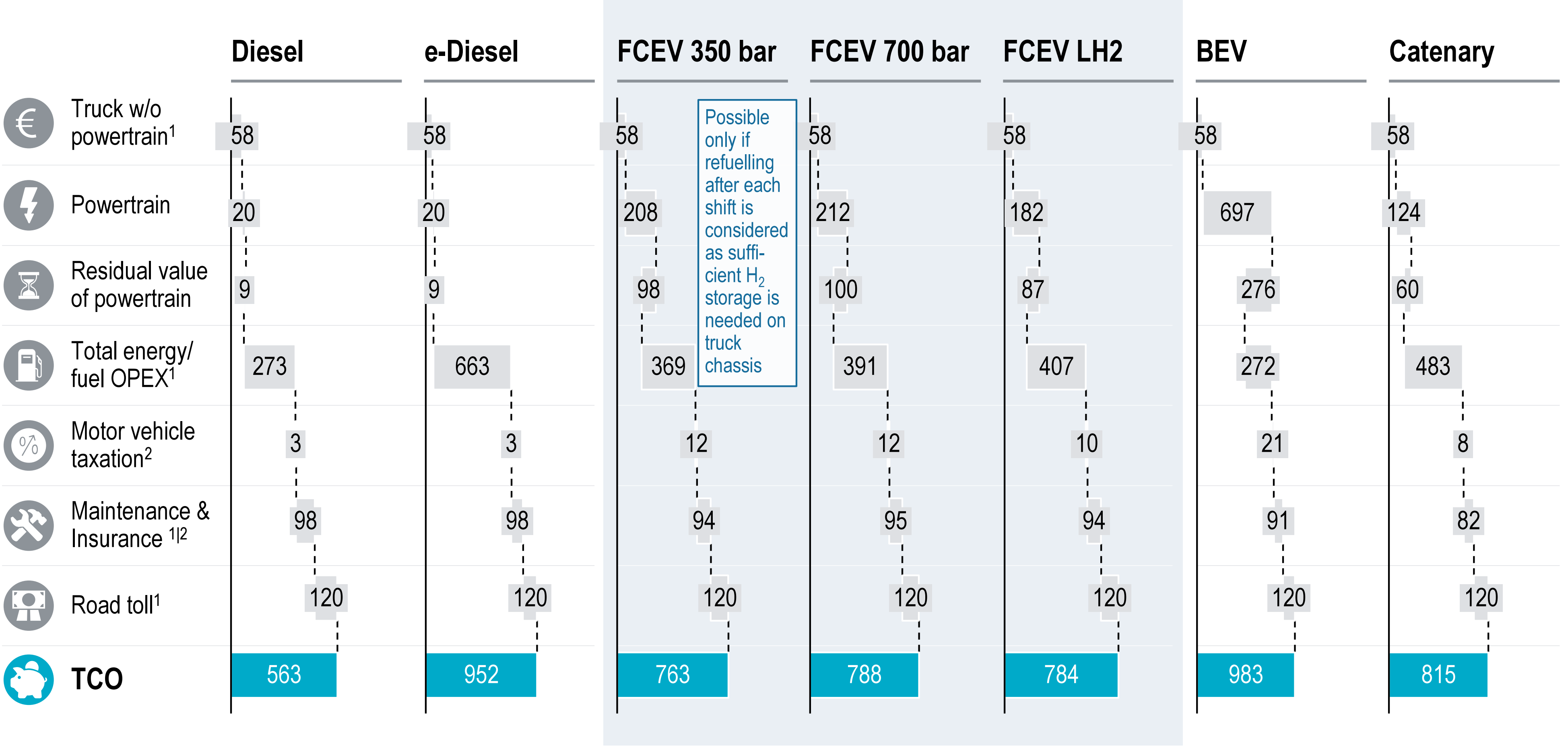
1) Deviations of results are related to payload differences of different technologies 2) Deviations of results are related to calculation based on higher CAPEX

Note: Battery replacement needed already in first life due to high mileage; Battery charging during the day is not possible as the truck is in a 2-shift operation

Source: Dachser; Roland Berger

The very high residual value of zero-emission vehicles are a disadvantage vs. diesel as the second life market is still uncertain

Hof-Kladno case – 2023 TCO cost breakdown [kEUR/truck; 1st life]



	Diesel	e-Diesel	FCEV 350 bar	FCEV 700 bar	FCEV LH2	BEV	Catenary
Truck w/o powertrain[1]	58	58	58	58	58	58	58
Powertrain	20	20	208	212	182	697	124
Residual value of powertrain	9	9	98	100	87	276	60
Total energy/ fuel OPEX[1]	273	663	369	391	407	272	483
Motor vehicle taxation[2]	3	3	12	12	10	21	8
Maintenance & Insurance [1][2]	98	98	94	95	94	91	82
Road toll[1]	120	120	120	120	120	120	120
TCO	563	952	763	788	784	983	815

Possible only if refuelling after each shift is considered as suffi-cient H_2 storage is needed on truck chassis

1) Deviations of results are related to payload differences of different technologies 2) Deviations of results are related to calculation based on higher CAPEX

Note: Battery replacement needed already in first life due to high mileage; Battery charging during the day is not possible as the truck is in a 2-shift operation

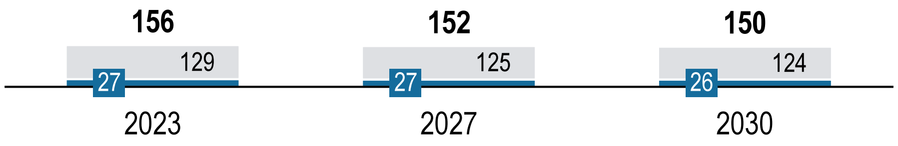
Source: Dachser; Roland Berger

Zero-emission vehicles will allow for significant emission savings on this route – Conversion of fleet would offer even higher potential

Hof-Kladno case – Environmental analysis

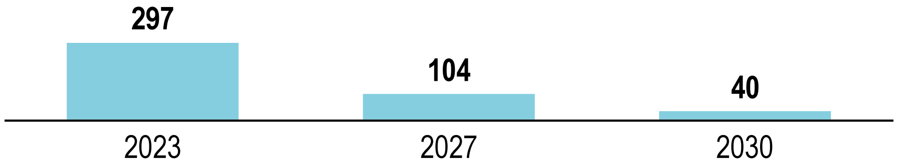
CO_2 savings potential[1]

Well to Wheel [tonnes CO_2e/year]



Estimated CO_2 price for FCEV cost parity

[EUR/tonnes CO_2e]



Pollution reduction potential[2]

- Conversion to zero-emission trucks allows for a total reduction of NOx pollutants
- Particulate matter can also be reduced due to more efficient driving patterns, incl. regenerative braking for electric vehicles

▨ Tank to Wheel ■ Well to Tank ▧ Est. CO2 price

Emissions reductions

- Total global greenhouse gas emissions reduction to be realized over five years with five trucks:

  7,521 tonnes CO_2e
- Potential for reduction of other pollutants equally targeted with zero-emission vehicles

Opportunities

- Potential conversion of higher number of trucks at the same depot would increase the emission savings
- Operation in cross-border transport could be set up as a 'flagship initiative' and lead to higher visibility of zero-emission trucks in two countries
- Access to nearby renewable wind energy at the depot offers potential for green hydrogen production

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1) CO_2 savings potential refers to one potential zero-emission vehicles for the specific route; Please refer to the Annex for the assumptions on the CO_2e calculation
2) Pollution reduction potential not quantified as specific limits are set for each heavy duty diesel engine on the vehicle test stand

Source: Dachser; Roland Berger

The Hof-Kladno case shows that current diesel utilisation patterns often impede the cost-competitiveness of zero-emission vehicles

Hof-Kladno case – Enablers and constraints for FCH technology

Potential enablers and constraints

!

- High plannability of line haulage and back-to-base distribution route offers good conditions for FCH technology uptake
- Opportunities for H_2 infrastructure (proximity to wind parks in Saxony and existing H_2 production in Saxony-Anhalt) has leverage to potentially replace a higher number of vehicles to FCH technology

?

- The TCO of alternative vehicles are influenced highly by the assumed residual value of the powertrain – as the second market is still uncertain, this could be a clear cost barrier
- A minimum utilisation (at least 10 trucks) for both private and public HRS installation would be advisable to be cost-effective, collaboration with ext. partners would need to be investigated
- Due to the maturity status of the different H_2 storage technologies, the TCO result is based on the assumption that sufficient hydrogen storage can be technically integrated in the truck chassis architecture. Potential length regulation adjustments could be required.

Synthesis[1]

- The case study offers a **fixed route operated on a regular schedule** – generally **good conditions** for setting up **hydrogen infrastructure**
- Due to the **combination of very high annual mileage, higher CAPEX[2]** with an **uncertain residual value** for zero-emission vehicles and **much lower OPEX costs for diesel**, FCH technology **not yet cost-competitive**
- If **OPEX costs and uncertainty over residual value** can be **reduced**, **FCH technology** could become **cost-competitive**
- **If utilisation patterns** are **optimised** for zero-emission vehicles (e.g. intra-day refuelling between shifts), **FCH technology could become a good fit** on this route – **BEV not possible** because the **operation would not allow for sufficient** charging time
- **Conversion of more trucks** to FCH technology stationed at the depot would offer **further potential for installation of refuelling infrastructure**

[1] This evaluation is based on the TCO calculated on the basis of the assumptions developed in the study; For these assumptions, please refer to the Annex of the study

[2] As the model assumes that the daily range needs to be achieved without intermediate refuelling or charging, a larger powertrain is assumed for the zero-emission vehicles

Source: Dachser; Roland Berger

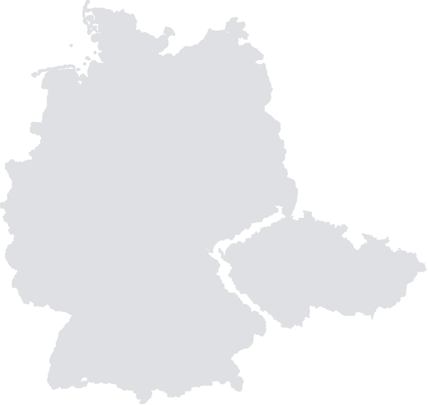
The case study on the cross-border route Hof (DE) – Kladno (CZ) was supported by specific information and data from Dachser

Hof-Kladno case – Background

Road freight sector in Germany & Czech Republic

Information on the road freight sector

- Germany is one of the top origin/destination countries for intra-EU trade flows
- Due to its central position within Europe, Germany is a transit country for (road) transport
- The highest country-to-country flow of goods from the Czech Republic goes to its main trading partner Germany



Main transport corridors

- Germany and the Czech Republic are connected by several cross-border highways
- Both countries are part of the Orient/East-Med Corridor of the TEN-T road network

Information on company supporting the case

Company information	DACHSER Intelligent Logistics
Name	DACHSER
Industry	Freight and logistics service company
Headquarters	Kempten, DE
Zero-emission ambition	Climate protection strategy with support on research and innovation into alternative drive systems and fuels for road freight transport
Depot linked to route	
Location	Hof, Germany
Description	Regional branch
Total number of trucks[1]	187

[1] Operated by subcontractors stationed at depot in Hof

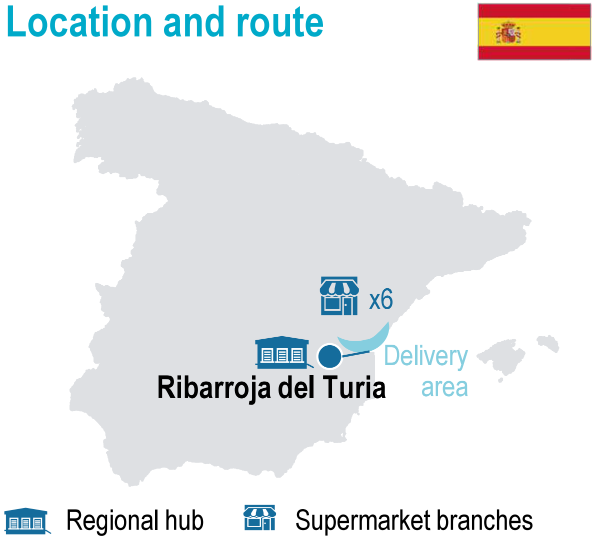
Source: Dachser; Statista; Destatis; Roland Berger

D.3.5 Valencia region case [DISFRIMUR]

The frequently driven delivery routes to various destinations in the Valencia area shows a good commercial potential for FCH trucks

Valencia region case – Overview

Location and route



- > The regional distribution operation links the local hub in Ribarroja with multiple supermarket branches in the Valencia region
- > The route is set on flat terrain with hot weather conditions in summer
- > It is driven on a well-developed network of regional motorways and includes inner-city deliveries

Setting – Truck and operations

Truck type	Rigid 6x2, 26 tonnes Truck with refrigeration equip.
Daily range	~300 km (on average)
Operation	298 days/year
Fleet size	4
Payload	11.3 tonnes

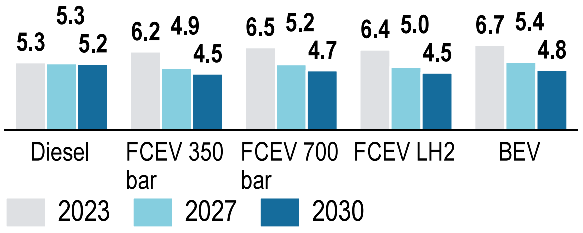
Logistic operation

Trucks linked to this case study run in a three-shift operation with different drivers to deliver food to several supermarket branches in the Valencia area. The individual routes of the trucks vary regarding daily range and annual mileage.
One refuelling stop is included per day

Infrastructure

- > Three-shift operation requires relatively fast refuelling processes for the fleet
- > Hydrogen refuelling infrastructure for trucks would need to be installed (private or public); private HRS would be carried out first at main company depot in Murcia (distance of ~200 km)

TCO analysis [EUR ct/tonne-km; 1st life]

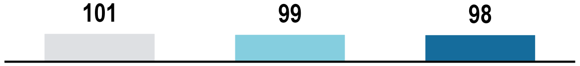


FCH and BEV technology both seem to present good zero-emission options. However, FCH tech. is more favourable as TCO for BEV depends strongly on the residual value (replaced battery)

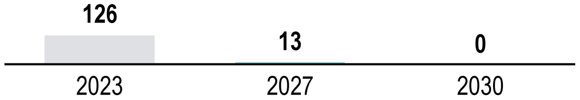
Environmental analysis

Zero-emission trucks offer significant annual CO_2 savings. The est. CO_2 price, as the price to be put on CO_2 to reach cost parity compared to diesel, demonstrates the FCEV cost premium

Yearly truck CO_2 savings potential – WTW [tCO_2e]



Est. CO_2 price for FCEV cost parity [EUR/tCO_2e]



Source: DISFRIMUR; Roland Berger

In the Valencia delivery area, various supermarkets are serviced in a three-shifts-per-day operation by refrigerated trucks

Valencia region case – Description

Investigated route

Existing HRS[2] (cars) Main depot Supermarkets

Potential HRS[2] (trucks) Potential H_2 production

- > The regional distribution operation links the local hub in Ribarroja with multiple supermarket branches in the area
- > Some trucks circulate back and forth the same supermarket location during all shifts while others cover more that one supermarket branch
- > The route is set on flat terrain with hot weather conditions in summer
- > No road toll needs to be paid on this route

Case description[1]

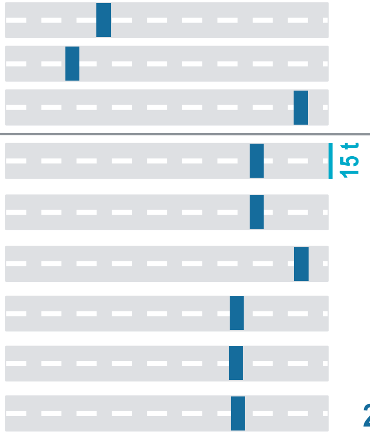
Truck type Rigid 6x2, 26 tonnes

Truck with refrigeration equipment

Logistic operation

The trucks run in a three shift operation with different drivers to deliver food to several supermarket branches in the Valencia area (in total, three go-and-return operations for each truck). The individual routes vary on daily range and annual mileage. One refuelling stop per day is included for the vehicle. The refrigerated equipment of the truck is operated by an additional engine fuelled by off-road diesel.

The trucks are owned and operated by the logistics company; for each route, the best suited truck is chosen in agreement with the customer.



Route	**Route length**	30-85 km
	Fleet size	4
	Operation	298 days
Truck performance	**Payload**	11.3 tonnes
	Avg. load. factor (weight)	75%
	Maximum speed	90 km/h
	Daily range (average)	~300 km
	Annual mileage (average)	~89,400 km
	H_2 consumption	22 kg(H_2)/day

Legend Low High

Infrastructure[3]

- > Each truck operates on avg. 300 km per day – this would be an avg. consumption of ~22 kg(H_2)/day (at 0.074 kg(H_2)/km) and a H_2 demand of ~90 kg(H_2)/day for the whole fleet

Potential truck HRS

- > Min. demand of 0.5 t(H2)/ day for HRS is recommended in order to be cost-attractive (private/public)
- > Inclusion of further routes or applications needed

Potential H_2 prod. facility

- > Hydrogen supply from electrolysis installation of at least 0.2 MW needed

Potential synergies

- > More trucks linked to depot could be replaced by FCEV
- > Supply chain for green hydrogen from Spain already in planning

---

1) Data verified with stakeholders

2) HRS = hydrogen refuelling station

3) The consumption of H_2 was increased by 0.003 kg(H_2)/km to reflect the increased need of energy for the additional refrigeration equipment (Garde et al. 2012)

Source: DISFRIMUR; World Hydrogen Energy Conference 2012; Roland Berger

Specific data is introduced in the total cost of ownership model to reflect the real-life operations of the case study

Valencia region case – Specific assumptions

Main input changes on the TCO model base assumptions

Operation	> Annual mileage set at 90,000 km/year > Operation on route set for 289 days/year > Max. payload set to 15 tonnes > Route profile set to a homogenous pattern due to the plannability of the routes
Maintenance costs	> Maintenance cost set at 0.06 EUR/km for diesel trucks and adapted for other technologies to reflect the cost relation
Private / public refuelling	> Currently private refuelling used for diesel trucks > Public refuelling assumed for alternative powertrain technologies
Energy and fuel[1]	> Diesel price set at 1.102 EUR/l net price in 2023 for private refuelling (surcharges for public refuelling not considered) > AdBlue cost set at 0.26 EUR/l > In order to approximate the costs of the two diesel sources used for the truck and refrigeration equipment[1], a 6% consumption increase is assumed using the cost for automotive diesel as the baseline; principle of a consumption increase is also applied for BEV and catenary (4.5% due to the electric powertrain)
Fuel cell and H_2 technology	> Additional 2 kW of fuel cell size are assumed for higher energy needs > Consumption of H_2 was increased by 0.003 kg(H_2)/km to reflect the increased need of energy for the additional refrigeration equipment (Garde et al. 2012)
Road toll	> No road toll charges introduced

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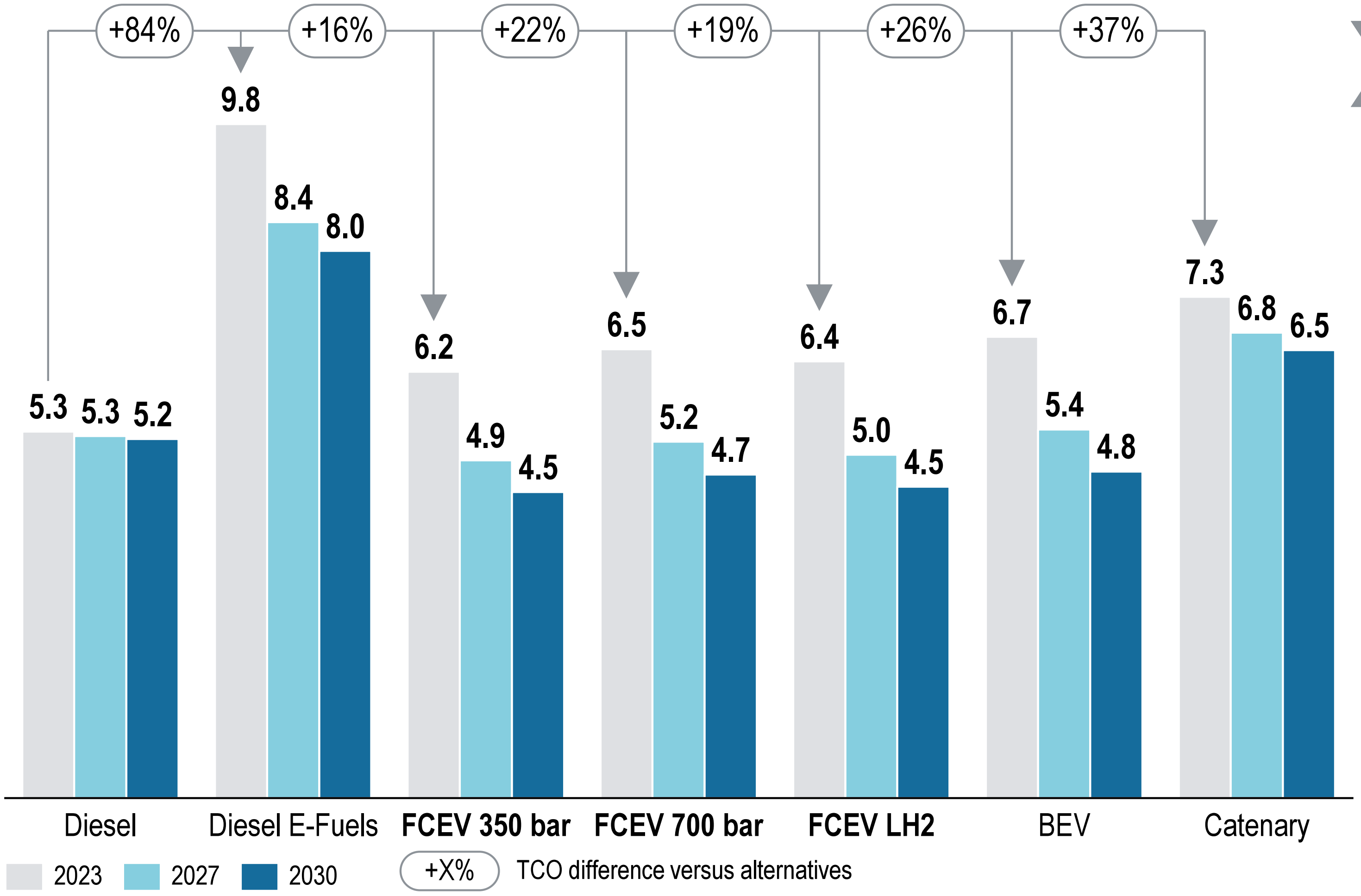
1) In Spain, the refrigeration equipment is run by an additional engine fuelled by off-road diesel, not regular automotive diesel; The additional cost for off-road diesel (Gasóleo B) is set at 0.5438 EUR/l (approx. 50% of aut. diesel) – Overall, the increased diesel consumption was found to be +12% compared to a truck without the refrigerated equipment (Garde et al. 2012)

Source: DISFRIMUR; Garde et al. World Hydrogen Energy Conference 2012; Roland Berger

FCH technology with a clear cost-down potential and a potential TCO advantage over diesel already from 2027 onwards

Valencia region case – High-level TCO assessment [EUR ct/tonne-km; 1st and 2nd life]



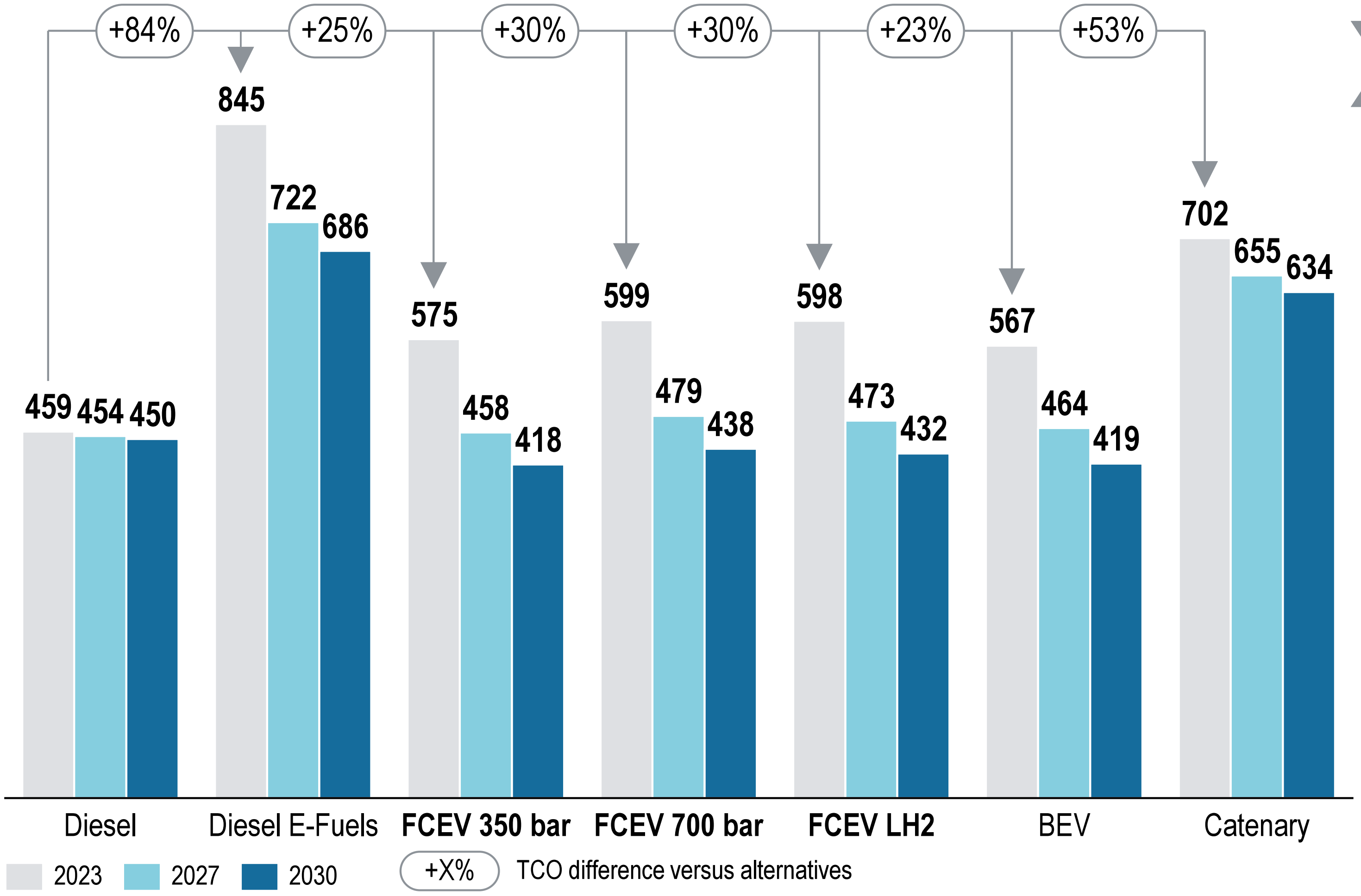
Comments

- A significant **cost down potential** for FCEV **at scale** exists **looking at 1st and 2nd life**
- FCH trucks have a **cost premium of up to ~22% in 2023** compared to diesel
- **FCH technologies** are the **most competitive zero-emission tech.** on a tonne-km basis
- **Payload reduction for BEV applies** as trucks would need a larger battery to operate on all routes with a max. of 440 km daily range

Source: DISFRIMUR; Roland Berger

On a EUR/truck basis, the analysis shows that both FCH and BEV technology could work well and are cost-competitive vs. diesel

Valencia region case – High-level TCO assessment [kEUR/truck; 1st and 2nd life]



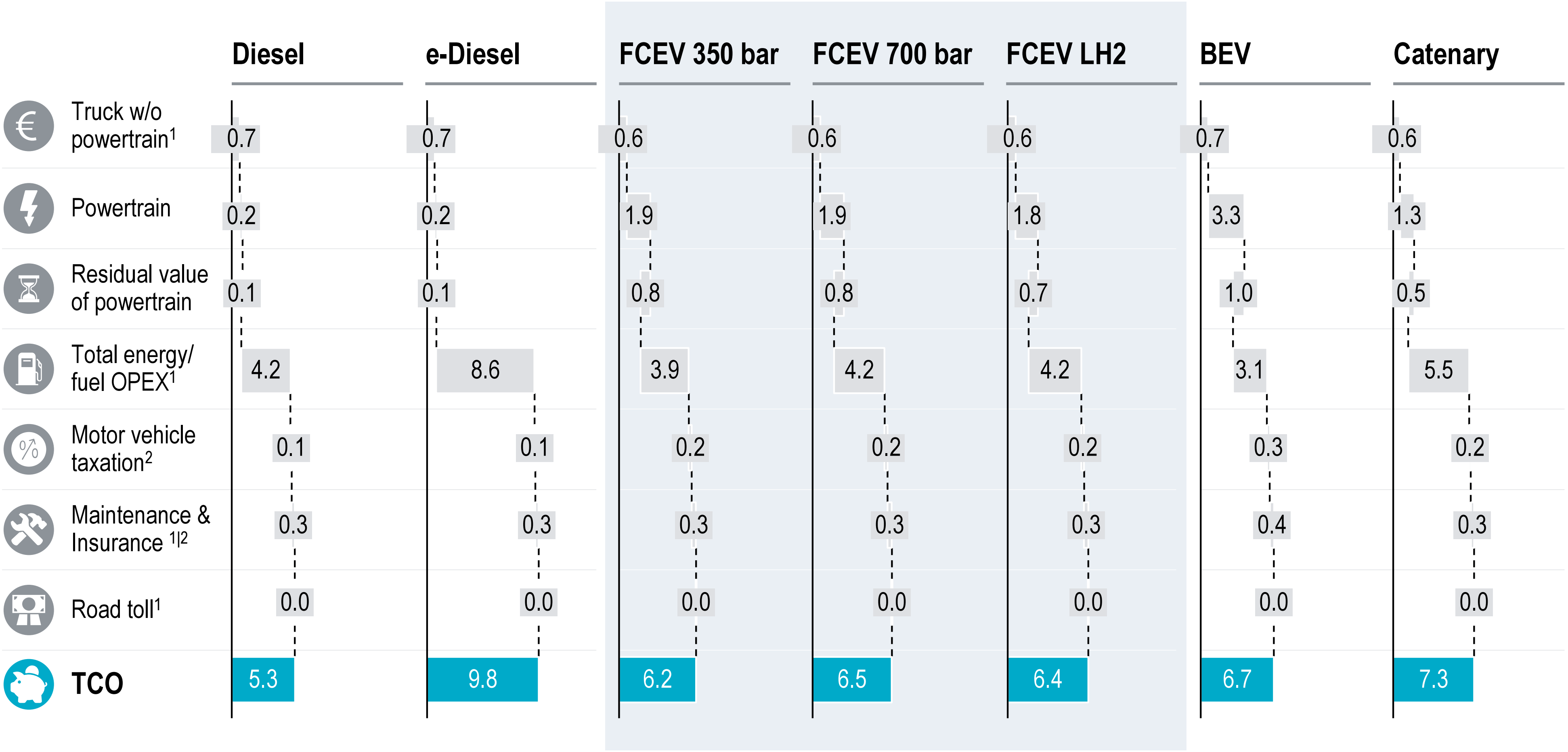
Comments

- > Also when looking at the EUR/truck TCO, **the cost down potential** for FCEV techn. **at scale** exists
- > FCH trucks have a **cost premium of up to ~30% in 2023**
- > **FCH and BEV technology are at the same cost level** on a EUR/truck basis, with **better TCO results than diesel in 2030**
- > **BEV would need a battery replacement in 2nd life** – TCO results depend strongly on assumed residual value

Source: DISFRIMUR; Roland Berger

Residual value and energy and fuel costs are uncertain cost drivers - Battery replacement expected for BEV in 1st life due to high mileage

Valencia region case – 2023 TCO cost breakdown [EUR ct/tonne-km; 1st and 2nd life]



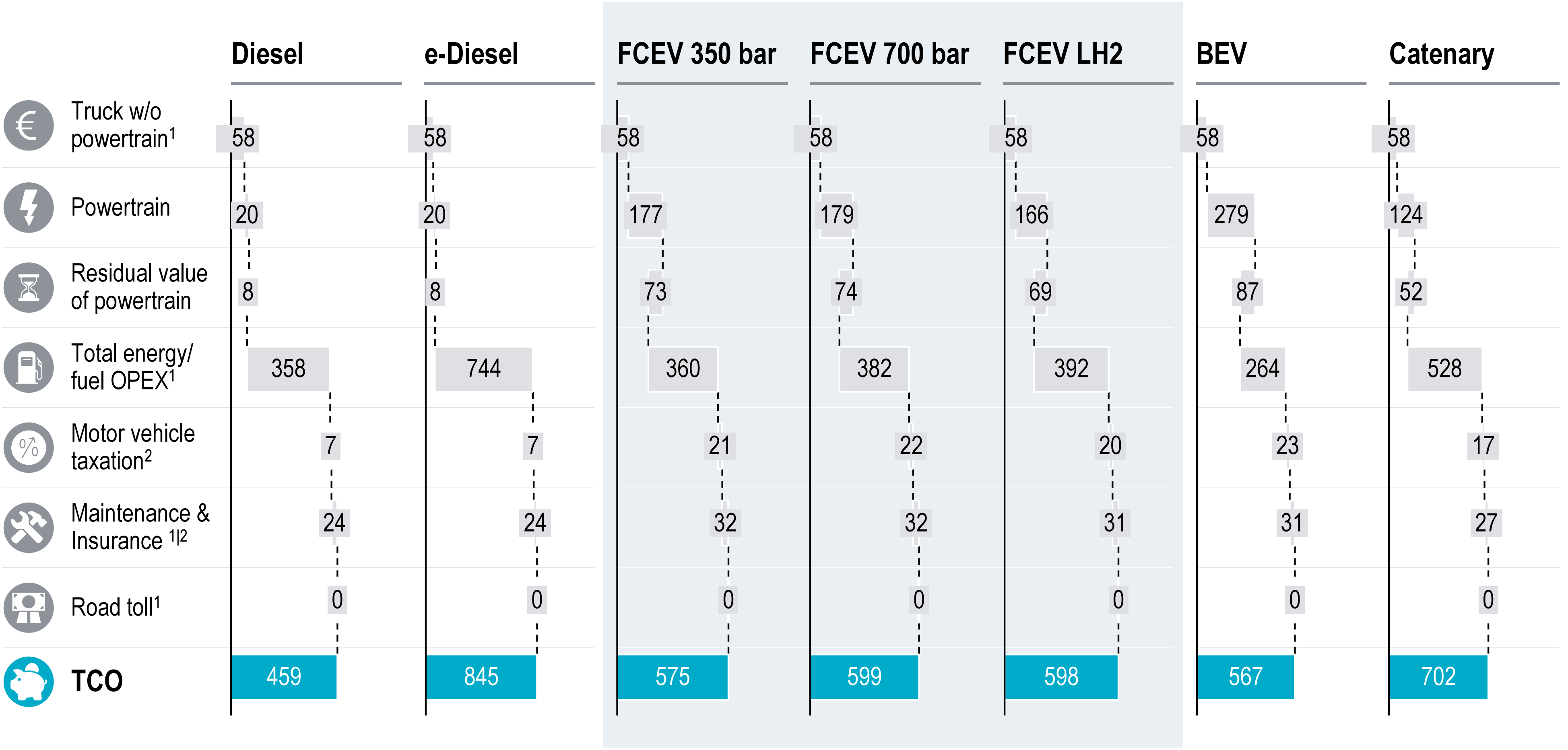
	Diesel	e-Diesel	FCEV 350 bar	FCEV 700 bar	FCEV LH2	BEV	Catenary
Truck w/o powertrain[1]	0.7	0.7	0.6	0.6	0.6	0.7	0.6
Powertrain	0.2	0.2	1.9	1.9	1.8	3.3	1.3
Residual value of powertrain	0.1	0.1	0.8	0.8	0.7	1.0	0.5
Total energy/ fuel OPEX[1]	4.2	8.6	3.9	4.2	4.2	3.1	5.5
Motor vehicle taxation[2]	0.1	0.1	0.2	0.2	0.2	0.3	0.2
Maintenance & Insurance [1|2]	0.3	0.3	0.3	0.3	0.3	0.4	0.3
Road toll[1]	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TCO	5.3	9.8	6.2	6.5	6.4	6.7	7.3

1) Deviations of results are related to payload differences of different technologies 2) Deviations of results are related to calculation based on higher CAPEX

Source: DISFRIMUR; Roland Berger

Residual value and energy and fuel costs are uncertain cost drivers - Battery replacement expected for BEV in 1st life due to high mileage

Valencia region case – 2023 TCO cost breakdown [EUR/truck; 1st and 2nd life]



	Diesel	e-Diesel	FCEV 350 bar	FCEV 700 bar	FCEV LH2	BEV	Catenary
Truck w/o powertrain[1]	58	58	58	58	58	58	58
Powertrain	20	20	177	179	166	279	124
Residual value of powertrain	8	8	73	74	69	87	52
Total energy/ fuel OPEX[1]	358	744	360	382	392	264	528
Motor vehicle taxation[2]	7	7	21	22	20	23	17
Maintenance & Insurance [1|2]	24	24	32	32	31	31	27
Road toll[1]	0	0	0	0	0	0	0
TCO	459	845	575	599	598	567	702

1) Deviations of results are related to payload differences of different technologies 2) Deviations of results are related to calculation based on higher CAPEX

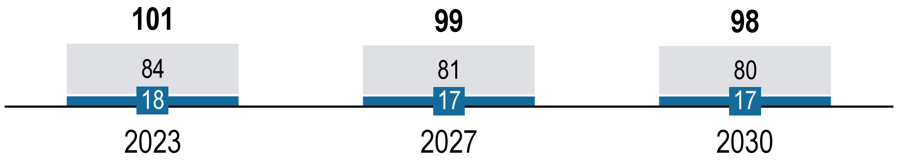
Source: DISFRIMUR; Roland Berger

Zero-emission vehicles will allow for significant emission savings on this route – Conversion of fleet would offer even higher potential

Valencia region case – Environmental analysis

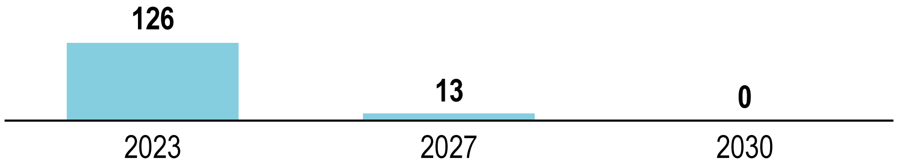
CO_2 savings potential[1]

Well to Wheel [tonnes CO_2e/year]



Estimated CO_2 price for FCEV cost parity

[EUR/tonnes CO_2e]



Pollution reduction potential[2]

- Conversion to zero-emission trucks allows for a total reduction of NOx pollutants
- Particulate matter can also be reduced due to more efficient driving patterns, incl. regenerative braking for electric vehicles

▨ Tank to Wheel ■ Well to Tank ■ Est. CO2 price

Emissions reductions

- Total greenhouse gas emissions reduction to be realised over ten years with four trucks: **3,907 tonnes CO_2e**
- Potential for reduction of other pollutants equally targeted with zero-emission vehicles

Opportunities

- Realising the envisaged change towards a lower carbon emission fleet with FCH trucks (or other zero-emission technologies) would increase the emission savings if done for all trucks at the depots
- Company plan to gradually build infrastructure and introduce trucks starting with one area can leverage collaboration with other players, such as customers (test cycles to gain confidence in technology)
- Pathway for green H_2 supply with Spanish electric utility company offers opportunities for the whole market

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1) CO_2 savings potential refers to one potential zero-emission vehicles for the specific route

2) Pollution reduction potential not quantified as specific limits are set for each heavy duty diesel engine on the vehicle test stand

Source: DISFRIMUR; Roland Berger

The Valencia case shows that regional delivery with FCEV could become a cost-attractive option to be replicated country-wide

Valencia region case – Enablers and constraints for FCH technology

Potential enablers and constraints

!

- High plannability of back-to-base delivery route offers good conditions for FCH technology uptake – refuelling during the day could even be an option as returns to the main depot are included in the route schedule
- Opportunities for H_2 infrastructure are being built up in Spain
- Company interest to potentially consider private infrastructure

?

- As the second market is still uncertain, the residual value could become a cost barrier to achieve the assumed TCO results
- A minimum utilisation (at least 10 trucks) for both private and public HRS installation would be advisable to be cost-effective, collaboration with local partners would need to be investigated
- Long-term security of investments depends on continued relationship with the main customer

Synthesis

- **FCH technology well suited** to offer zero-emission technology **for different mileages of delivery route** and **refrigerated equipment** with **higher energy need**
- Battery electric technology offers good TCO results, yet the predicted **payload reduction for BEV would potentially restrict operations** as trucks need to flexibly operate on other routes as well
- Due to the **fixed schedule and plannable operations** as well as the company **interest,** the Valencia case provides **good conditions** for setting up the necessary (private) **hydrogen infrastructure – minimum utilisation would need to be ensured**
- **Mid-term synergies** with **trucks from depots in proximity** could be leveraged as **infrastructure would first be placed strategically** to enable access for most trucks possible
- A cost barrier could lie in high **OPEX costs and uncertain residual value of FCH equipment** which could **decrease cost-competitivity**

Source: DISFRIMUR; Roland Berger

The case study on the routes in the Valencia area was supported by specific information and data from DISFRIMUR

Valencia region case – Background

Road freight sector in Spain

Information on the road freight sector

- Spain sees the third highest volume of road transport in Europe with approx. 1.5 m tonnes of goods transported in 2018
- The highest country-to-country flows of goods from Spain go to the neighbouring countries France and Portugal
- Overall, the road freight industry revenue for transport by road in Spain is EUR 33 bn (2018)
- The Spanish road freight sector is rather fragmented with >100,000 companies with 5 trucks on average

Main transport corridors

- The main Spanish transport corridors cross the country from North-East to South-West, connecting the important hubs (e.g. capital, Mediterranean coast) to Central Europe

Information on company supporting the case

Company information	GRUPO DISFRIMUR
Name	DISFRIMUR
Industry	Logistics service company
Headquarters	Murcia, Spain
Zero-emission ambition	Company objective to achieve a carbon footprint reduction with alternative powertrain technologies
Depot linked to route	
Location	Ribarroja del Turia
Description	Local hub
Total number of trucks[1]	25

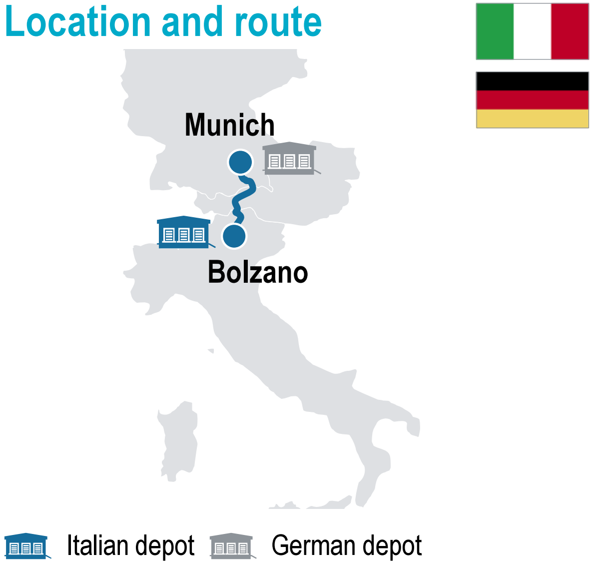
Source: DISFRIMUR; Statista; European Commission; Roland Berger

D.3.6 Bolzano-Munich case [FERCAM]

The cross-border route between Northern Italy and Southern Germany indicates potential for FCH technology at scale

Bolzano-Munich case – Overview

Location and route



- > The route connects the main depot in Bolzano, Italy, with the depot in Munich, Germany and crosses Italy, Austria and Germany
- > The operation is set on mountainous, trans-alpine terrain on the Brenner route, an important freight transport corridor in Europe
- > Road conditions can be affected by snow and ice during winter months

Setting – Truck and operations

Truck type	Rigid 6x2, 26 tonnes Swap body truck
Daily range[1]	582 + 175 km
Operation	240 days/year
Fleet size	10
Payload	12.8 tonnes

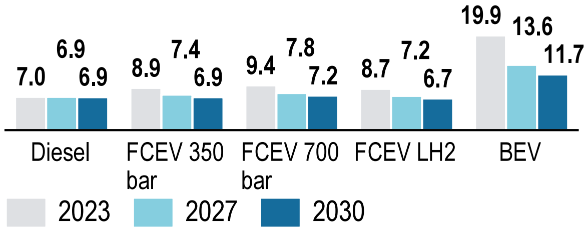
Logistic operation

The cross-country, go-and-return route is driven at night in a one-shift operation from Bolzano, Italy to Munich, Germany. The operation transports groupage goods that are then further distributed at the end point of the route. During the day, the trucks carry out local distribution operations around the depot in Bolzano.

Infrastructure

- > Existing HRS (700 bar) with green hydro-power electrolysis for passenger cars and buses in close proximity to the main depot in Bolzano
- > Access and supply for additional trucks at this HRS would need to be ensured

TCO analysis [EUR ct/tonne-km; 1st life]

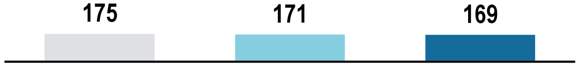


The TCO results at scale indicate that FCH tech. is the most competitive zero-emission technology at scale. However, FCH trucks are not yet cost-competitive with diesel until 2030.

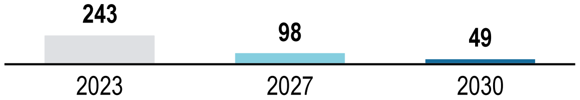
Environmental analysis

Zero-emission trucks offer significant annual CO_2 savings. The est. CO_2 price, as the price to be put on CO_2 to reach cost parity compared to diesel, demonstrates the FCEV cost premium

Yearly truck CO_2 savings potential – WTW [tCO_2e]



Est. CO_2 price for FCEV cost parity [EUR/tCO_2e]



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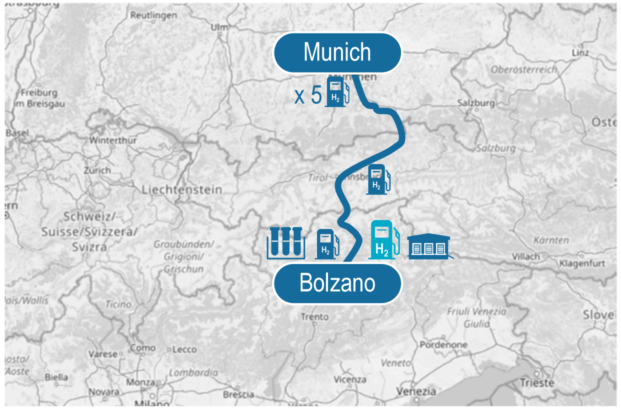
1) The operation includes a fixed route during the night (round trip 582 km) and the deployment of the trucks during the day in regional distribution (150-200 km)
2) HRS = hydrogen refuelling station
Source: FERCAM; Roland Berger

The two-shift operational data on this route demonstrates the high mileage and durability that is often required from rigid trucks

Bolzano-Munich case – Description

Investigated route



Existing & planned HRS[2] for cars · Main depot · Existing H_2 production · Potential HRS[2] for trucks

- The route connects the main depot in Bolzano, Italy, with the depot in Munich, Germany and crosses Italy, Austria and Germany
- The operation is set on mountainous, trans-alpine terrain on the Brenner route, an important freight transport corridor in Europe
- Road conditions can be affected by snow and ice during winter months
- Road toll applies in all countries linked to the route

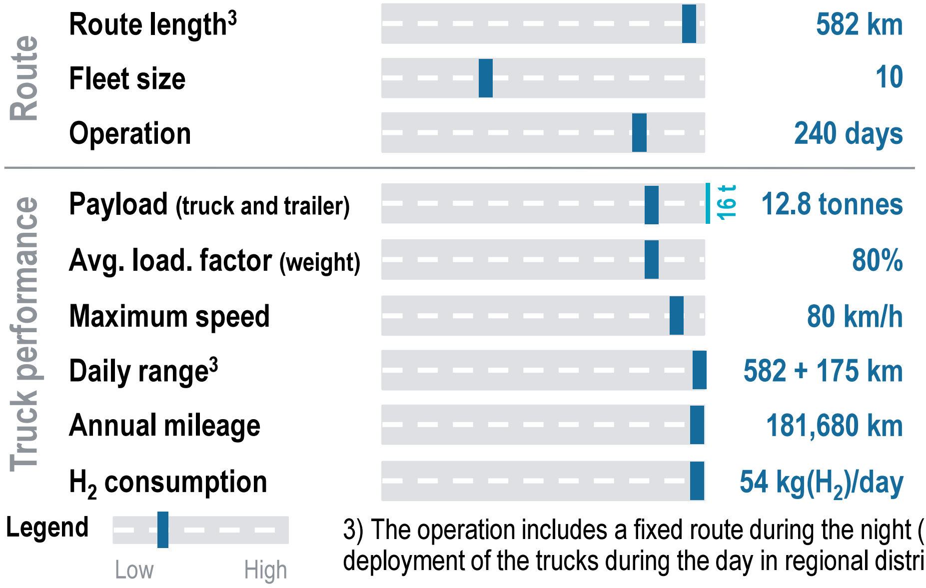
Case description[1]

Truck type Rigid 6x2, 26

Swap body truck

Logistic operation

The cross-country, go-and-return route is driven at night from Bolzano, Italy to Munich, Germany. The operation transports groupage goods that is then further distributed at the end point of the route. During the day in a second shift, the trucks carry out local distribution operations around the depot in Bolzano. The operation is volume restricted due to the varying weight of transported pallets.



Route	Route length[3]	582 km
	Fleet size	10
	Operation	240 days
Truck performance	Payload (truck and trailer)	12.8 tonnes
	Avg. load. factor (weight)	80%
	Maximum speed	80 km/h
	Daily range[3]	582 + 175 km
	Annual mileage	181,680 km
	H_2 consumption	54 kg(H_2)/day

Legend

Infrastructure[2]

- Each truck operates on avg. 757 km per day – this would be an avg. consumption of ~54 kg(H_2)/day (at 0.071 kg(H_2)/km) and a H_2 demand of ~537 kg(H_2)/day for the whole fleet

Potential truck HRS

- Use of public station in proximity to depot could be used together with cars and buses; on-site electrolysis would need to be increased for min. +0.5 t(H_2)/day

Potential H_2 prod. facility

- Hydrogen supply from electrolysis installation of at least 1 MW needed

Potential synergies

- More trucks linked to depot could be replaced by FCEV as rigid trucks are only 5% of vehicles on this route
- Link to regional H_2 activities

---

1) Data verified with stakeholders

2) HRS = hydrogen refuelling station

3) The operation includes a fixed route during the night (round trip 582 km) and the deployment of the trucks during the day in regional distribution (150-200 km)

Source: FERCAM; Roland Berger

Specific data is introduced in the total cost of ownership model to reflect the real-life operations of the case study

Bolzano-Munich case – Specific assumptions

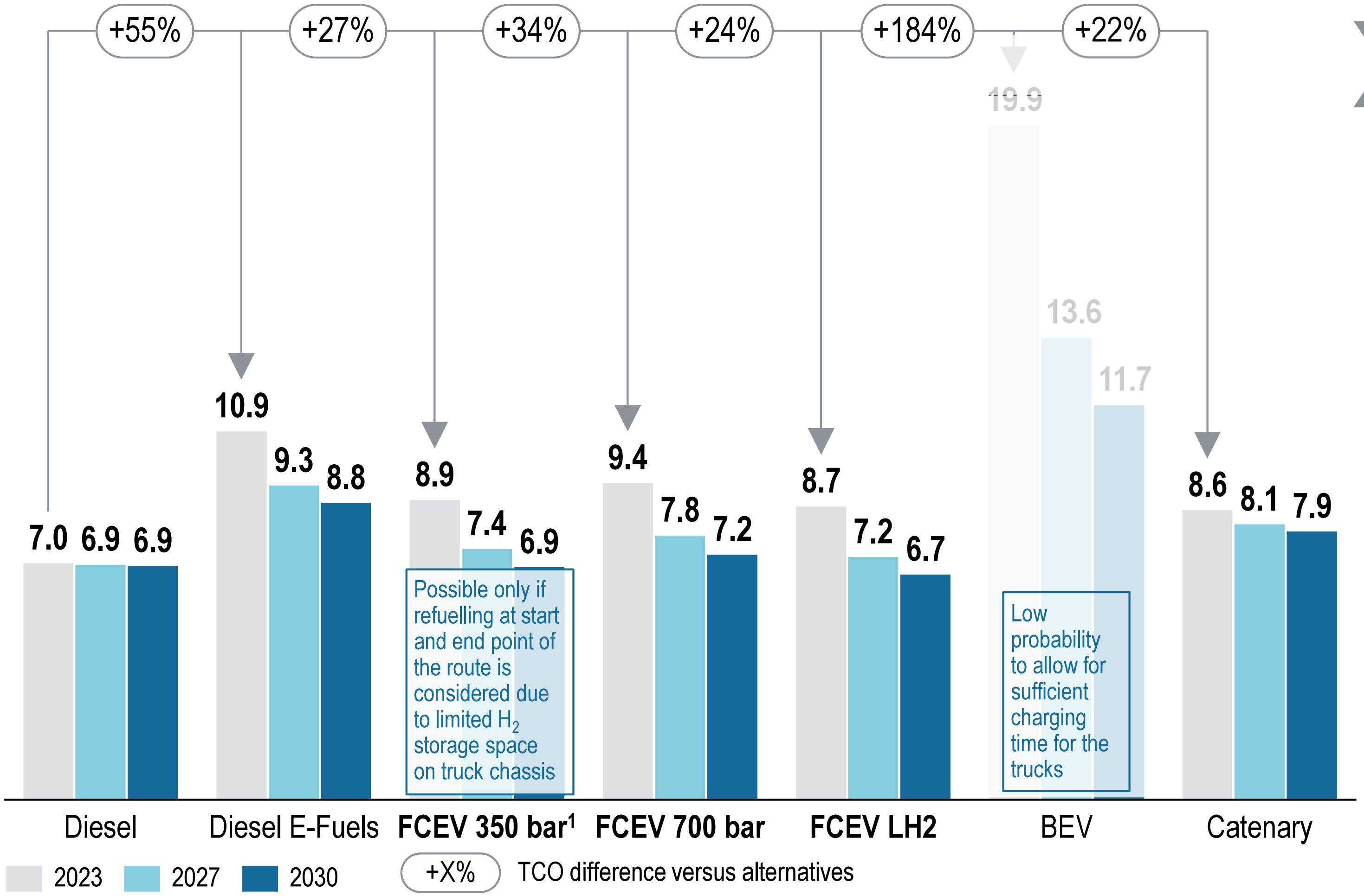
Main input changes on the TCO model base assumptions

Operation	> Only consideration of first life to very high annual mileage > Annual mileage set at 180,000 km/year > Operation on route set for 240 days/year > Max. payload set to 16 tonnes > Route profile set to a rather homogenous pattern due to plannability of fixed route by night and varying regional distribution by day
Motor vehicle tax	> Motor vehicle tax set at 0.78% of initial vehicle cost for 2023 and adjusted for 2027 and 2030 to reflect case specific data on the tax of 620 EUR/year
Maintenance costs	> Maintenance cost kept at 0.12 EUR/km for diesel trucks
Private / public refuelling	> Currently private refuelling used for Diesel trucks > Public refuelling assumed for alternative powertrain technologies
Energy and fuel	> Diesel price kept at base assumption for private refuelling (1.00 EUR/l net price in 2023; surcharges for public refuelling not consid.) > Consumption figures set to the average of the base assumptions for the 6x2 rigid and 4x2 tractor vehicles to reflect the high mileage
Road toll	> Road toll set to 0.33 EUR/km to reflect the average of the current costs of road toll in Italy, Austria and Germany

Source: FERCAM; Roland Berger

The TCO analysis shows that FCH technology becomes cost-competitive over time – However, high investment costs are required

Bolzano-Munich case – High-level TCO assessment [EUR ct/tonne-km; 1st life]



Possible only if refuelling at start and end point of the route is considered due to limited H_2 storage space on truck chassis

Low probability to allow for sufficient charging time for the trucks

Comments

> A **cost down potential** for FCEV **at scale** exists **looking at 1st life**, yet with a **cost premium of up to ~34% in 2023** compared to diesel

> **FCEV** are the **most competitive zero-emission technology at scale** on a tonne-km basis – However, the **cost proximity to catenary and diesel e-fuels** trucks illustrates that there is a **high investment** involved for the FCH powertrain

> **Payload reduction for BEV** applies due to the large size of the battery

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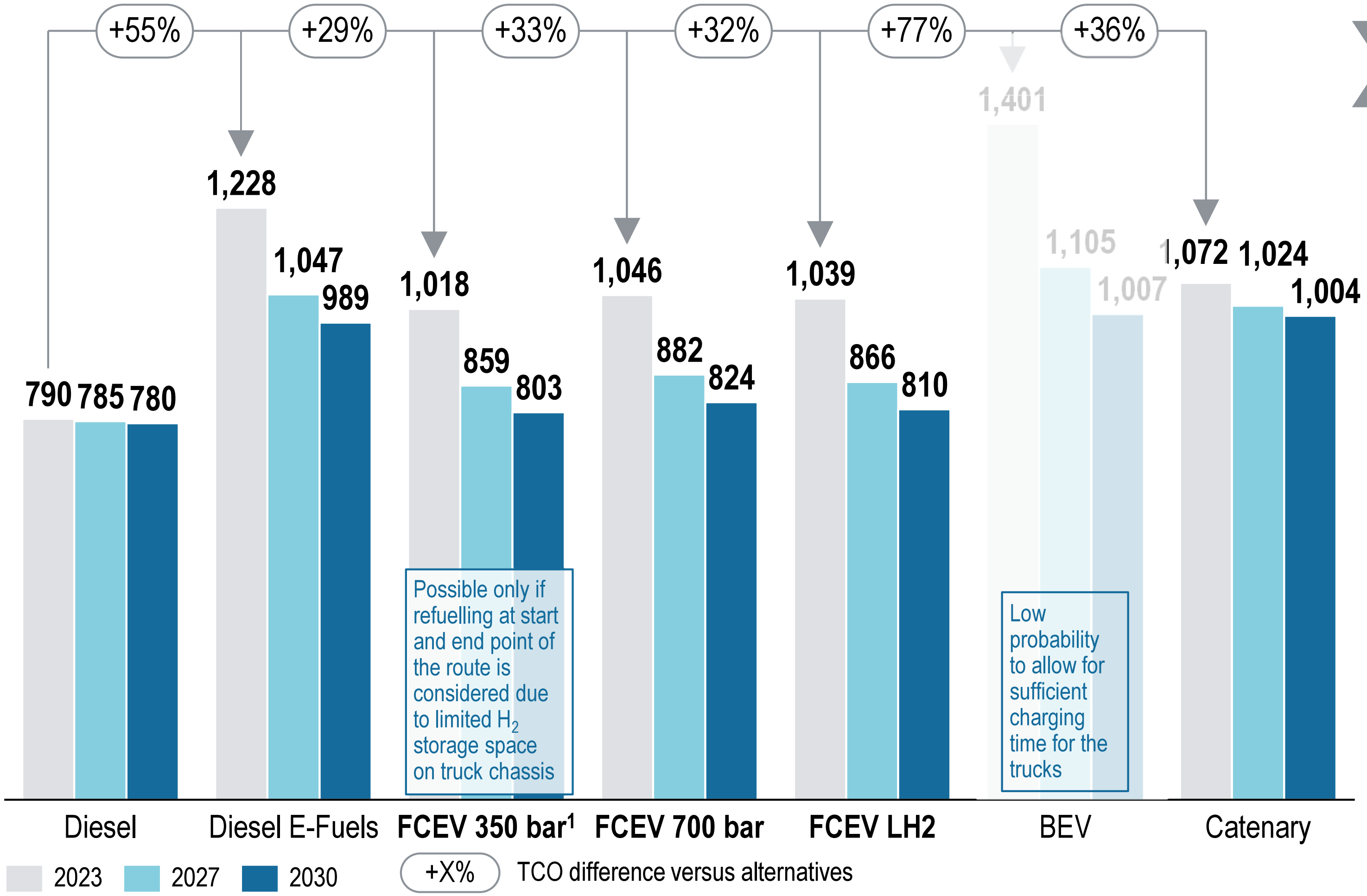
[1] Under the assumption that sufficient hydrogen storage can be technically integrated in the current truck chassis architecture; Potential length regulation adjustments required

Source: FERCAM; Roland Berger

The EUR/truck perspective shows the lowest TCO results of all zero-emission technologies for FCH technology – Diesel still cheaper

Bolzano-Munich case – High-level TCO assessment [kEUR/truck; 1st life]



Possible only if refuelling at start and end point of the route is considered due to limited H_2 storage space on truck chassis

Low probability to allow for sufficient charging time for the trucks

Comments

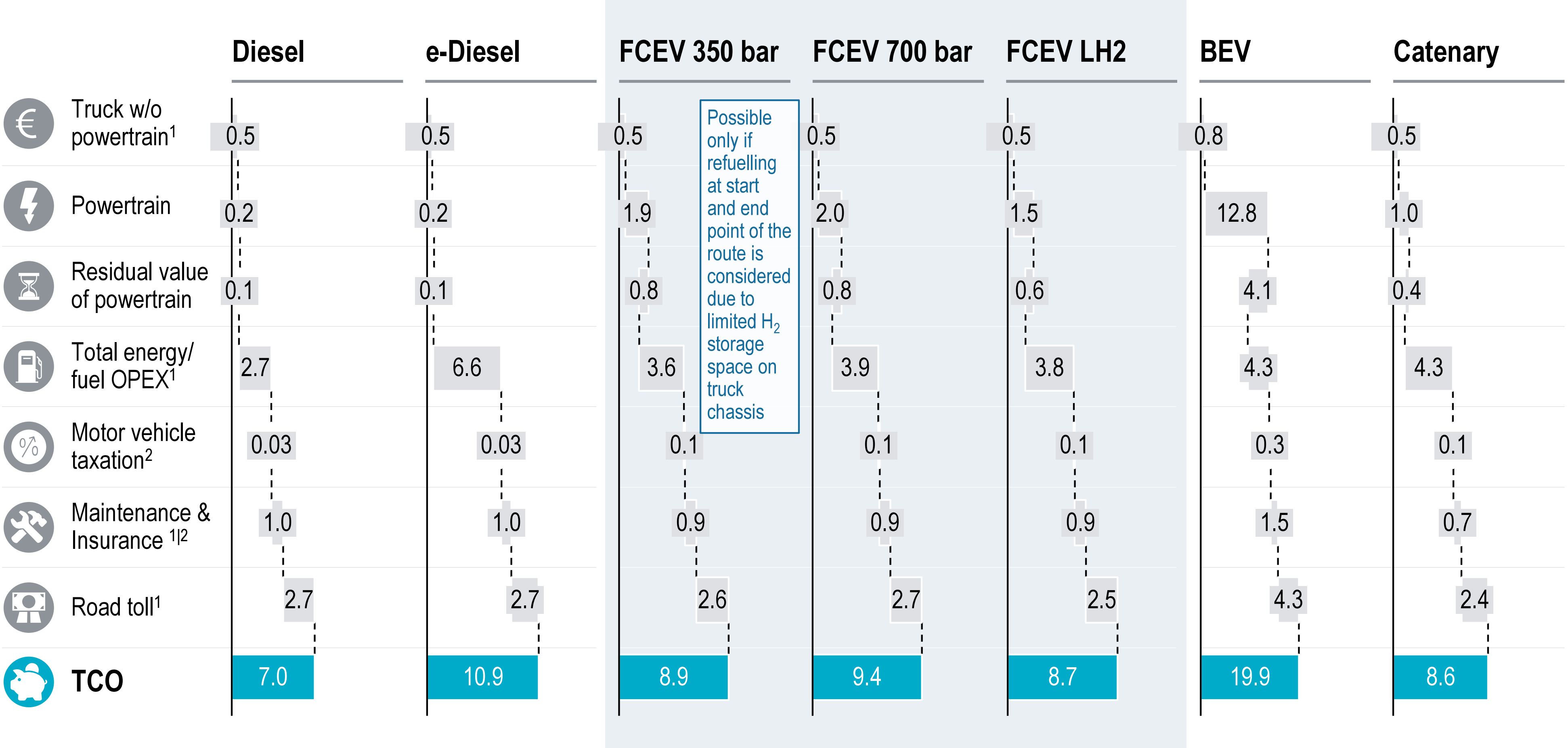
- Also when looking at the EUR/truck TCO, **the cost down potential** for FCEV **at scale** exists – Yet **diesel is the cheapest technology option** still in 2030 on a EUR/truck basis
- FCH trucks have a **cost premium of up to ~33% in 2023**
- **BEV not cost-competetive** due to the **cost for the large battery** needed for the daily range
- TCO results of **zero-emission technologies strongly rely** on assumptions **on second life market**

[1] Under the assumption that sufficient hydrogen storage can be technically integrated in the current truck chassis architecture; Potential length regulation adjustments required

Source: FERCAM; Roland Berger

Cost of powertrain is varying the most across technologies – Fuel/ energy cost of ZEV cannot offset cost disadvantage

Bolzano-Munich case – 2023 TCO cost breakdown [EUR ct/tonne-km; 1st life]



	Diesel	e-Diesel	FCEV 350 bar	FCEV 700 bar	FCEV LH2	BEV	Catenary
Truck w/o powertrain[1]	0.5	0.5	0.5	0.5	0.5	0.8	0.5
Powertrain	0.2	0.2	1.9	2.0	1.5	12.8	1.0
Residual value of powertrain	0.1	0.1	0.8	0.8	0.6	4.1	0.4
Total energy/ fuel OPEX[1]	2.7	6.6	3.6	3.9	3.8	4.3	4.3
Motor vehicle taxation[2]	0.03	0.03	0.1	0.1	0.1	0.3	0.1
Maintenance & Insurance [1|2]	1.0	1.0	0.9	0.9	0.9	1.5	0.7
Road toll[1]	2.7	2.7	2.6	2.7	2.5	4.3	2.4
TCO	7.0	10.9	8.9	9.4	8.7	19.9	8.6

Possible only if refuelling at start and end point of the route is considered due to limited H_2 storage space on truck chassis

---

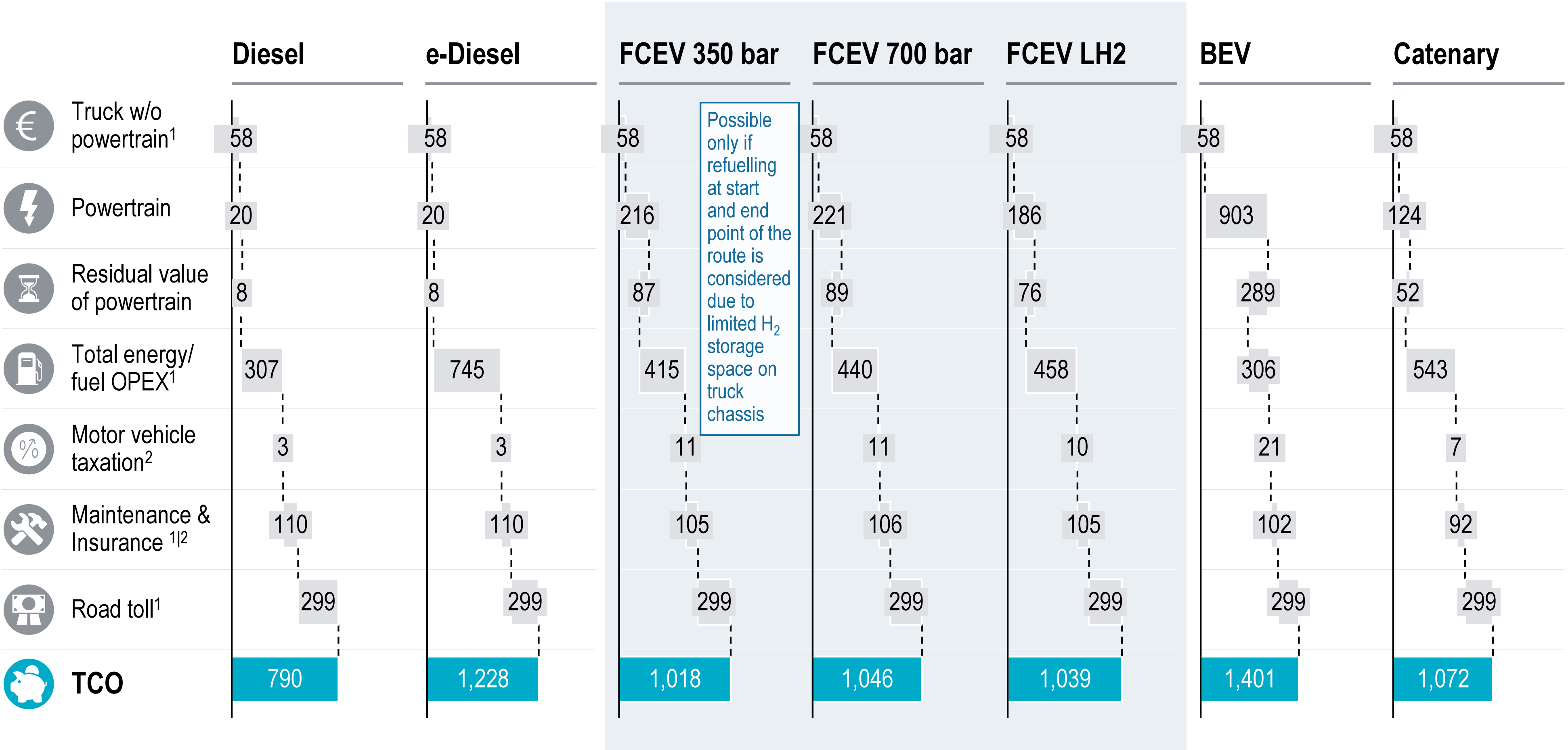
1) Deviations of results are related to payload differences of different technologies 2) Deviations of results are related to calculation based on higher CAPEX

Note: Battery replacement needed already in first life due to high mileage; Battery charging during the day is not possible as the truck is in a 2-shift operation

Source: FERCAM; Roland Berger

The TCO results rely on high residual value of ZEV – However, the 2nd life market is still uncertain and might not realise as predicted

Bolzano-Munich case – 2023 TCO cost breakdown [kEUR/truck; 1st life]



	Diesel	e-Diesel	FCEV 350 bar	FCEV 700 bar	FCEV LH2	BEV	Catenary
Truck w/o powertrain[1]	58	58	58	58	58	58	58
Powertrain	20	20	216	221	186	903	124
Residual value of powertrain	8	8	87	89	76	289	52
Total energy/ fuel OPEX[1]	307	745	415	440	458	306	543
Motor vehicle taxation[2]	3	3	11	11	10	21	7
Maintenance & Insurance [1|2]	110	110	105	106	105	102	92
Road toll[1]	299	299	299	299	299	299	299
TCO	790	1,228	1,018	1,046	1,039	1,401	1,072

Possible only if refuelling at start and end point of the route is considered due to limited H_2 storage space on truck chassis

1) Deviations of results are related to payload differences of different technologies 2) Deviations of results are related to calculation based on higher CAPEX

Note: Battery replacement needed already in first life due to high mileage; Battery charging during the day is not possible as the truck is in a 2-shift operation

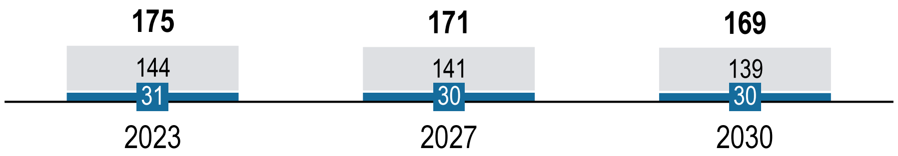
Source: FERCAM; Roland Berger

Zero-emission vehicles will allow for significant emission savings on this route – Conversion of fleet would offer even higher potential

Bolzano-Munich case – Environmental analysis

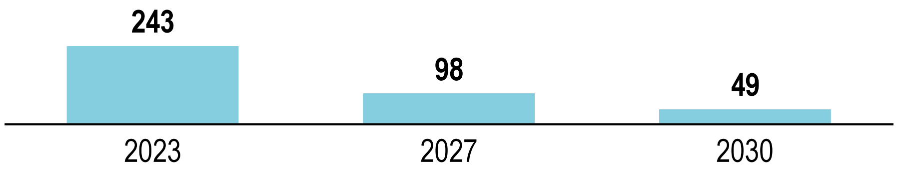
CO_2 savings potential[1]

Well to Wheel [tonnes CO_2e/year]



Estimated CO_2 price for FCEV cost parity

[EUR/tonnes CO_2e]



Pollution reduction potential[2]

- Conversion to zero-emission trucks allows for a total reduction of NOx pollutants
- Particulate matter can also be reduced due to more efficient driving patterns, incl. regenerative braking for electric vehicles

▨ Tank to Wheel ■ Well to Tank ▨ Est. CO2 price

Emissions reductions

- Total greenhouse gas emissions reduction to be realized over five years with ten trucks (max.): **8,461 tonnes CO_2e**
- Potential for reduction of other pollutants equally targeted with zero-emission vehicles on the frequently driven route across Italy, Austria and Germany

Opportunities

- Ongoing activities and 'hydrogen master plan' to set up a regional H_2 eco-system with opportunities for further multi-modal applications, e.g. set target to transform the Brenner transport corridor into a 'green corridor' through hydrogen application, wind energy generation, electric cableways
- If existing H_2 refuelling infrastructure can be adapted for heavy-duty trucks, the direct connection to the heavily used Brenner motorway offers access to infrastructure to a very high number of further trucks (company fleet and all passing vehicles)
- Potentially, the green hydro-powered electrolysis facility to produce hydrogen for the local HRS could be extended

---

1) CO_2 savings potential refers to one potential zero-emission vehicles for the specific route
2) Pollution reduction potential not quantified as specific limits are set for each heavy duty diesel engine on the vehicle test stand

Source: FERCAM; Roland Berger

The Bolzano-Munich case study shows that deploying FCH trucks for high daily ranges could imply a change of operation schedules

Bolzano-Munich case – Enablers and constraints for FCH technology

Potential enablers and constraints

!

- The TCO results at scale indicate a promising cost development of FCH trucks over time, supporting the use of the vehicles on this route
- The high frequency on the fixed route together with the back-to-base distribution operation generally offer good preconditions for FCEV uptake
- Existing infrastructure could be made suitable to serve heavy-duty trucks
- The strong regional support for hydrogen application can be leveraged to foster technology acceptance and potentially engage further collaborators

?

- Current refuelling patterns would be difficult to maintain with FCH trucks as the daily range would not be possible (except with an oversized tank system)
- As FCH trucks are not predicted to become cost-competitive with diesel in this operation in the short-to-mid-term, the cost premium would need to be assumed by the involved parties of the logistics operations or mitigated by public funding
- The TCO costs of alternative vehicles are influenced highly by the assumed residual value of the powertrain – as the second market is still uncertain, this could be a barrier for decision-making today

Synthesis

- The case study with its **fixed route and plannable operations** and the direct **access to already existing infrastructure** offers **good conditions** for deploying FCH trucks already in the short-term
- However, FCH trucks are **not yet cost-competitive with diesel**: The analysis indicates **a higher TCO** – This is due to the **very high annual mileage, higher CAPEX[1]** with an **uncertain residual value for ZEV** and **lower OPEX costs for diesel**
- Of the ZEV, **FCH technology seems the best suited to fulfil the requirements on this route** – BEV would see a payload reduction, a very high cost of powertrain and the two-shift schedule would not allow for the charging time
- **If utilisation patterns** are **optimised** for zero-emission vehicles (e.g. intra-route refuelling at each end point), **FCH technology could become a more cost-competitive fit** as CAPEX could be lower due to smaller tanks
- Various **opportunities linked to the H_2 infrastructure** on this route (Brenner motorway) will potentially have a **large influence** on the **type of truck driven on this route in the future**, both from a company perspective and in general

[1] As the model assumes that the daily range needs to be achieved without intermediate refuelling or charging, a larger powertrain is assumed for the zero-emission vehicles

Source: FERCAM; Roland Berger

The case study on the cross-border route Bolzano (IT) – Munich (DE) is supported by specific information and data from FERCAM

Bolzano-Munich case – Background

Road freight sector in Italy

Information on the road freight sector

- Italy has the sixth highest volume of road transport in Europe with approx. 1 billion tonnes of goods transported in 2018
- The highest country-to-country flow of goods takes places between Italy and Germany, France, Austria and Slovenia
- Road freight industry revenue for transport by road in Italy is approx. EUR 43 bn (2018)

Main transport corridors

- Northern regions of Lombardia, Veneto and Emilia-Romagna are the centres of domestic road freight transport
- The Brenner route connects Italy with Austria and Germany and is the most heavily travelled transalpine corridor for freight transport

Information on company supporting the case

Company information FERCAM Logistics & Transport

Name	FERCAM
Industry	Freight and logistics service company
Headquarters	Bolzano, Italy
Zero-emission ambition	FERCAM follows a company strategy to move towards zero emission transport

Depot linked to route

Location	Bolzano, Italy
Description	Main company depot
Total number of trucks	300

Source: FERCAM; Statista; Eurostat; Desk research; Roland Berger

D.3.7 Hatfield case
[DHL]

The plannable multi-drop route with scheduled operations around Hatfield is a good fit for both fuel cell and battery technology

Hatfield case – Overview

Location and route

- The route connects the regional hub with the client's stores in inner cities and is operated with two different types of trucks (18 tonnes and 10 tonnes)
- The delivery area is within a radius of approx. 100 km from the regional hub
- The route is set on mostly flat terrain and involves deliveries in towns / cities

Setting – Truck and operations

Truck type	Rigid 4x2, 18 tonnes Ambient Dry Box vehicle
Daily range	200 km
Operation	365 days/year
Fleet size	6
Payload	3.5 tonnes

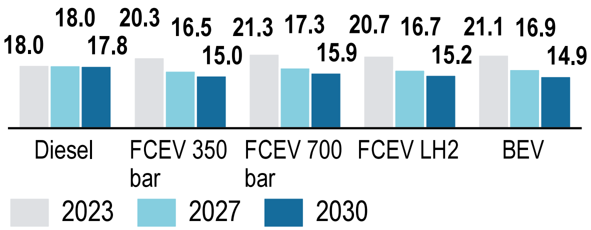
Logistic operation

The closed loop route involves the delivery of clothing and home goods from the regional hub to the client's stores. The trucks run daily and carry out several drops in one shift.

Infrastructure

- Hydrogen refuelling infrastructure for trucks would need to be installed (private or public), as there currently is no refuelling station in proximity of the depot (potential link to London HRS supply from Rotterdam)
- No refuelling time restrictions apply

TCO analysis [EUR ct/tonne-km; 1st & 2nd life]

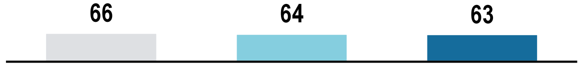


FCH and battery technology both represent cost-competitive zero-emission alternatives over time. BEV with a slight cost advantage in 2030.

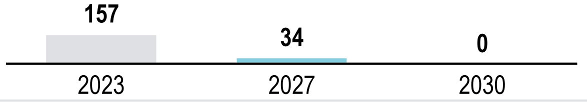
Environmental analysis

Zero-emission trucks offer significant annual CO_2 savings. The est. CO_2 price, as the price to be put on CO_2 to reach cost parity compared to diesel, demonstrates the FCEV cost premium

Yearly truck CO_2 savings potential – WTW [tCO_2e]



Est. CO_2 price for FCEV cost parity [EUR/tCO_2e]

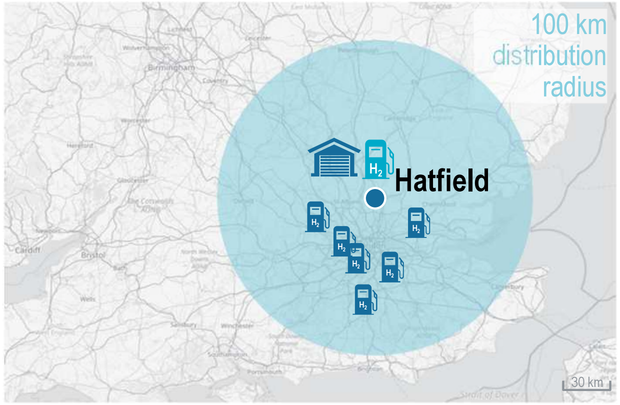


Source: DHL; Roland Berger

The daily delivery route for a clothing retailer illustrates a "bus stop" logistics operation in the UK and includes inner-city driving

Hatfield case – Description

Investigated route



HRS[2] for cars
Main distribution center
Potential HRS[2] for trucks

- The route connects the regional logistics hub with the client stores in cities and is operated with two different types of trucks (18 tonnes and 10 tonnes)
- The delivery area is within a radius of approx. 100 km from the regional hub, predominantly into London
- The route is set on mostly flat terrain and involves deliveries in towns / cities
- Road toll charges do not apply

Case description[1]

Truck type

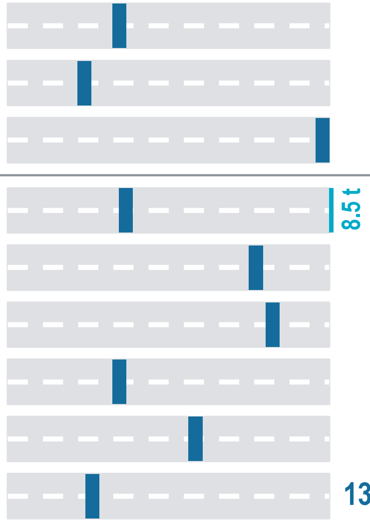
Rigid 4x2, 18 tonnes

Ambient Dry Box vehicle

Logistic operation

The trucks on this route run on a fixed "bus stop" type schedule to deliver clothing and home goods from the regional hub to the client's stores. The back-to-base route involves a daily multi drop operation of one or two deliveries per trip. The trucks are operated in one or two shifts per day with one driver each. A fuel stop per shift is carried out at a public station.

Route	**Route length**	200 km
	Fleet size[3]	6
	Operation	365 days
Truck performance	**Payload**	3.5 tonnes
	Avg. loading factor (weight)	41%
	Maximum speed	85 km/h
	Daily range	200 km
	Annual mileage	75,000 km
	H_2 consumption	13 kg(H_2)/day



Legend Low High

Infrastructure[2]

- Each truck operates on avg. 200 km per day – this would be an avg. consumption of ~13 kg(H_2)/day (at 0.066 kg(H_2)/km) and a H_2 demand of ~80 kg(H_2)/day for the whole fleet

Potential truck HRS

- H_2 demand not sufficient for private HRS (minimum of 0.5 t/day advisable for commercial benefit); public HRS required with ext. H_2 supply

Potential H_2 prod. facility

- Supply from electrolysis installation with at least 0.2 MW power needed, e.g. link to London HRS

Potential synergies

- Other DHL trucks passing the depot/London area (~20 trucks)
- H_2 infrastructure use by ext. operators in N. London area

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1) Data verified with stakeholders
2) HRS = hydrogen refuelling station
3) The route is operated with two types of trucks: 6 x 18 tonnes trucks, 6 x 10 tonnes trucks

Source: DHL; Roland Berger

Specific data is introduced in the total cost of ownership model to reflect the real-life operations of the case study

Hatfield case – Specific assumptions

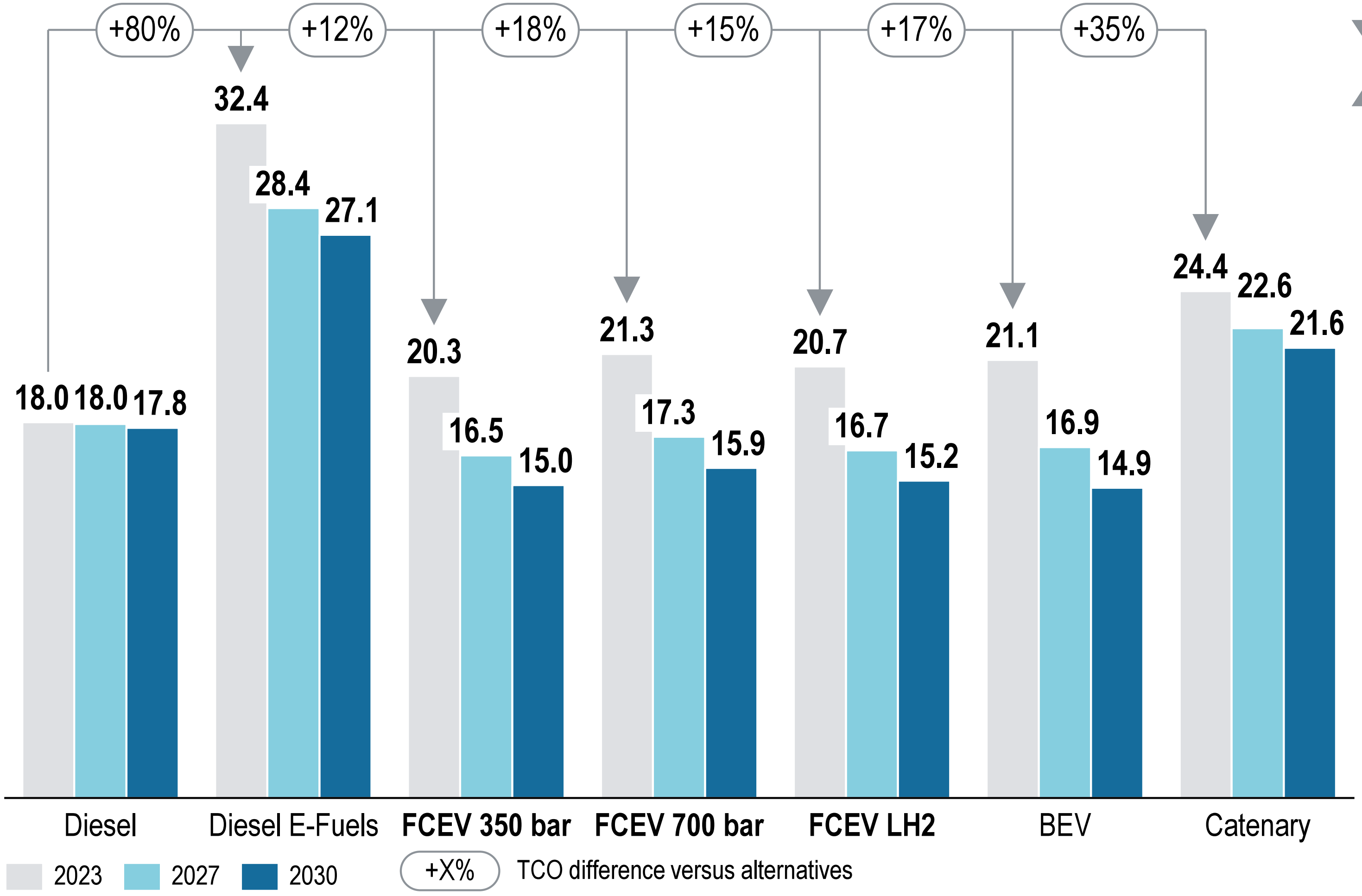
Main input changes to the TCO model base assumptions

Operation	> Annual mileage set at ~75,000 km/year > Operation on route set for 365 days/year > Max. payload set to 8.5 tonnes > Route profile set to a homogenous pattern due to plannability of 'bus stop' route
Motor vehicle tax	> Motor vehicle tax set at 0.7% of initial vehicle cost for 2023 and adjusted for 2027 and 2030 to reflect case specific data on the tax of 504 EUR/year
Maintenance costs	> Maintenance cost set at 0.046 EUR/km for diesel, at 0.041 EUR/km for FCEV and at 0.037 EUR/km for BEV and catenary
Private / public refuelling	> Public refuelling assumed for all technologies
Energy and fuel costs	> Energy price for diesel set at 1.08 EUR/l net price > AdBlue costs set at 0.29 EUR/l
Road toll	> No road toll charges apply on this route

Source: DHL; Roland Berger

Both FCH and battery technology are attractive zero-emission options for this route from a commercial point of view

Hatfield case – High-level TCO assessment [EUR ct/tonne-km; 1st & 2nd life]



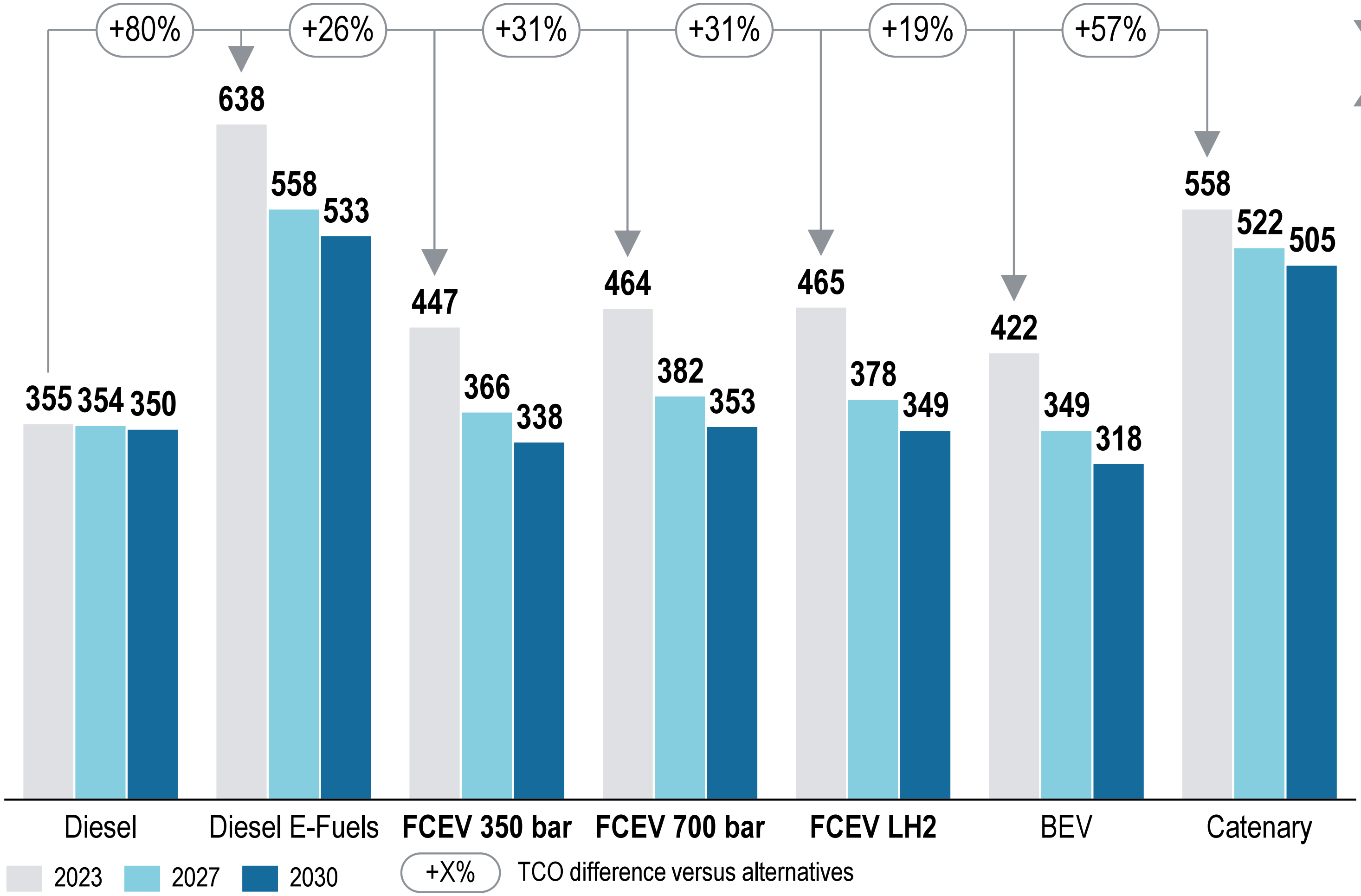
Comments

- > A significant **cost down potential** for FCEV **at scale** exists **looking at 1st and 2nd life**
- > **FCH technologies and BEV** at a **very comparable cost level** on a tonne-km basis
- > FCH trucks still have a **cost premium of up to ~18% in 2023** compared to diesel but become **more cost-competitive by 2027**
- > **No payload reduction** for FCEV and BEV apply

Source: DHL; Roland Berger

Also on a EUR/truck basis, the TCO shows that FCEV and BEV will perform at diesel level – Slight cost advantage of BEV in 2030

Hatfield case – High-level TCO assessment [kEUR/truck; 1st & 2nd life]



	2023	2027	2030
Diesel	355	354	350
Diesel E-Fuels	638	558	533
FCEV 350 bar	447	366	338
FCEV 700 bar	464	382	353
FCEV LH2	465	378	349
BEV	422	349	318
Catenary	558	522	505

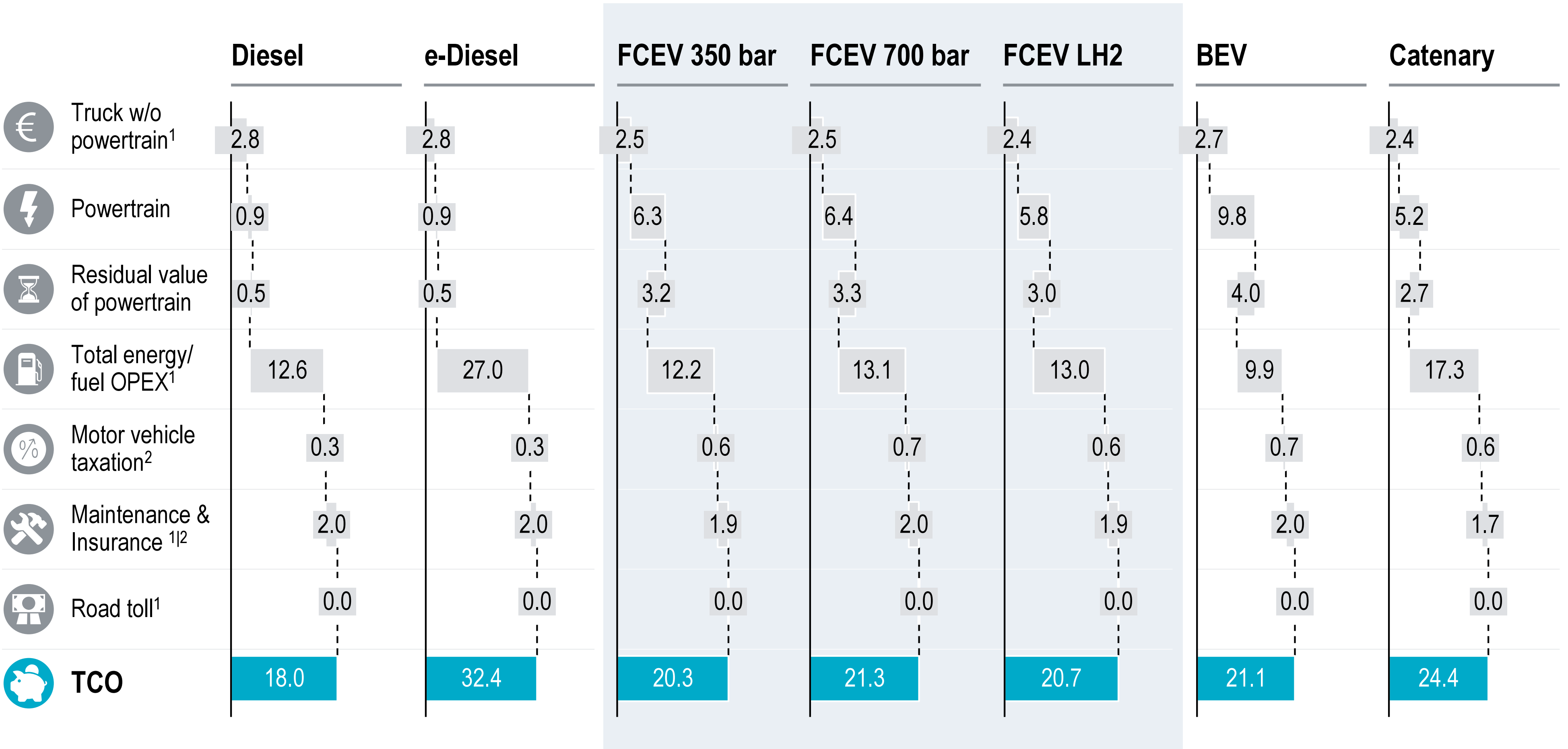
Comments

- Also when looking at the EUR/truck TCO costs, **the cost down potential** for FCEV technology **at scale** exists
- FCH trucks have a **cost premium of up to ~31% in 2023**, yet approach diesel cost levels by 2030
- **BEV replaces diesel as the cheapest technology option** in 2030, demonstrating the increasingly **positive commercial development of zero-emission technologies**

Source: DHL; Roland Berger

Energy and fuel costs are the main cost drivers, followed by the powertrain costs – Dependence on second market for residual value

Hatfield case – 2023 TCO cost breakdown [EUR ct/tonne-km; 1st & 2nd life]



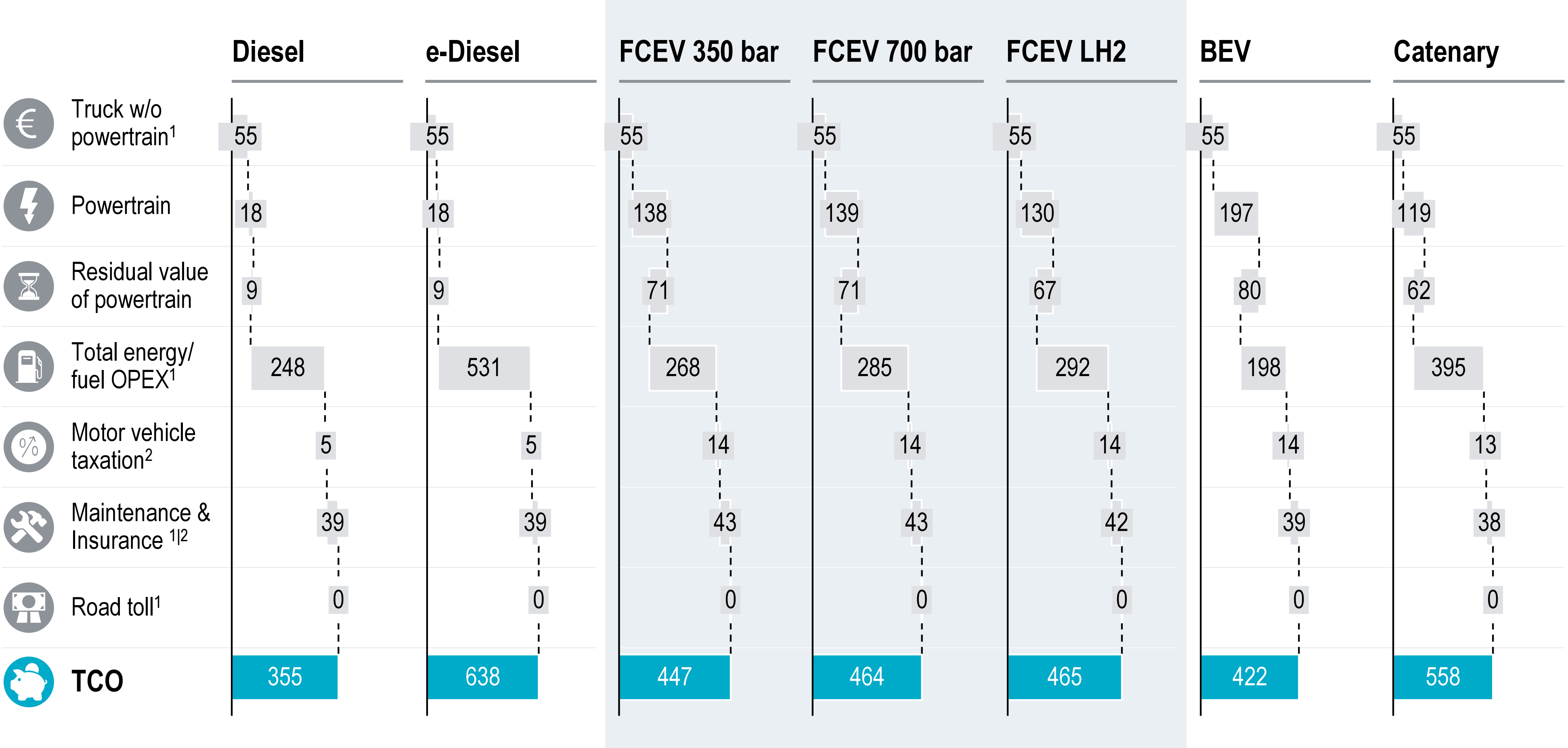
	Diesel	e-Diesel	FCEV 350 bar	FCEV 700 bar	FCEV LH2	BEV	Catenary
Truck w/o powertrain[1]	2.8	2.8	2.5	2.5	2.4	2.7	2.4
Powertrain	0.9	0.9	6.3	6.4	5.8	9.8	5.2
Residual value of powertrain	0.5	0.5	3.2	3.3	3.0	4.0	2.7
Total energy/ fuel OPEX[1]	12.6	27.0	12.2	13.1	13.0	9.9	17.3
Motor vehicle taxation[2]	0.3	0.3	0.6	0.7	0.6	0.7	0.6
Maintenance & Insurance [1][2]	2.0	2.0	1.9	2.0	1.9	2.0	1.7
Road toll[1]	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TCO	18.0	32.4	20.3	21.3	20.7	21.1	24.4

1) Deviations of results are related to payload differences of different technologies 2) Deviations of results are related to calculation based on higher CAPEX

Source: DHL; Roland Berger

Energy and fuel costs are the main cost drivers, followed by the powertrain costs – Dependence on second market for residual value

Hatfield case – 2023 TCO cost breakdown [kEUR/truck; 1st & 2nd life]



	Diesel	e-Diesel	FCEV 350 bar	FCEV 700 bar	FCEV LH2	BEV	Catenary
Truck w/o powertrain[1]	55	55	55	55	55	55	55
Powertrain	18	18	138	139	130	197	119
Residual value of powertrain	9	9	71	71	67	80	62
Total energy/ fuel OPEX[1]	248	531	268	285	292	198	395
Motor vehicle taxation[2]	5	5	14	14	14	14	13
Maintenance & Insurance [1|2]	39	39	43	43	42	39	38
Road toll[1]	0	0	0	0	0	0	0
TCO	355	638	447	464	465	422	558

1) Deviations of results are related to payload differences of different technologies 2) Deviations of results are related to calculation based on higher CAPEX

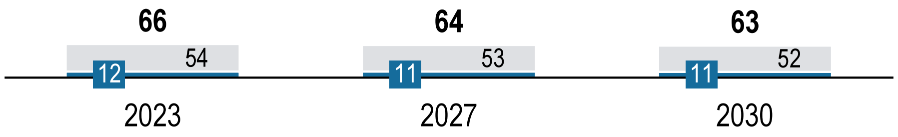
Source: DHL; Roland Berger

Zero-emission vehicles will allow for significant emission savings on this route – Conversion of fleet would offer even higher potential

Hatfield case – Environmental analysis

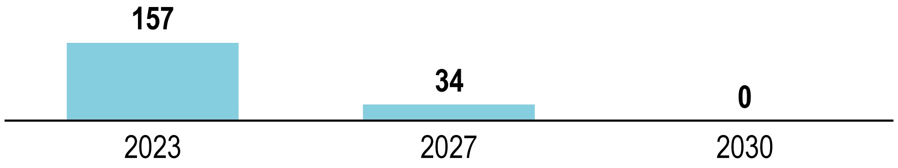
CO_2 savings potential[1]

Well to Wheel [tonnes CO_2e/year]



Estimated CO_2 price for FCEV cost parity

[EUR/tonnes CO_2e]



Pollution reduction potential[2]

- Conversion to zero-emission trucks allows for a total reduction of NOx pollutants
- Particulate matter can also be reduced due to more efficient driving patterns, incl. regenerative braking for electric vehicles

▨ Tank to Wheel ■ Well to Tank ■ Est. CO2 price

Emissions reductions

- Total greenhouse gas emissions reduction to be realised over ten years with six trucks:

  3,776 tonnes CO_2e
- Potential for reduction of other pollutants equally targeted with zero-emission vehicles

Opportunities

- Potential conversion of higher number of trucks at the same depot would increase the emission savings
- Further collaboration and initiatives with the client could build on sustainability commitment to jointly improve carbon efficiency, e.g. adaption of delivery schedules

---

[1] CO_2 savings potential refers to one potential zero-emission vehicles for the specific route

[2] Pollution reduction potential not quantified as specific limits are set for each heavy duty diesel engine on the vehicle test stand

Source: DHL; Roland Berger

The Hatfield case shows that short daily routes on a fixed schedule provide a good opportunity for FCH technology

Hatfield case – Enablers and constraints for FCH technology

Potential enablers and constraints

!

- High plannability of multi-drop, back-to-base distribution route offers good conditions for FCH technology uptake
- Leverage to potentially replace a higher number of vehicles in the fleet with FCH technology trucks
- Potential connection to the larger London HRS network for buses and cars could enable a public station in Hatfield to be also used by DHL (would need to be investigated)
- Experience in setting up private refuelling stations for CNG/LNG trucks

?

- Public infrastructure needed as H_2 demand not sufficient for private HRS – Minimum utilisation (at least 10 trucks) of HRS installation would be advisable, collaboration with ext. partners would need to be investigated
- Positive TCO outlook depends a reliable second market in order to achieve the assumed residual value for the powertrain
- Payload requirements for vehicles need to be ensured

Synthesis

- The case study offers a **fixed route operated on a regular schedule**, establishing **good conditions** for FCH trucks
- Compared with diesel, FCH technology represents **an attractive zero-emission alternative** looking at the TCO cost-down potential over time
- The installation of required **hydrogen infrastructure would be necessary**, yet **currently no clear point of access** in the nearer Hatfield area (to be investigated)
- Cost advantages of **FCH technology** (also compared to BEV) could become **even clearer**
  - **if external influences**, e.g. energy consumption in winter, would **require higher levels of energy**
  - **if charging of a fleet of BEV** would lead to **high energy costs** and a (potentially too) **high demand on the electricity grid** in addition to the cost of infrastructure

Source: DHL; Roland Berger

The case study on the regional delivery route in the UK is supported by specific information and data from DHL Supply Chain

Hatfield case – Background

Road freight sector in United Kingdom

Information on the road freight sector

- More than 1,4 billion tonnes of freight are carried in the UK: 63% by articulated vehicles, 37% by rigid vehicles (2018)
- The majority of road freight transported is domestic freight carried within the country
- Overall, the road freight industry revenue for transport by road in the UK is EUR ~29 bn (2018)

Main transport corridors

- The road network in England consists of approx. 7,000 km of 'strategic roads' connecting North and South, as well as East and West
- The so-called logistics 'Golden Triangle' in the country's centre is a high traffic area and sees a significant concentration of logistics warehouses

Information on company supporting the case

Company information	DHL
Name	DHL Supply Chain Ltd.
Industry	Logistics service company
Headquarters	Milton Keynes, England
Zero-emission ambition	DHL's 2025 target is to improve CO_2 efficiency by 50% over 2007 levels. This sustainability ambition is supported by clients.
Depot linked to route	
Location	Hatfield, UK
Description	Regional hub
Total number of trucks	14

Source: DHL; UK Department for Transport; Statista; Roland Berger

D.3.8 Leoben-Göss case [Brau Union Austria (part of the HEINEKEN Company)]

For the Leoben-Göss case study, several fundamental assumptions were adjusted in alignment with the case study partners

Case study-specific disclaimer

For the development of this case study and due to the particularity of the operation, several assumptions in the base TCO model were manually changed in alignment with Brau Union Austria and Heineken.

Introduced specific changes in the case study in alignment with the Advisory Board case study partners

Dynamic capacity sizing of powertrain of FCEV/BEV	> The truck fleet in the case study operations demonstrate a low daily range and annual mileage. Different routes are driven by the trucks within a defined parameter of outlets around the brewery, yet the specific daily range varies over the weekdays on effects such as seasonality. Due to these varying routes in the operation and the flexibility needed for the fleet, the vehicle capacity was set to reflect the maximum of annual mileage (CAPEX: vehicle chassis, powertrain; motor vehicle tax based on vehicle value), while the daily operational requirements were set to reflect the average of operations (OPEX: fuel/energy cost, maintenance cost and road toll). The results calculated by the dynamic sizing logic of the TCO model regarding the powertrain components were manually changed to reflect these criteria.
TCO calculation w/o the residual value	> The case study illustrated that with a low annual mileage, the assumed residual value as calculated by the TCO model has a strong impact on the results. With the low mileage, the TCO model (due to the calculation logic of the model) shows a high residual value compared to the cost of powertrain due to the calculation depending on the kilometres run by the truck (decreasing residual value with an increasing utilisation). Such high residual value is unlikely to be achieved in the second market (for a technology from 10 years ago) and introduced uncertainty of results. In this case, it was decided in alignment with Brau Union Austria and Heineken to only show the results without considering a potential residual value. At the same time, this consideration shows that with a certain driving profile and mileage a lifetime of >10 years would be possible.
Tonne-km calculation	> With the manually adjusted TCO calculation based on two parameters of annual mileage (for CAPEX and OPEX), the tonne-km calculation was defined as referring to the average profile of operations.
Environ-mental analysis	> The calculation of the estimated CO_2 price for FCEV cost parity in this case study is based on a calculation without considering the residual value[1]. In this specific case study, the results can be skewed and are not 1:1 comparable to the CO_2 price for FCEV cost parity calculated in other case studies in which the residual value is considered in the overall TCO view. This is due to the fact that considering the residual value shows a more favourable view on the cost development of FCEV and BEV technology, with a lower cost delta to be bridged in order to achieve cost parity with diesel technology.

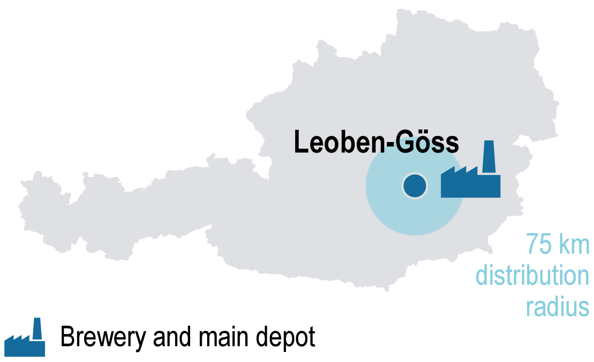
1) Due to the early stage of the market with very limited re-sale of zero-emission vehicles, general uncertainty with regards to the residual value of truck exists

Source: Brau Union Austria; Roland Berger

The Leoben-Göss routes show a local distribution operation with own trucks – BEV technology identified as best option

Leben-Göss case – Overview

Location and route



> The distribution area is set in the Leoben-Göss district and connects the Göss brewery with various regional outlets in an approx. 60-80 km radius on varying routes

> The main depot is located at the brewery facility with a total of 14 trucks (of which 10 in operation)

> The routes are set on hilly terrain and included rural and city deliveries

Setting – Truck and operations

Truck type	Rigid 4x2, 18 tonnes Side-loading with keg lifter
Daily range	avg. 75 km
Operation	250 days/year
Fleet size	10
Payload	5.4 tonnes

Logistic operation

Milk run, back to base distribution from a brewery within the same district on varying routes. Trucks leave the production facility in the morning and return in the afternoon with empty crates and kegs after visiting 10-20 outlets.

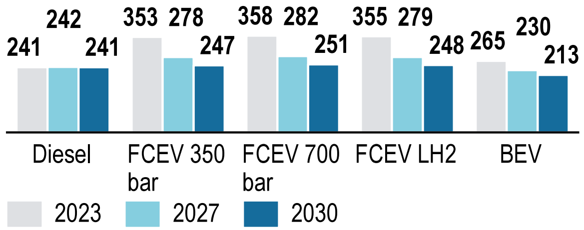
The route is operated with owned / leased trucks (used for approx. 15 years) by drivers employed by the company.

Infrastructure

> Currently no HRS near the brewery location

> Further applications with H_2 demand needed / to be leveraged due to low probability for set up of infrastructure for singular operation in rural area

TCO analysis [kEUR/truck; 1st & 2nd life]

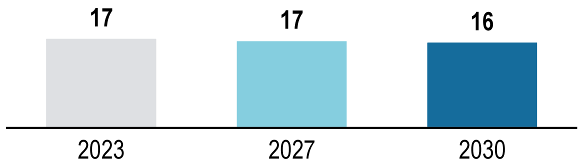


The analysis illustrates that BEV is the most cost-competitive zero-emission option in this operation, in a similar cost range with diesel already in 2023. Also, there are no payload restrictions for BEV.

Environmental analysis

Zero-emission trucks offer significant annual CO_2 savings. Over the assumed lifetime of ten years, the electrification of the fleet of ten trucks could lead to a total of 1,722 t CO_2 emissions savings

Yearly truck CO_2 savings potential – WTW [tCO_2e]



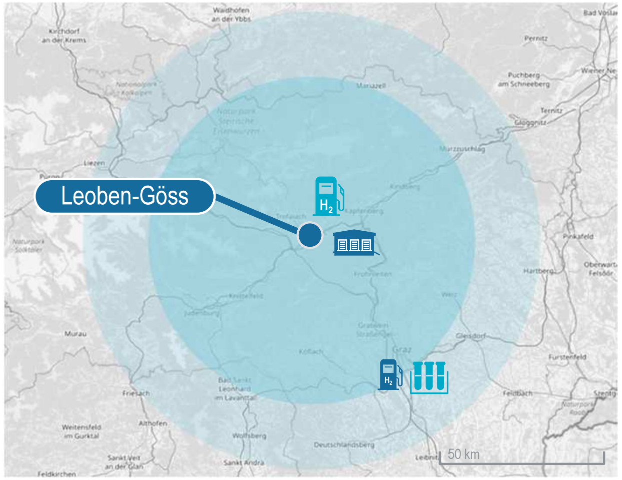
HRS = Hydrogen refuelling station

Source: Brau Union Austria; Roland Berger

The case study looks at regional distribution in plannable, yet differing operations – Variations in daily range, volume, and stops

Leoben-Göss case – Description

Investigated route



🛢 Existing HRS[2] for buses 🏭 Main depot

🛢 Potential HRS[2] for trucks ▥ Potential H_2 production

- > The beer delivery routes connect the Göss brewery with various regional outlets in an approx. 60-80 km radius (10-20 stops per route)
- > Individual routes are very different: on average the annual mileage is ~18,000 km with some trucks driving ~27,000 km per year
- > The route includes rural and city deliveries with very limited driving on highways

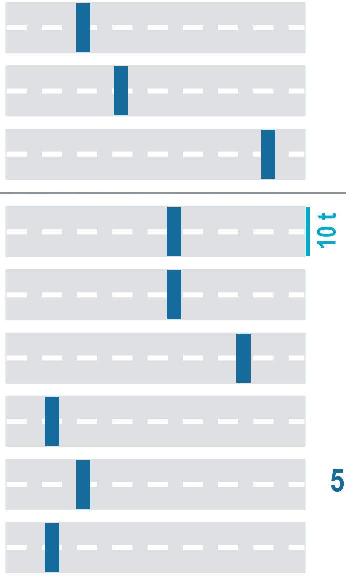
Case description[1]

Truck type Rigid 4x2, 18 tonnes

Side-loading with keg lifter

Logistic operation

Milk run distribution from a regional brewery to outlets in the same district. Trucks leave the production facility with palletised beer and return with empty crates and kegs. The operation is volume restricted due to specific picking per route and different brands of crates/kegs (limited floor space).



Route	**Route length**	15-150 km
	Fleet size	10 trucks
	Operation	250 days
Truck	**Payload**	5.4 tonnes
	Avg. loading factor	54%
	Maximum speed	85 km/h
	Daily range (average)	76 km
	Annual mileage	5,000-25,000 km
	H_2 consumption	5 $kg(H_2)/day$

Legend

Infrastructure

The trucks drive on average 76 km daily - this amounts to a potential consumption of approx. 5 $kg(H_2)/day$ per truck (at 0.066 $kg(H_2)/km$) and 50 $kg(H_2)/day$ for the whole fleet

Potential truck HRS[2]

H_2 demand not sufficient for private HRS (minimum of 0.5 t/day advisable for commercial benefit); public HRS required with external H_2 supply

Potential H_2 prod. facility

Supply from electrolysis installation with at least 0.1 MW power needed or other low CO_2 hydrogen source

Potential synergies

Strong interest in hydrogen techn. in the Steiermark region with H_2 research activities and HRS for buses (Graz); H_2 production in neighbour region Carinthia[3]

---

1) Data verified with stakeholders
2) HRS = hydrogen refuelling station
3) Planned for 2021

Source: Brau Union Austria; Roland Berger

Specific data is introduced in the total cost of ownership model to reflect the real-life operations of the case study

Leoben-Göss case – Specific assumptions

Main input changes to the TCO model base assumptions

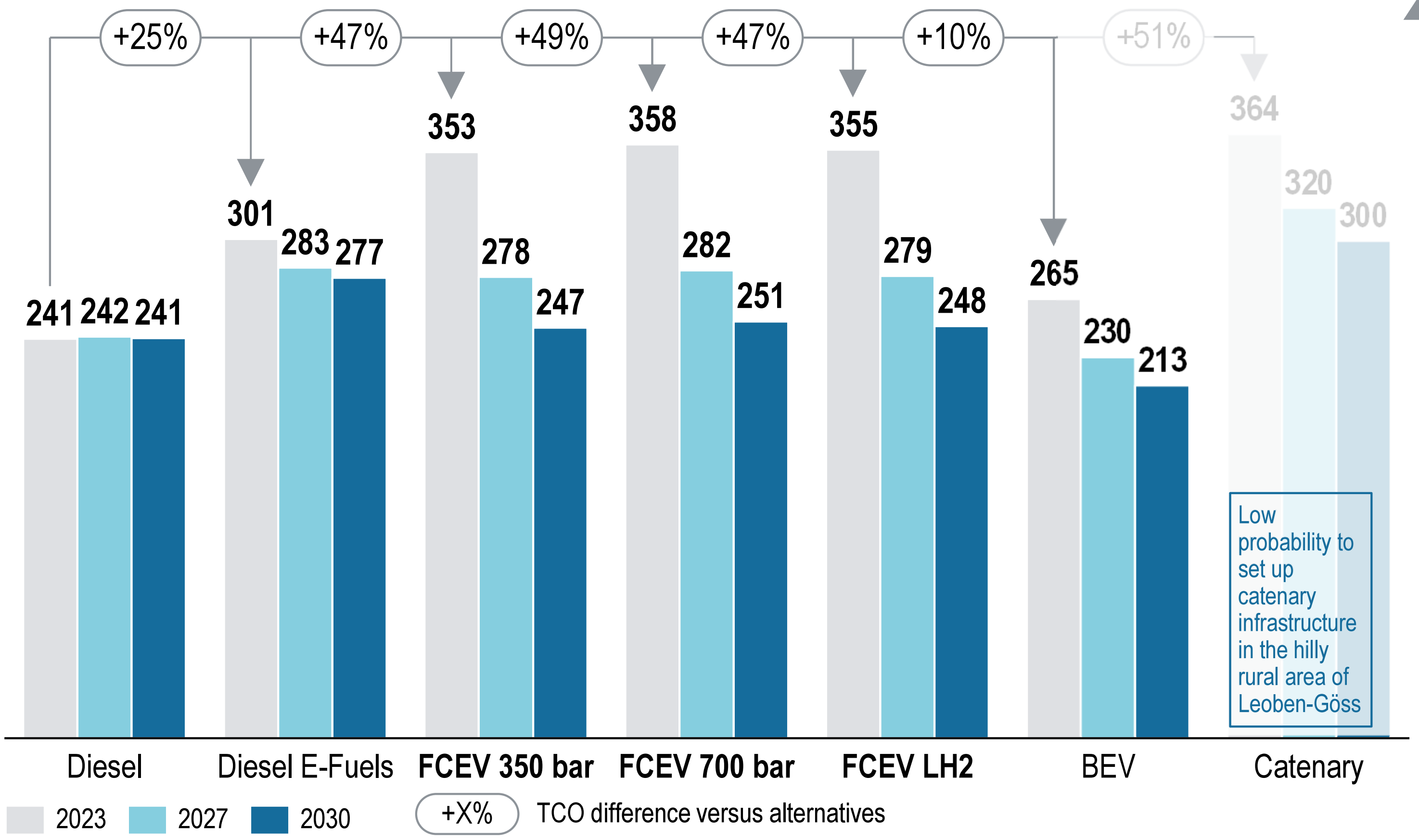
Operation	> Annual mileage set at 18,151 km/year > Capacity sizing of the truck set for a maximum of 25,000 km/year > Max. payload set to 10 tonnes > Route profile set to a rather homogenous pattern as trucks have more or less fixed routes, but stops differ per weekday
Motor vehicle tax	> Motor vehicle tax set at 1.1 % of initial vehicle cost for 2023 and adjusted for 2027 and 2030 to reflect case specific combined data on insurance and tax of 943 EUR/year
Maintenance costs[1]	> Maintenance costs range between 0.38-0.45 EUR/km for diesel; set at 0.40 EUR/km for FCEV and at 0.35 EUR/km for BEV and catenary trucks
Private / public refuelling	> Public refuelling assumed for diesel, FCH technologies and catenary trucks; private charging for battery electric trucks assumed > Cost of private BEV charging infrastructure set at 15,000 EUR/truck
Energy and fuel costs	> Energy price for diesel set at 1.125 EUR/l net price incl. 0.397 EUR/l fuel tax; with consumption set at 30.6 l/100km > AdBlue costs set at 0.90 EUR/l > Electricity cost set at 0.10 EUR/kWh
CO$_2$ emissions	> CO$_2$ emssions per litre diesel set at 3,100 gCO$_2$/l to reflect the 7% biofuel diesel blend in Austria
Road toll	> Road toll set to 0.055 EUR/km

Source: Brau Union Austria; Roland Berger

BEV technology is the most commercially attractive zero-emission option – FCEV at scale become comparable to diesel in 2030

Leoben-Göss case – High-level TCO assessment [kEUR/truck; 1st & 2nd life]

TCO w/o residual value



	2023	2027	2030
Diesel	241	242	241
Diesel E-Fuels	301	283	277
FCEV 350 bar	353	278	247
FCEV 700 bar	358	282	251
FCEV LH2	355	279	248
BEV	265	230	213
Catenary	364	320	300

Comments

- > **BEV** is significantly **more competitive than the alternatives** E-Fuels and FCEV and in a similar range with diesel already in 2023
- > **FCH trucks** have the **highest TCO in 2023 compared to other zero-emission technologies** (except catenary), yet show a significant **cost down potential at scale**
- > **Catenary not considered** as infrastructure set-up not likely in rural distribution area

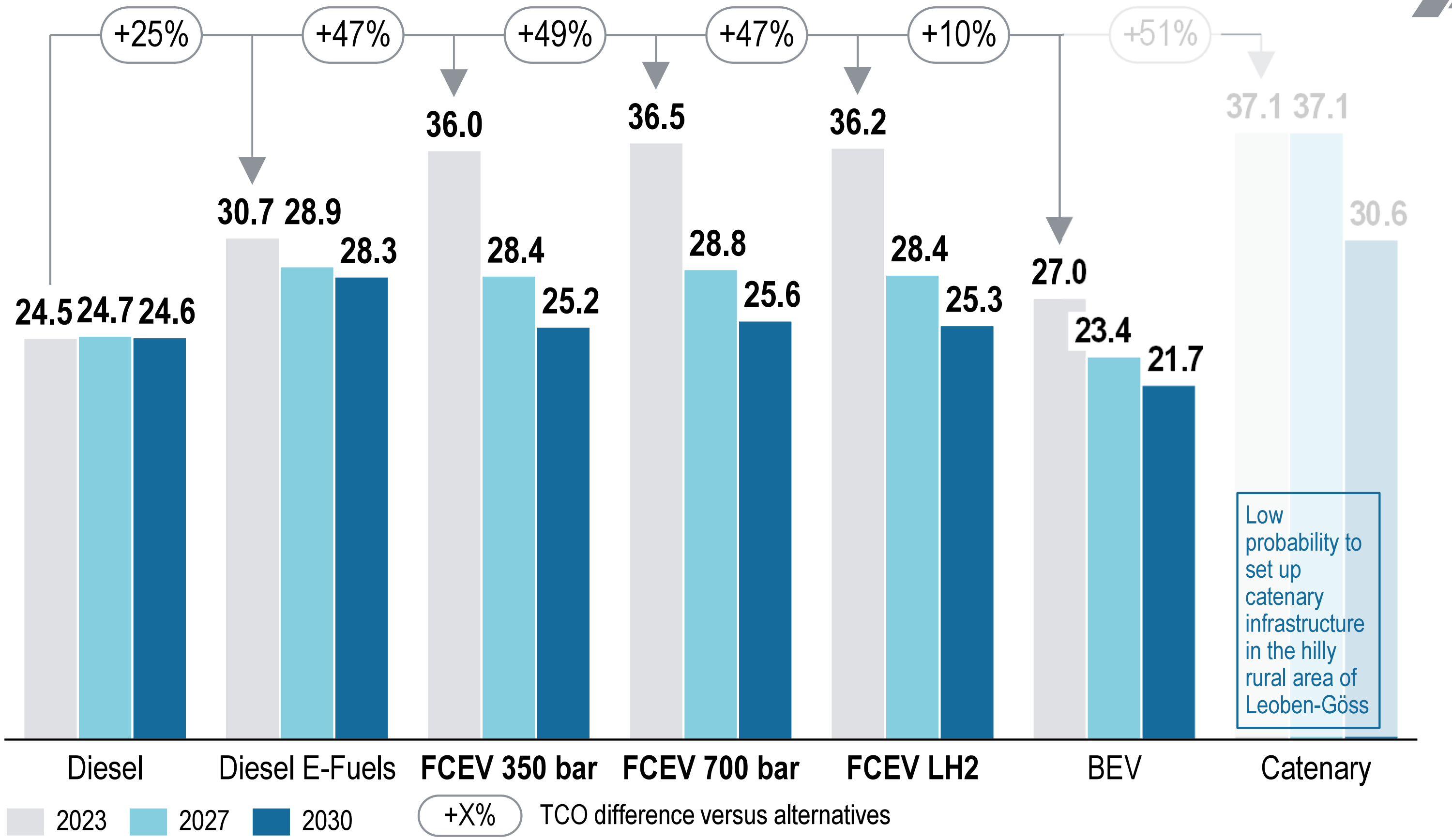
Note: Diesel maintenance cost set at a higher level compared to base assumption; cost for all other technologies was adapted to maintain the assumed relation of costs for diesel vs. ZEV

Source: Brau Union Austria; Roland Berger

Also on a EUR ct/tonne-km basis, the TCO shows the competiveness of BEV and the potential for FCEV starting in 2030

Leoben-Göss case – High-level TCO assessment [EUR ct/tonne-km; 1st & 2nd life]

TCO w/o residual value



Comments

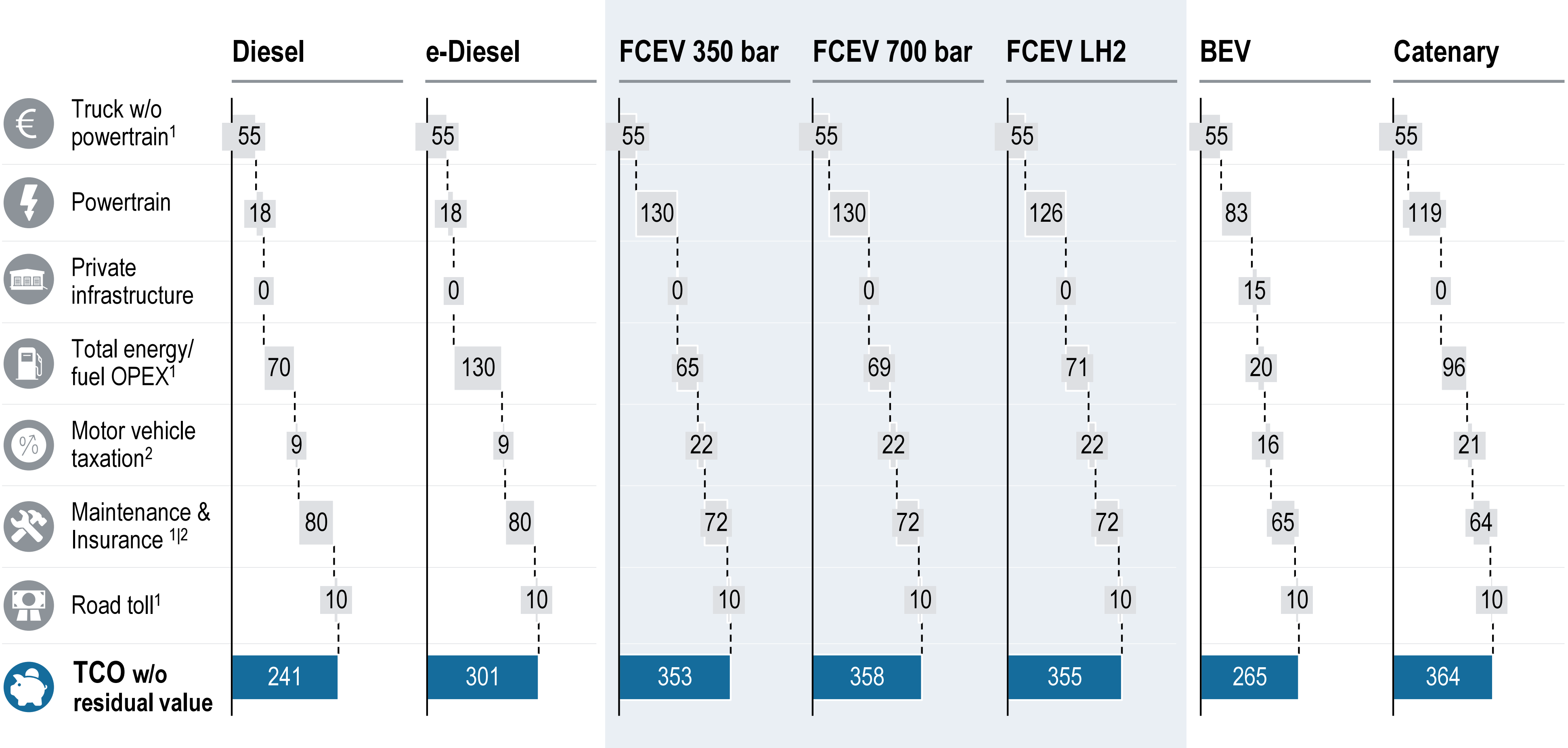
- Also when looking at the EUR ct/tonne-km TCO view, **the cost down potential** for FCEV technology **at scale** exists – However, FCEV have a **cost premium of up to ~49% in 2023**
- **BEV is the cheapest zero-emission technology option**, payload correction not necessary due to a low average payload
- **Diesel e-fuels more cost-competitive than FCEV in 2023** due to low fuel requirements & high FCEV powertrain costs

Note: Diesel maintenance cost set at a higher level compared to base assumption; cost for all other technologies was adapted to maintain the assumed relation of costs for diesel vs. ZEV

Source: Brau Union Austria; Roland Berger

2023 cost breakdown identifies the powertrain as main cost driver for zero-emission technologies, based on the max. capacity sizing

Leoben-Göss case – 2023 TCO cost breakdown [kEUR/truck; 1st & 2nd life]



	Diesel	e-Diesel	FCEV 350 bar	FCEV 700 bar	FCEV LH2	BEV	Catenary
Truck w/o powertrain[1]	55	55	55	55	55	55	55
Powertrain	18	18	130	130	126	83	119
Private infrastructure	0	0	0	0	0	15	0
Total energy/ fuel OPEX[1]	70	130	65	69	71	20	96
Motor vehicle taxation[2]	9	9	22	22	22	16	21
Maintenance & Insurance [1]|[2]	80	80	72	72	72	65	64
Road toll[1]	10	10	10	10	10	10	10
TCO w/o residual value	241	301	353	358	355	265	364

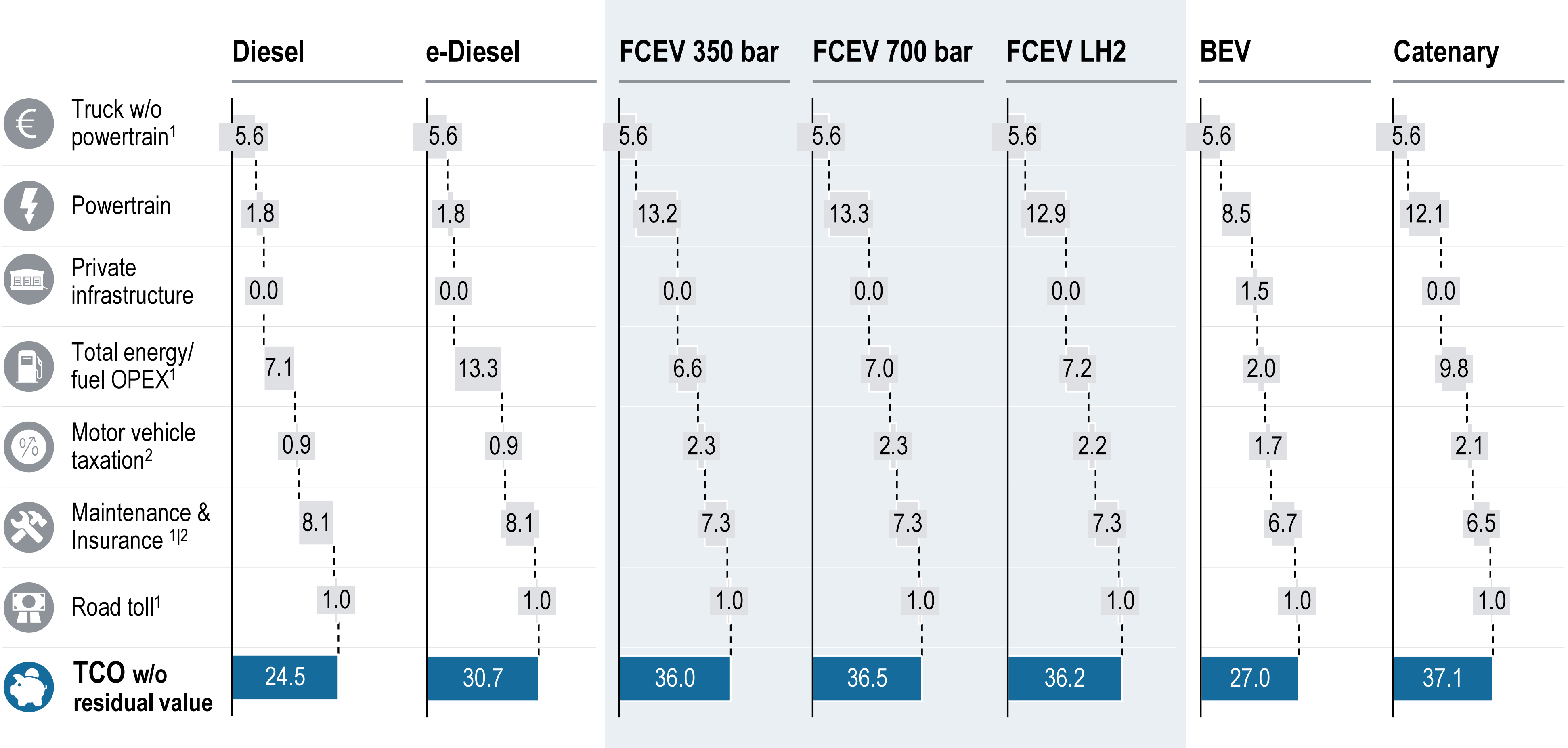
1) Deviations of results are related to payload differences of different technologies 2) Deviations of results are related to calculation based on higher CAPEX

Note: Diesel maintenance cost set at a higher level compared to base assumption; cost for all other technologies was adapted to maintain the assumed relation of costs for diesel vs. ZEV

Source: Brau Union Austria; Roland Berger

Looking at the OPEX side, the cost for vehicle maintenance partly result in higher costs than energy and fuel on the short routes

Leoben-Göss case – 2023 TCO cost breakdown [EUR ct/tonne-km; 1st & 2nd life]



	Diesel	e-Diesel	FCEV 350 bar	FCEV 700 bar	FCEV LH2	BEV	Catenary
Truck w/o powertrain[1]	5.6	5.6	5.6	5.6	5.6	5.6	5.6
Powertrain	1.8	1.8	13.2	13.3	12.9	8.5	12.1
Private infrastructure	0.0	0.0	0.0	0.0	0.0	1.5	0.0
Total energy/ fuel OPEX[1]	7.1	13.3	6.6	7.0	7.2	2.0	9.8
Motor vehicle taxation[2]	0.9	0.9	2.3	2.3	2.2	1.7	2.1
Maintenance & Insurance [1|2]	8.1	8.1	7.3	7.3	7.3	6.7	6.5
Road toll[1]	1.0	1.0	1.0	1.0	1.0	1.0	1.0
TCO w/o residual value	24.5	30.7	36.0	36.5	36.2	27.0	37.1

1) Deviations of results are related to payload differences of different technologies 2) Deviations of results are related to calculation based on higher CAPEX

Note: Diesel maintenance cost set at a higher level compared to base assumption; cost for all other technologies was adapted to maintain the assumed relation of costs for diesel vs. ZEV

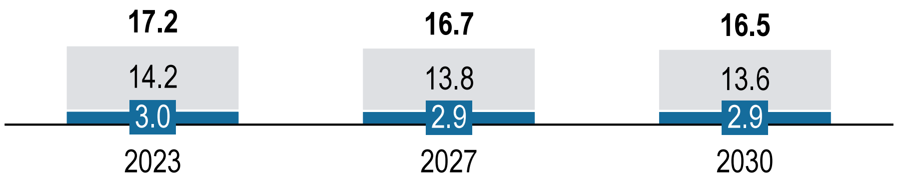
Source: Brau Union Austria; Roland Berger

Replacing the distribution fleet with zero-emission vehicles on this route will allow for a significant annual emission savings potential

Leoben-Göss case – Environmental analysis

CO_2 savings potential[1]

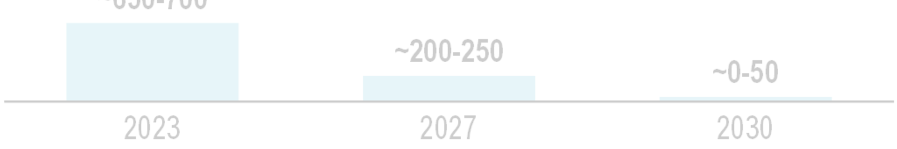
Well to Wheel [tonnes CO_2e/year]



Estimated CO_2 price for FCEV cost parity

[EUR/tonnes CO_2e]

Due to neglected consideration of residual value, results not 1:1 comparable to CO_2 price in other case studies (skewed results).



Pollution reduction potential[2]

- Fleet change towards zero-emission trucks allows for a total reduction of NOx pollutants
- Particulate matter can also be reduced due to more efficient driving patterns, incl. regenerative braking for electric vehicles

■ Tank to Wheel ■ Well to Tank ■ Est. CO2 price

Emissions reductions

- Total greenhouse gas emissions reduction to be realised over 10 years with 10 trucks: **1,722 t CO_2e**
- Increased emissions from frequent stops and drop-offs could be mitigated as no emissions and lower pollution would be produced compared to diesel

Opportunities

- Steiermark to potentially become a key region in hydrogen applications – Regional activities promoting FCH technologies in mobility and transport provide an good point of reference for cooperation with other actors to reduce emissions in the larger region
- Activities in neighbouring region Carinthia also develop optimised use of green hydrogen, benefitting the further development of zero-emission transport in the area

1) CO_2 savings potential refers to one potential zero-emission vehicles for the specific route
2) Pollution reduction potential not quantified as specific limits are set for each heavy duty diesel engine on the vehicle test stand

Source: Brau Union Austria; Roland Berger

BEV are the best fit on this route from a TCO and operations perspective – FCEV need further support to become competitive

Leoben-Göss case – Enablers and constraints for FCH technology

Potential enablers and constraints

!

- Strong company interest in zero-emission distribution processes pushes for alternative technologies
- TCO results shows that FCH technology could potentially be an option – Yet only under the condition that access to public infrastructure is provided
- The relatively low mileage offers potential to operate the trucks for up to 15 years which would benefit the TCO

?

- A potentially positive case for FCEV depends on the residual value and the development of public hydrogen refuelling stations
- As the H_2 demand of the fleet would be rather low, the potential refuelling infrastructure would need to be used for other applications and by other regional actors (i.e. enabling a business case for the refuelling station operator)

Synthesis

- The case study shows that the **potential for FCH technology** is **limited** for this regional distribution route – **BEV technology seems better suited as indicated by TCO result**
- Furthermore, as there are **no payload constraints** in this operation, **BEV are a good** fit from both a **commercial and operational point of view**
- Once **higher certainty** is achieved **on the FCEV (second) market development, incl. the residual value** of a truck and powertrain, also **FCH technology** could develop a **more favourable TCO**
- If the **uptake of BEV is not possible due to constraints** to set up the required charging stations at the brewery, **FCEV could be considered**, under the **key prerequisite** of setting up the required **H_2 infrastructure:**
  - **Public refuelling infrastructure and further synergies** in the Steiermark region would be needed to build a case for FCH trucks as **private infrastructure is not cost-effective** for this number of trucks with low consumption
- **Also, more H_2 demand and synergies** would need to be stimulated, e.g. forklifts, passing (long-haul) trucks

Source: Brau Union Austria; Roland Berger

The case study on the Austrian route in Leoben-Göss was supported by specific information and data from Brau Union Austria

Leoben-Göss case – Background

Road freight sector in Austria

Information on the road freight sector

- Austria sees an increasing volume of road transport with approx. 574 m tonnes of goods transported in 2018
- 70% of Austrian trucks drive regionally, while foreign trucks transport the majority of their cargo on routes over 500 kilometres
- Overall, the Austrian road freight industry revenue for transport by road is EUR 10,3 bn (2018)

Main transport corridors

- Austria's largest cities are connected by a network of highways; the country is positioned on three important European road corridors (Baltic-Adriatic, Rhine-Danube, Scandinavian-Mediterranean) and is considered a transit country

Information on company supporting the case

Company information

BRAU UNION ÖSTERREICH

Name	Brau Union Austria (part of the HEINEKEN Company)
Industry	Brewery (local distribution with owned fleet of vehicles)
Headquarters	Linz
Zero-emission ambition[1]	The "green brewery Göss" is a zero-emission production since 2016 with plans to extend the sustainability ambition to the distribution processes

Depot linked to route

Location	Leoben-Göss
Description	Brewery, production facility
Total number of trucks	14 trucks (owned and leased)

[1] Local strategy is linked to the HEINEKEN group sustainability strategy with its mission to „Brewing a better world“

Source: Brau Union Austria; Statista; Statistik Austria; Roland Berger

D.3.9 Flen-Stockholm case [Unilever]

For the Flen-Stockholm case study, several underlying assumptions were adjusted in alignment with the case study partner

Case study-specific disclaimer

For the development of this case study and due to the particularity of the operation, several assumptions in the base TCO model were adjusted in close alignment with Unilever.

Introduced specific changes in the case study in alignment with the Advisory Board case study partners

TCO calculation w/o the residual value	> The case study illustrates that with a low annual mileage, the assumed residual value as calculated by the TCO model has a strong impact on the results. Moreover, the data in this case study reflect the TCO that can be attributed to Unilever operations as the operation is currently carried out by a subcontractor. As such, it can be assumed that the utilisation of the deployed vehicle is generally higher and trucks do not only operate on this particular route but also serve further clients. In this case study, it was decided to show the TCO results "as if the route were operated by Unilever with own trucks". Therefore, the results without considering a potential residual value are included[1].
Tonne-km calculation	> Considering the average loading factor as well as the low mileage, the tonne-km calculation is calculated assuming the same payload capacity for all technologies. In this view, considering potential payload gains/losses through zero-emission technologies are not considered.
Environ-mental analysis	> The calculation of the estimated CO_2 price for FCEV cost parity in this case study is based on a calculation without considering the residual value[1]. In this specific case study, the results can be skewed and are not 1:1 comparable to the CO_2 price for FCEV cost parity calculated in other case studies in which the residual value is considered in the overall TCO view. This is due to the fact that considering the residual value shows a more favourable view on the cost development of FCEV and BEV technology, i.e. a lower cost delta to be bridged in order to achieve cost parity with diesel technology.

1) Due to the early stage of the market with very limited re-sale of zero-emission vehicles, general uncertainty with regards to the residual value of truck exists

Source: Unilever; Roland Berger

FCH technology could be a good fit and suited for the additional energy needs of the operation with refrigerated trucks in Sweden

Flen-Stockholm case – Overview

Location and route

- The route connects a factory with warehouses and stores in the capital - In this operation, the delivery of goods is carried out within the inner city area
- The route is carried out with different truck types –smaller rigid trucks (18 tonnes) and large tractor/trailer combinations (64 tonnes)
- The route is set on mostly flat terrain and involves deliveries in towns / cities
- In the winter months, snow and ice regularly have an impact on road conditions

Setting – Truck and operations

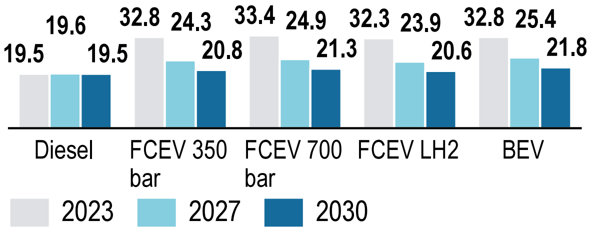
Truck type	Rigid 4x2, 18 tonnes Refrigerated truck
Daily range	260 km
Operation	173 days/year
Fleet size	5
Payload	5.3 tonnes

Logistic operation
Refrigerated trucks transport ice cream from the production site in Flen to the capital on a secondary outbound route. The route connects the factory with outlets in the Stockholm area, including 1-10 stops per route. The transported volume follows seasonal patterns.

Infrastructure

- Installation of H_2 refuelling station required – There is no hydrogen refuelling infrastructure in proximity of the factory and the Stockholm stations are not suited for trucks
- Nordic Hydrogen Corridor initiative could provide hydrogen supply, looking at production and distribution

TCO analysis [EUR ct/tonne-km; 1st & 2nd life]

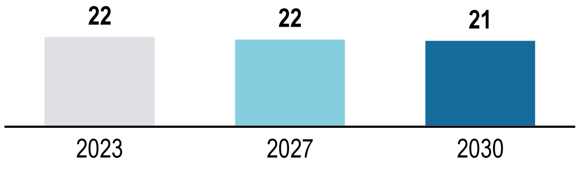


FCEV could be an attractive zero-emission alternative over time. Also, BEV are comparable cost level at scale. However, diesel TCO still lower also in 2030 compared to both technologies.

Environmental analysis

Zero-emission trucks offer significant annual CO_2 savings. Over the assumed lifetime of ten years, the electrification of the fleet of five trucks could lead to a total of 1,113 t CO_2 emissions savings

Yearly truck CO_2 savings potential – WTW [tCO_2e]



Source: Unilever; Roland Berger

The Flen-Stockholm ice cream delivery route illustrates that plannability and additional energy needs can make a case for FCEV

Flen-Stockholm case – Description

Investigated route

Existing HRS[2] (cars) Main depot Stores

Potential HRS[2] for trucks

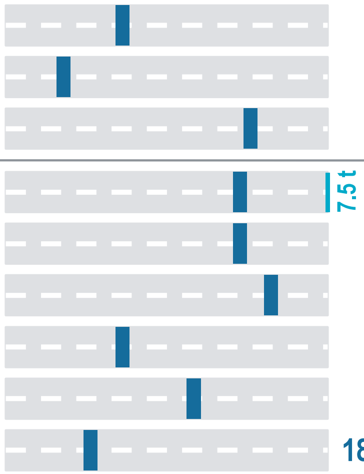
- The route connects a factory with warehouses and stores in the capital - In this operation, the delivery of goods is carried out within the inner city area
- The route is carried out with different truck types – smaller rigid trucks (18 tonnes) and large tractor/trailer combinations (64 tonnes)
- The route is set on mostly flat terrain and involves deliveries in towns / cities
- In the winter months, snow and ice regularly have an impact on road conditions

Case description[1]

Truck type	Rigid 4x2, 18 tonnes Refrigerated truck

Logistic operation

Refrigerated trucks transport ice cream from the production site to the capital on a secondary outbound route. The route connects the factory with outlets in the capital, including 1-10 stops per route. The number of stops and transported volume depend on the seasons, with higher demand in summer. The transport is carried out by subcontractors as 'less than truckload' (LTL) shipping as the operation doesn't require the use of the entire truck and the subcontractor also transports goods for other clients.



Route	**Route length**	260 km
	Fleet size (on average)[3]	5
	Operation	73 days
Truck performance	**Payload**	5.3 tonnes
	Avg. loading factor (weight)	70%
	Maximum speed	80 km/h
	Daily range	260 km
	Annual mileage	18,980 km
	H_2 consumption	18 kg(H_2)/day

Legend Low High

Infrastructure[2]

- Each truck operates on avg. 260 km per day – this would be an avg. consumption of ~18 kg(H_2)/day (at 0.069 kg(H_2)/km) and a H_2 demand of ~90 kg(H_2)/day for the whole fleet

Potential truck HRS

- H_2 demand not sufficient for private HRS (minimum of 0.5 t/day advisable for commercial benefit); public HRS required with ext. H_2 supply

Potential H_2 prod. facility

- Supply from electrolysis installation with at least 0.1 MW power needed

Potential synergies

- Production at the factory is linked to a higher number of trucks of different types
- Further (multi-modal) applications could be leveraged at the factory

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1) Data verified with stakeholders

2) HRS = hydrogen refuelling station

3) The route is operated with different types of trucks: 18 tonnes trucks and 64 tonnes trucks, depending on the subcontractor; this number refers to the 18 t trucks

Source: Unilever; Roland Berger

Specific data is introduced in the total cost of ownership model to reflect the real-life operations of the case study

Flen-Stockholm case – Specific assumptions

Main input changes to the TCO model base assumptions

Operation	> Annual mileage set at 18,980 km/year > Operation on route set for 73 days/year > Max. payload set to 7.5 tonnes > Route profile set to a rather homogenous pattern due to the plannability of the route, yet with varying stops for delivery
Fuel cell and H_2 technology	> Additional 2 kW of fuel cell size are assumed for higher energy needs > Consumption of H_2 was increased by 0.003 kg(H_2)/km to reflect the increased need of energy for the additional refrigeration equipment (Garde et al. 2012)
Energy and fuel	> Energy price for diesel set at 1.03 EUR/l net price > Diesel consumption set at 0.37 l/km to reflect the need of energy on this route for the refrigerated truck; the principle of a consumption increase is also applied for BEV and catenary (+4%, calculated on the basis of the increased hydrogen consumption incl. advantages of the electric powertrain)[1]
Private / public refuelling	> Public refuelling assumed for all technologies
CO_2 emissions	> CO_2 emssions per litre diesel set at 3,170 gCO_2e/l to reflect the diesel B5 blend in Sweden
Road toll	> No direct road toll charges apply on this route, however the city of Stockholm applies a congestion charge per day of max. ~4.50 EUR that is reflected as 0.02 EUR/km

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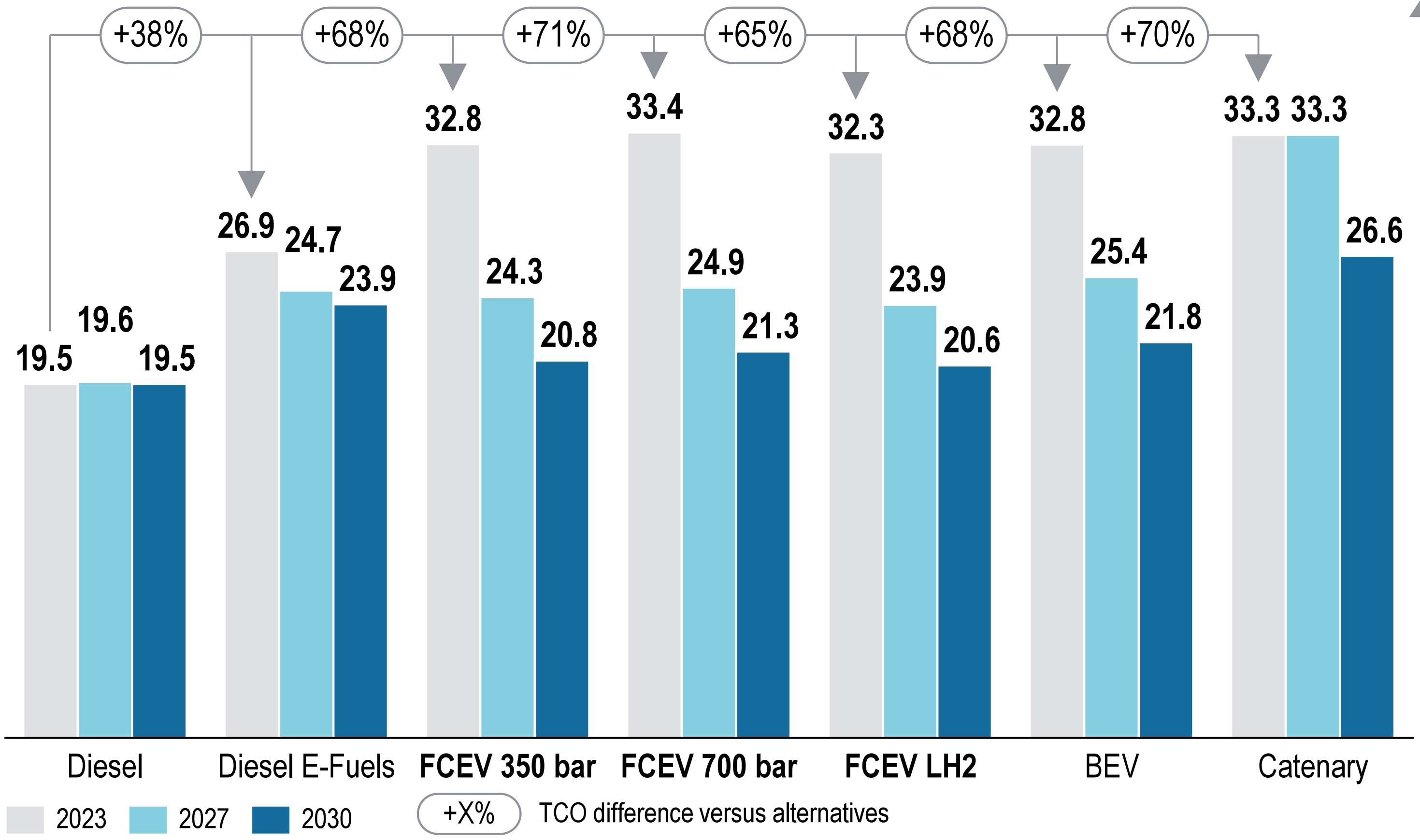
[1] This approach ensures the consistent calculation of all case studies and is based on data gathered in the Alsace region case study

Source: Unilever; Garde et al. at World Hydrogen Energy Conference 2012; Roland Berger

TCO results demonstrate that FCEV and BEV at scale will get closer to diesel TCO – Both technologies at very comparable cost levels

Flen-Stockholm case – High-level TCO assessment [EUR ct/tonne-km; 1st & 2nd life]

TCO w/o residual value



Comments

- A significant **cost down potential** for FCEV **at scale** exists **looking at 1st and 2nd life**

On a tonne-km basis:

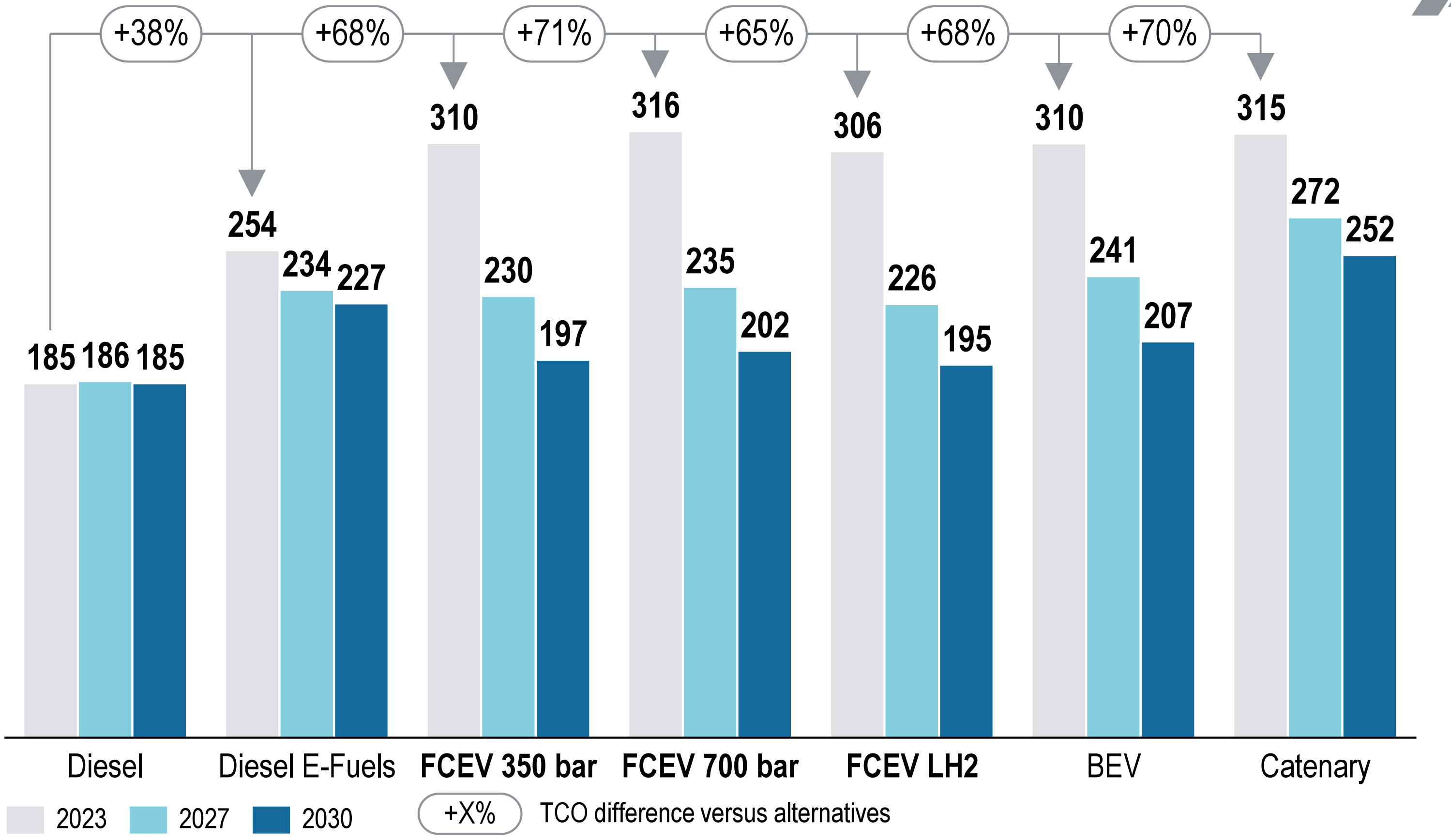
- FCH trucks still have a **cost premium of up to ~71% in 2023** compared to diesel but become **more cost-competitive by 2030**
- **FCEV and BEV** are overall at a **very comparable cost level**
- The **payload corrected** view indicates that **diesel e-fuels trucks** could be a **potential alternative in 2023/2027** – yet not at scale in 2030

Source: Unilever; Roland Berger

Also the EUR/truck TCO results show the commercial potential of FCH and BEV technology – Slight cost advantage of FCEV possible

Flen-Stockholm case – High-level TCO assessment [kEUR/truck; 1st & 2nd life]

TCO w/o residual value



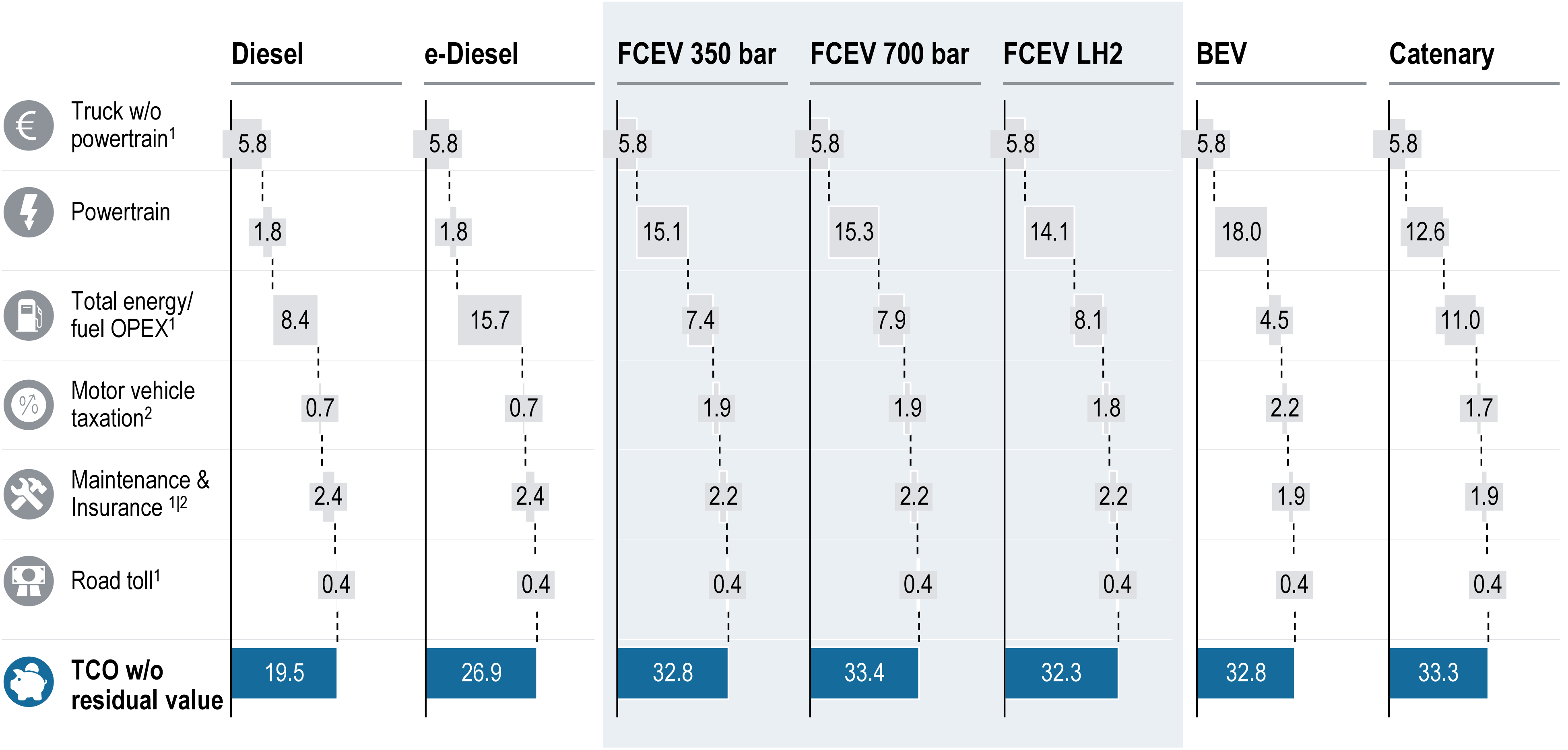
Comments

- The EUR/truck TCO perspective also shows **the cost down potential** for FCEV technology **at scale**
- FCH trucks get closer to diesel TCO in 2030, yet a cost premium remains
- Looking at **BEV and FCEV**, both **technologies are at very comparable cost levels, however not yet cost-competitive with diesel trucks**
- **Diesel e-fuels trucks would not be cost-competitive at scale** – positive TCO in 2023/ 2027 due to low mileage

Source: Unilever; Roland Berger

For all technologies, the cost of energy/fuel is a main cost driver across technologies – Cost of powertrain decisive for all ZEV

Flen-Stockholm case – 2023 TCO cost breakdown [EUR ct/tonne-km; 1st & 2nd life]



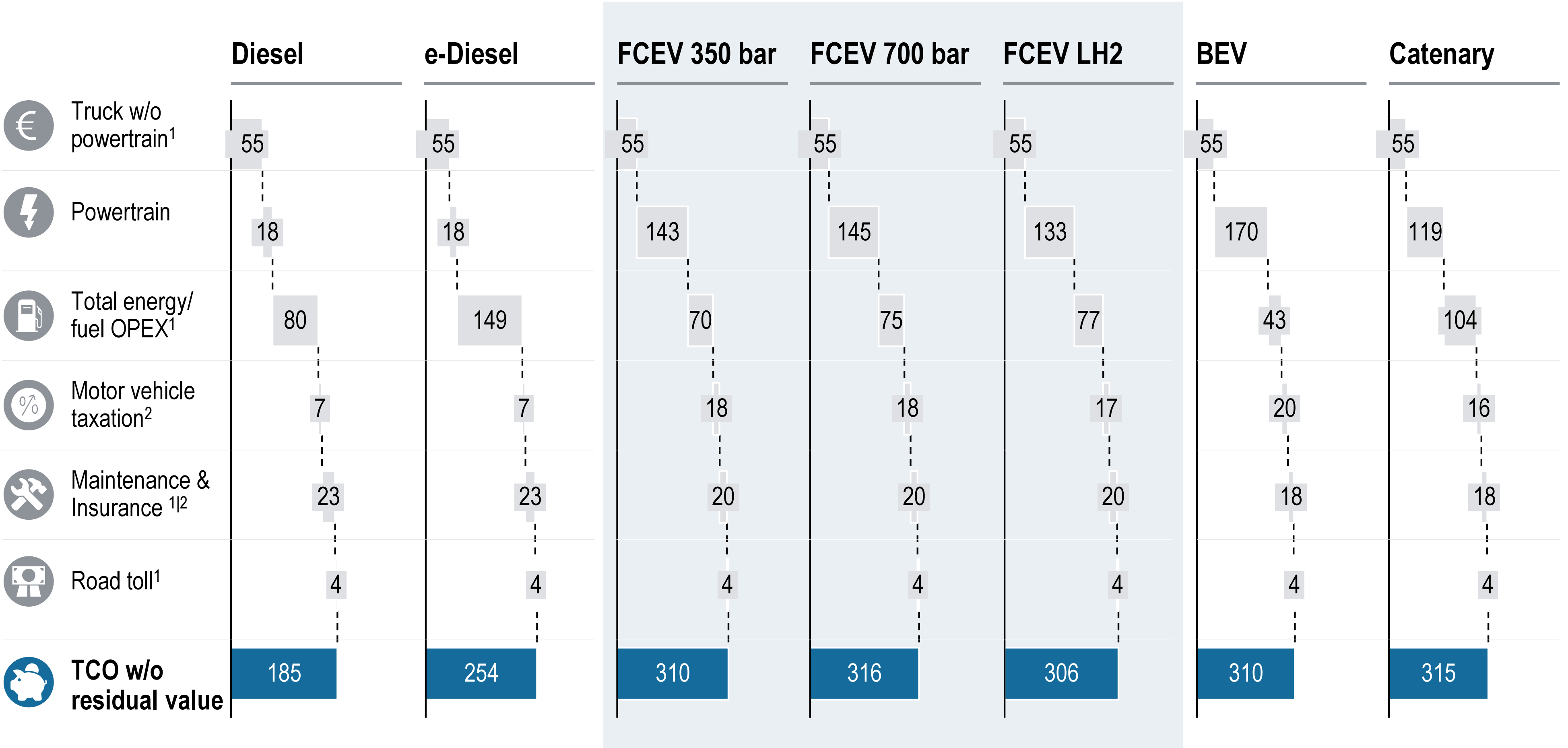
	Diesel	e-Diesel	FCEV 350 bar	FCEV 700 bar	FCEV LH2	BEV	Catenary
Truck w/o powertrain[1]	5.8	5.8	5.8	5.8	5.8	5.8	5.8
Powertrain	1.8	1.8	15.1	15.3	14.1	18.0	12.6
Total energy/ fuel OPEX[1]	8.4	15.7	7.4	7.9	8.1	4.5	11.0
Motor vehicle taxation[2]	0.7	0.7	1.9	1.9	1.8	2.2	1.7
Maintenance & Insurance [1|2]	2.4	2.4	2.2	2.2	2.2	1.9	1.9
Road toll[1]	0.4	0.4	0.4	0.4	0.4	0.4	0.4
TCO w/o residual value	19.5	26.9	32.8	33.4	32.3	32.8	33.3

1) Deviations of results are related to payload differences of different technologies 2) Deviations of results are related to calculation based on higher CAPEX
ZEV = Zero emission vehicles

Source: Unilever; Roland Berger

The relatively high powertrain cost of ZEV indicate that the assumed cost-down potential over time is crucial to reach competitiveness

Flen-Stockholm case – 2023 TCO cost breakdown [kEUR/truck; 1st & 2nd life]



	Diesel	e-Diesel	FCEV 350 bar	FCEV 700 bar	FCEV LH2	BEV	Catenary
Truck w/o powertrain[1]	55	55	55	55	55	55	55
Powertrain	18	18	143	145	133	170	119
Total energy/ fuel OPEX[1]	80	149	70	75	77	43	104
Motor vehicle taxation[2]	7	7	18	18	17	20	16
Maintenance & Insurance [1|2]	23	23	20	20	20	18	18
Road toll[1]	4	4	4	4	4	4	4
TCO w/o residual value	185	254	310	316	306	310	315

1) Deviations of results are related to payload differences of different technologies 2) Deviations of results are related to calculation based on higher CAPEX

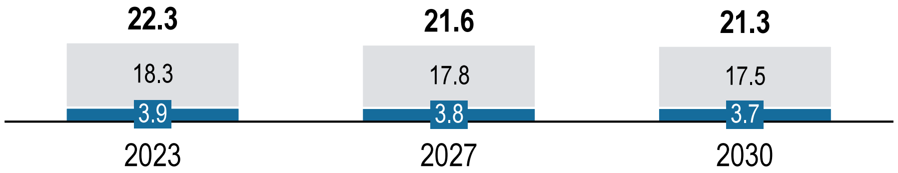
Source: Unilever; Roland Berger

Replacing the investigated fleet with zero-emission vehicles on this route will allow for a significant annual emission savings potential

Flen-Stockholm case – Environmental analysis

CO_2 savings potential[1]

Well to Wheel [tonnes CO_2e/year]



Estimated CO_2 price for FCEV cost parity

[EUR/tonnes CO_2e]

Due to neglected consideration of residual value, results not 1:1 comparable to CO_2 price in other case studies (skewed results).

Pollution reduction potential[2]

- > Fleet change towards zero-emission trucks allows for a total reduction of NOx pollutants
- > Particulate matter can also be reduced due to more efficient driving patterns, incl. regenerative braking for electric vehicles

■ Tank to Wheel ■ Well to Tank ■ Est. CO2 price

Emissions reductions

- > Total greenhouse gas emissions reduction to be realised over 10 years with five trucks: **1,113 t CO_2e**
- > Increased emissions from frequent stops and drop-offs could be mitigated as no emissions and lower pollution would be produced compared to diesel

Opportunities

- > The access to renewable energy in Sweden, esp. from hydropower, can serve as a good foundation of green hydrogen production at a larger scale
- > Current activities in the Stockholm region around hydrogen application, e.g. hydrogen buses, refuelling stations, and the initiative on the Nordic Hydrogen Corridor can support companies in making the change towards FCH trucks, as increasing infrastructure and technology knowledge is built

---

1) CO_2 savings potential refers to one potential zero-emission vehicles for the specific route
2) Pollution reduction potential not quantified as specific limits are set for each heavy duty diesel engine on the vehicle test stand
Source: Unilever; Roland Berger

The Flen-Stockholm case shows that the fixed go-and-return operation could provide a good opportunity for FCH technology

Flen-Stockholm case – Enablers and constraints for FCH technology

Potential enablers and constraints

!

- The LTL[1] delivery route offers good conditions for FCH technology uptake due to high plannability
- There is further leverage to potentially replace a higher number of vehicles in the fleet with FCH trucks linked to the specific route
- Access to renewable energy offers potential for green hydrogen production
- The route link to the Swedish capital and the existing infrastructure (to be adapted for trucks) could be leveraged as refuelling stations in the city will offer further potential also for other companies

?

- Access to public infrastructure needed as H_2 demand not sufficient for private HRS – Collaboration with ext. partners (e.g. in Stockholm) to aggregate demand from multiple routes/multiple logistic companies would need to be investigated
- The TCO outlook depends on the utilisation of the vehicle – Generally, it is assumed that a higher utilisation of the vehicle is carried out by the sub-contractor, yet the modelled TCO reflects only the potential costs that can be attributed to the case study company's operations

Synthesis

- Compared with diesel and looking at the TCO cost-down potential over time, FCH technology represents **an potential suitable zero-emission alternative**
- However, **FCH as well as battery technology** are at very **comparable cost levels** and **not yet competitive with diesel trucks until 2030**
- Once **higher clarity on the secondary market for FCEV exists in relation to the residual value** of a truck and powertrain, **FCH technology** could develop a **more favourable TCO**
- Cost advantages of **FCH technology** (also compared to BEV) could become **clearer if**
  - there is **no space to charge vehicles** at the depot
  - **external influences**, e.g. as the energy consumption in winter, would **require higher levels of energy**
  - **charging of a fleet of BEV** would lead to **high energy costs** and a (potentially too) **high demand on the electricity grid** in addition to the cost of infrastructure
- The installation of **hydrogen infrastructure would be necessary**, with higher **potential for set up in Stockholm** (assuming refuelling stops can be integrated into the route)

---

[1] The 'less than truckload' (LTL) shipping operation doesn't require the entire truck by the case study company; the subcontractor also transports goods for other clients in the same truck

Source: Unilever; Roland Berger

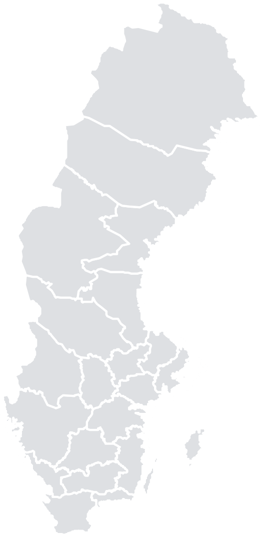
The case study on the regional delivery route in Sweden was supported by specific information and data from Unilever

Flen-Stockholm case – Background

Road freight sector in Sweden

Information on the road freight sector

- More than 500 m tonnes of freight are carried in Sweden per year (2018)
- More than 90% of road freight transported is domestic freight carried within the country
- Overall, the road freight industry revenue for transport by road in Sweden is EUR ~10.5 bn (2017)



Main transport corridors

- Sweden has 57 national roads with a total length of 8,900 km connecting North and South, as well as East and West
- The national roads are present in 20 of the 21 counties of Sweden, with Gotland County as a Swedish island being the only exception

Information on company supporting the case

Company information

Name	Unilever
Industry	Consumer goods company
Headquarters	London, United Kingdom; Rotterdam, Netherlands
Zero-emission ambition	Unilever commits to ensure net-zero carbon emissions from all its products from cradle to shelf b y 2039

Depot linked to route

Location	Flen, Sweden
Description	Production facility

Source: Statista; Eurostat; Unilever; Desk research; Roland Berger

E. Barriers and recommendations

The potential of FCH technology for heavy-duty trucks is recognised – Remaining barriers for commercialisation need to be addressed

Overview

Rationale

- **Fuel cell and hydrogen technology for heavy-duty trucks** is a **relatively new application** with mostly demonstration projects on the roads – High technology potential considered
- **Some research has been done** and is ongoing – Current **need is to identify areas for targeted support** for research, development and innovation

Focus on targeted areas relevant to further research & development

Objectives

- **Identification of barriers** for FCH technology for HD trucks (in the short-term)
- **Identification of Research and Innovation (R&I) priorities** for commercialisation
- **Identification of levers** for enabling the **market uptake and commercialisation**

Definition of main roadblocks for commercialisation

Sources of information

- **Project knowledge and learnings** along the study process, e.g. state of the art analysis, TCO modelling, case study development
- **Interviews with 20+ industry experts along the value chain** (Advisory Board and further contacts)
- **Advisory Board discussions** and **internal expert network**

Involvement of industry experts to solidify and amend findings

Approach

- Collection of a **long-list of constraints and obstacles, points of policy discussions** and **industry requirements** raised over the course of the study
- **Identification of barrier clusters** and **in-depth analysis of problem statements**
- **Prioritisation** of barriers and **development of recommendations**[1]

Analysis and prioritisation

---

1) For the developed recommendations, please refer to chapter E.3

Source: Roland Berger

Barriers reflect the current status of technology development –Their prioritisation shows fields of action to ensure commercialisation

Identification and prioritisation process

Input

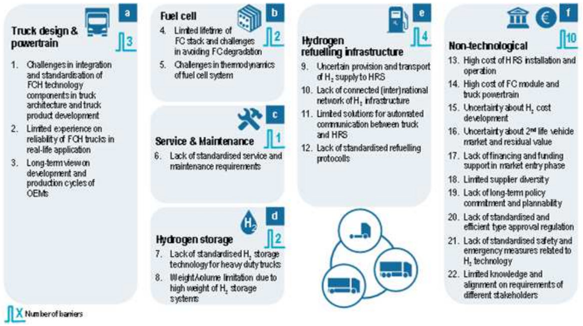
Selection criteria

Project knowledge and research

Case studies and expert interviews

- > Relevance for most truck types and models
- > Urgency for technology commercialisation
- > Number of technical areas concerned
- > Frequency with which barriers were named in the stakeholder responses and expert interviews

Identification of barriers



Truck design & powertrain a 3

1. Challenges in integration and standardisation of FCH technology components in truck architecture and truck product development
2. Limited experience on reliability of FCH trucks in real-life application
3. Long-term view on development and production cycles of OEMs

Fuel cell b 2

4. Limited lifetime of FC stack and challenges in avoiding FC degradation
5. Challenges in thermodynamics of fuel cell system

Service & Maintenance c 1

6. Lack of standardised service and maintenance requirements

Hydrogen storage d 2

7. Lack of standardised H_2 storage technology for heavy duty trucks
8. Weight/volume limitation due to high weight of H_2 storage systems

Hydrogen refuelling infrastructure e 4

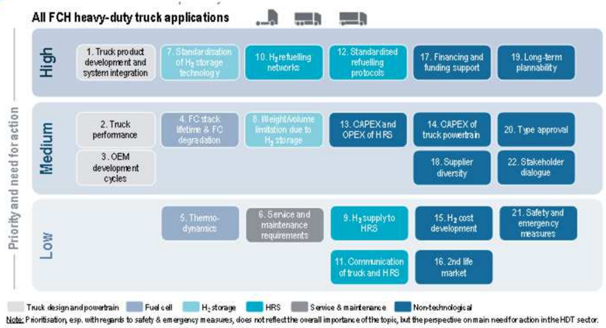
9. Uncertain provision and transport of H_2 supply to HRS
10. Lack of connected (inter)national network of H_2 infrastructure
11. Limited solutions for automated communication between truck and HRS
12. Lack of standardised refuelling protocolls

Non-technological f 10

13. High cost of HRS installation and operation
14. High cost of FC module and truck powertrain
15. Uncertainty about H_2 cost development
16. Uncertainty about 2nd life vehicle market and residual value
17. Lack of financing and funding support in market entry phase
18. Limited supplier diversity
19. Lack of long-term policy commitment and plannability
20. Lack of standardised and efficient type approval regulation
21. Lack of standardised safety and emergency measures related to H_2 technology
22. Limited knowledge and alignment on requirements of different stakeholders

X Number of barriers

Prioritisation of barriers



All FCH heavy-duty truck applications

Priority and need for action

High	1. Truck product development and system integration	7. Standardisation of H_2 storage technology	10. H_2 refuelling networks	12. Standardised refuelling protocols	17. Financing and funding support	19. Long-term plannability
Medium	2. Truck performance	4. FC stack lifetime & FC degradation	8. Weight/volume limitation due to H_2 storage	13. CAPEX and OPEX of HRS	14. CAPEX of truck powertrain	20. Type approval
	3. OEM development cycles				18. Supplier diversity	22. Stakeholder dialogue
Low		5. Thermo-dynamics	6. Service and maintenance requirements	9. H_2 supply to HRS	15. H_2 cost development	21. Safety and emergency measures
				11. Communication of truck and HRS	16. 2nd life market	

Truck design and powertrain · Fuel cell · H_2 storage · HRS · Service & maintenance · Non-technological

Note: Prioritisation, esp. with regards to safety & emergency measures, does not reflect the overall importance of the topic, but the perspective on main need for action in the HDT sector.

Source: Roland Berger

E.1 Technological and non-technological barriers

Overcoming the remaining barriers will accelerate the widespread adoption of FCH technology in the heavy-duty truck sector

Key insights from the analysis

- Fuel cells and hydrogen applications are **clean, safe and innovative technologies** that are **key for a future of decarbonised mobility and transport** solutions
- The challenges and barriers FCH technology currently faces in the heavy-duty truck sector mainly stem from **being a relatively novel technology** for this application area that **needs initial support to unlock its full market potential**
- **None of the identified technological and non-technological barriers** are deemed **showstoppers for its successful commercialisation** within the next decade
- **Technological barriers** have been identified **along the FCH truck value chain**, from truck design to infrastructure availability, refuelling technology and service & maintenance offerings
- **Non-technological barriers** relate to **economic, political, legal and social framework conditions** within the FCH eco-system, relating to the cost premium of FCH trucks, regulatory harmonisation, planning security as well as technology acceptance and safety concerns
- There are viable options and **promising opportunities** in order to **speed up and optimise a large-scale roll-out of FCH technology in the HDT sector** in the upcoming years
- After identifying and prioritising key barriers, a set of **policy recommendations, including a Research & Innovation roadmap with four tailored project frameworks**, was formulated that could directly address these remaining barriers[1]

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1) For the developed recommendations, please refer to chapter E.3

Source: Roland Berger

Technological barriers focus on aspects along the FCH truck value chain – From truck design to infrastructure to service & maintenance

Technological barrier clusters

Truck design and powertrain

- > Barriers on integrating the FCH powertrain in existing chassis options while optimising weight and dimensions, overall cost and reliability of the vehicles

Fuel cell powertrain

- > Barriers regarding fuel cell specific challenges, such as lifetime, thermodynamics, optimisation of fuel cell integration

H_2 onboard storage

- > Barriers regarding the lack of standardised H_2 onboard storage technology[1]

Hydrogen refuelling infrastructure

- > Barriers regarding high space requirements for H_2 storage on-site the HRS, sufficient network coverage for future rollouts and uncertainty about the wide-spread availability of green /low-carbon H_2

Service & maintenance

- > Barriers regarding the lack of standardised service and maintenance requirements, workshop density, and spare part availability in early rollout markets

FCH technology is becoming increasingly mature

- > **Progress in research and industrial development** is bringing FCH heavy-duty trucks **closer to fulfilling** the **operational requirements of (long-haul) transport and logistics operations** in terms of range, refuelling time and payload capacity
- > **Further research and development** as well as technology optimisation is needed to **overcome remaining barriers** and **fulfil the requirements of all stakeholders**

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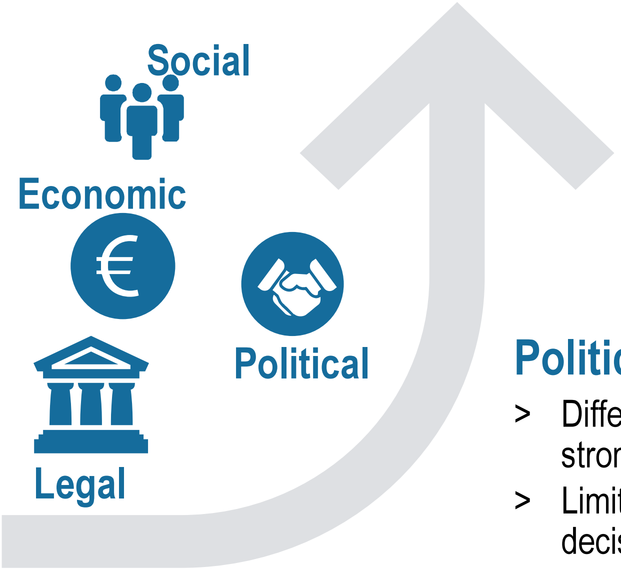
[1] Various options on storage technologies are currently being discussed, tested and announced, e.g. 350 bar, 500 bar and 700 bar gaseous compressed hydrogen or cryogenic liquid hydrogen at -253 °C as well as combinations such as cryo-compressed hydrogen storage

Source: Roland Berger

Non-technological barriers relate to economic, political, social and legal framework conditions within the FCH ecosystem

Non-technological barrier clusters



Economic aspects

> FCH technology for trucks is not yet commercially attractive, yet the opportunities exist for accelerated future uptake if volumes are ramped up (e.g. serial manufacturing of fuel cell systems > 3.000 p.a.)

> Barriers concern the lack of targeted funding and incentive schemes, e.g. financial support to mitigate the cost premium of FCH technology in order to make it cost-competitive for truck operators and logistics users

Political aspects

> Different zero-emission technologies see differing levels of political attention, with some actors strongly supporting battery technology, others the development of hydrogen technologies

> Limited planning security on the 'leading technology of the future' leads to reservation in business decisions and affects a potentially faster developments of the market

Legal aspects

> Limited harmonisation across European countries within their respective legal and regulatory frameworks affects international transport operations due to different rules and standards on heavy-duty trucks

> Regulatory harmonisation also plays an important role regarding the FCH truck approval processes that today are without standardised permitting procedures and see time consuming approval processes

Social aspects

> Limited experience and security concerns on hydrogen technology both within the concerned industries and among the public cause hesitation regarding technology acceptance

Source: Roland Berger

The identified barriers encompass technological and non-technological challenges along the truck development and operation

a

Truck design & powertrain

3

1. Challenges in integration and standardisation of FCH technology components in truck architecture and truck product development
2. Limited experience on reliability of FCH trucks in real-life application
3. Long-term view on development and production cycles of OEMs

b

Fuel cell

2

4. Limited lifetime of FC stack and challenges in avoiding FC degradation
5. Challenges in thermodynamics of fuel cell system

c

Service & Maintenance

1

6. Lack of standardised service and maintenance requirements

d

Hydrogen storage

2

7. Lack of standardisation of available H_2 storage technology for heavy-duty trucks
8. Weight/volume limitation due to high weight of H_2 storage systems

e

Hydrogen refuelling infrastructure

4

9. Insufficient development of very large-scale H_2 supply and transport to HRS
10. Lack of connected (inter)national network of H_2 infrastructure
11. Limited solutions for automated communication between truck and HRS
12. Lack of standardised refuelling protocols optimised for fast refuelling

f

Non-technological

10

13. High cost of HRS installation and operation
14. High cost of FC module and truck powertrain
15. Uncertainty about H_2 cost development
16. Uncertainty about 2nd life vehicle market and residual value
17. Lack of financing and funding support in market entry phase
18. Limited supplier diversity
19. Lack of long-term policy commitment and plannability
20. Lack of standardised and efficient type approval regulation
21. Lack of standardised safety and emergency measures related to H_2 technology
22. Limited knowledge and alignment on requirements of different stakeholders

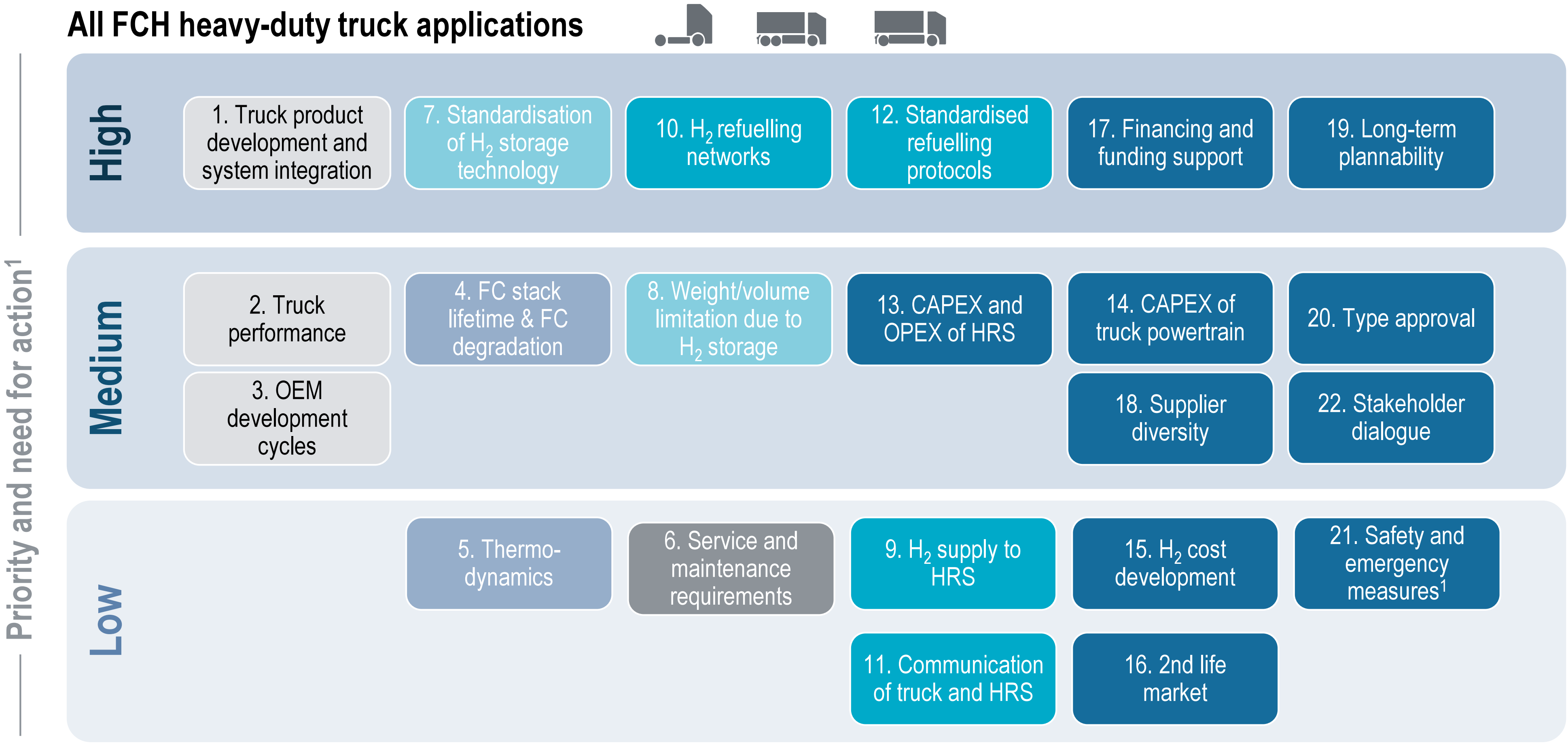
X Number of barriers

Source: Roland Berger

None of the barriers are deemed to be actual roadblocks for the wider implementation of fuel cell and hydrogen technology for HDT

Overview of barriers and priority for short-term R&I

All FCH heavy-duty truck applications



Priority and need for action[1]

High

- 1. Truck product development and system integration
- 7. Standardisation of H_2 storage technology
- 10. H_2 refuelling networks
- 12. Standardised refuelling protocols
- 17. Financing and funding support
- 19. Long-term plannability

Medium

- 2. Truck performance
- 3. OEM development cycles
- 4. FC stack lifetime & FC degradation
- 8. Weight/volume limitation due to H_2 storage
- 13. CAPEX and OPEX of HRS
- 14. CAPEX of truck powertrain
- 18. Supplier diversity
- 20. Type approval
- 22. Stakeholder dialogue

Low

- 5. Thermo-dynamics
- 6. Service and maintenance requirements
- 9. H_2 supply to HRS
- 11. Communication of truck and HRS
- 15. H_2 cost development
- 16. 2nd life market
- 21. Safety and emergency measures[1]

Truck design and powertrain · Fuel cell · H_2 storage · HRS · Service & maintenance · Non-technological

[1] Prioritisation, esp. with regards to safety & emergency measures, does not reflect the overall importance of the topic, but the perspective on main need for action in the HDT sector.

Source: Roland Berger

Based on the analysis of barriers, important overarching levers are identified to enable and promote widespread FCH truck deployment

Levers to enable FCH truck deployment

Joint development timeline

- In order to solve the chicken-and-egg dilemma of the hydrogen eco-system, it is imperative for all stakeholders to move along on the same sequenced timeline
- The politically driven decarbonisation agenda can be reflected in industry commitments – Levels of ambition should be aligned

Stringent and harmonised long-term policy frameworks

- Long-term policy frameworks are needed that are consistent with other policy and industry goals, such as high safety standards and standards on weights and dimensions for heavy-duty trucks
- This also refers to European legislation, e.g. a joint stance on the European toll system (Eurovignette Directive)

Financial and funding support mechanisms

- Tailored, overarching financial support and funding mechanisms for FCH HDT uptake need to harness and complement existing schemes at national and EU level[1]
- Unilateral and multilateral funding needed as technology deployment can be supported through multi-partner consortia (often international coalitions); funding for smaller scale projects should also be accessible more swiftly (at EU and national level)

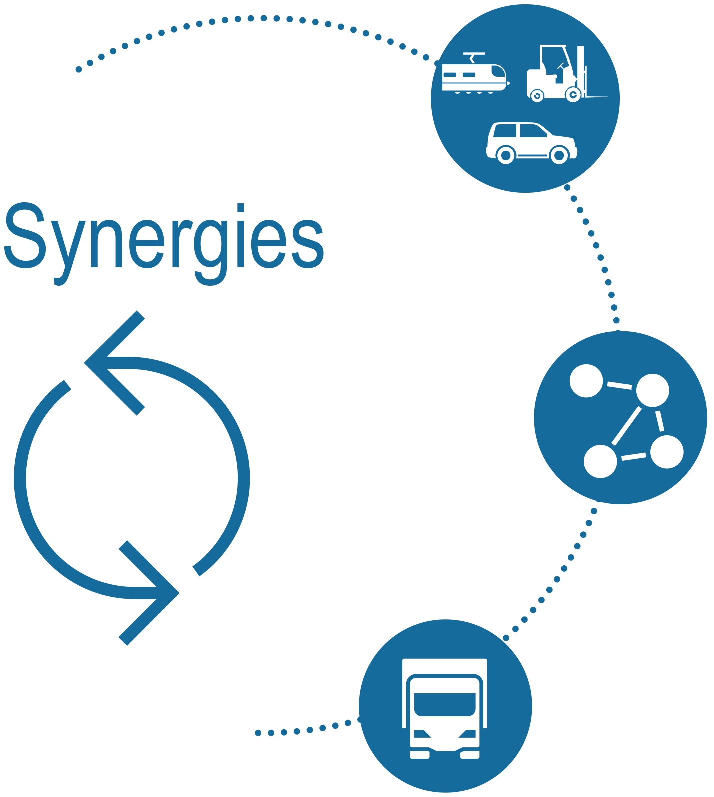
[1] Such as the EU Recovery Plan, the CEF Fund and other incentives and financial instruments from national hydrogen strategies

Source: Roland Berger

E.2 Synergies

Synergies with other modes of transport and hydrogen application in other sectors support can FCH technology implementation for trucks

Synergies



1 A key factor for the successful commercialisation of FCH technologies in the heavy-duty truck industry is **exploiting potential synergies of FCH applications** from **other modes of transport**, such as cars, buses, taxis, trains, forklifts and maritime (e.g. shared infrastructure, shared component production)

2 **Multimodal synergies** along the entire hydrogen value chain **create spill-over effects** for the commercial and operational roll-out of FCH technology

3 **Overcoming barriers** to FCH adoption **in the heavy-duty trucking** industry can **result in positive synergies** for other industries and vice-versa

Source: Roland Berger

Potential synergies have been identified that are to be explored further to accelerate the implementation of FCH technologies

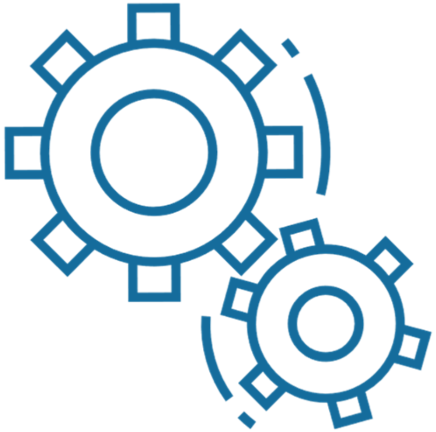
General synergies for FCH technology

1	**Decreasing production costs**	**Increasing production** of FCH components and parts **generate economies of scale** and thereby also contribute to **lower production costs** for specific FCH HDT components, e.g. volume production of fuel cells for passenger vehicles will positively influence the cost reduction for heavy-duty trucks	✓
2	**Transferable experience**	**Existing data on real-life operations** and related service & maintenance procedures from other transport industry segments, such as passenger vehicles and buses provide **valuable insights and knowledge** for truck operators and OEMs	✓
3	**Higher infrastructure utilisation**	Establishing a **network of multi-purpose hydrogen refuelling stations** that serve different transport applications results in **higher asset utilisation**, with **lower costs** for providers of refuelling infrastructure, H_2 suppliers and truck operators	✓
4	**Optimised production, use and transport of hydrogen**	Synergies can be achieved by **linking emerging hydrogen transport and energy ecosystems**, e.g. through geographical alignment of the EU's TEN-T and TEN-E corridors. Additionally, an increasing density of hydrogen production and distribution networks will **increase fuel availability** and **reduce transport distances and cost**	✓
5	**Demand for renewable hydrogen**	Increasing deployment of FCH HDT will **increase the demand for renewable hydrogen**, i.e. providing **additional revenue streams** with relatively high willingness to pay in contrast to large-scale industrial use while at the same time **decreasing the import dependency of other forms of (fossil) energy**	✓

Source: Roland Berger

Through the analysis of case study routes, concrete synergies for FCH trucks were identified in real-life transport operations

Synergies linked to case studies



1 HRS upgrading for trucks when link to existing infrastructure

> The availability of existing H_2 refuelling infrastructure, e.g. for passenger cars or buses, offers good potential for trucks as the existing technology can be upgraded for trucks; this would also have positive effects for the existing HRS as a utilisation close to 100% could reduce the OPEX of HRS by up to 25%[1]

2 Multi-partner collaboration in industrial hubs

> Proximity to industrial hubs, such as port operations, large production sites or transport hubs increases chances of hydrogen collaborations as multiple applications could benefit from the eco-system – Access to other hydrogen applications and the respective infrastructure, e.g. rail or maritime transport

3 Infrastructure availability to main transport corridors

> Like the link to industrial hubs, the connection to main transport corridors offers higher realisation potential for infrastructure set-up – Decarbonisation efforts will address heavily travelled routes first as the urgency is there and a constant, significant demand for H_2 can be ensured

4 Support and knowledge exchange in H_2 eco-systems

> The set-up of (mostly regional) hydrogen eco-systems provides companies and the public with access to infrastructure and local knowledge, as well as a stakeholder network to promote the deployment of FCH trucks, e.g. the 'Black Horse' project in Slovakia or the South Tyrolean Hydrogen Valley

5 Access to renewable energy and H_2 production

> Access to renewable energy production or existing H_2 production in vicinity to the depot or operations can lead to a facilitated set-up of a H_2 supply chain, with potential of earlier truck refuelling infrastructure availability, as investigated with on-site H_2 hubs for a logistics service provider in France

1) Based on industry expert interviews

Source: Advisory Board; Expert interviews; Roland Berger

E.3 Recommendations for Research and Innovation

Ambitious research and innovation projects can jump-start the transition of the transport and logistics industry to FCH technology

Research and innovation projects

R&I project framework

> The four technological high priority barriers should be addressed **by four research & innovation projects**, while **policy recommendations** are provided for the non-technology high priority barriers

> The **proposed comprehensive R&I projects** are particularly suited to **overcome the remaining technological barriers in the short-term** and accelerate the successful commercialisation of FCH HDT in the transport and logistics industry

> Their **project design should ensure a wide scope** so that they potentially also address the identified medium and low priority barriers to FCH market introduction

R&I Focus

> **Technology development and optimisation for HRS infrastructure** (including refuelling protocol development) as well as standardised hydrogen storage systems for FCH heavy-duty trucks

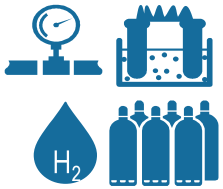
> **Development of prototypes** for all three use cases (i.e. 40, 27 and 18 tonnes GVW trucks for long-, medium- and short-haul distances respectively) in the area of truck and powertrain design to **improve integration and standardisation of FCH technology in existing truck architecture** and **designing new truck models** optimised for FCH applications

> **Cross-border multi-national large-scale demonstration project** of FCH heavy-duty fleets and the associated HRS infrastructure

> **Technology development** for build-up of high throughput, low footprint and energy-efficient **HRS networks**

Source: Roland Berger

Comprehensive R&I projects targeting high priority needs for action can address the remaining technological barriers in the short-term

	A **Technology development and optimisation for standardised on-board hydrogen storage systems for FCH HDT and refuelling protocol development**	**B** **Development of FC truck and powertrain prototypes for integration and standardisation of FCH technology**	**C** **Cross-border multi-national demonstration of FCH HDT fleets**	**D** **Technology development for high throughput, low footprint and high energy efficiency HRS for HDT**
High-level project scope	 350 bar 700 bar LH_2 Other options: 500 bar ccH_2 1)	 5-20 units 5-20 units 5-20 units	 500  20	 GH_2 supply to gaseous refuelling On-site production to gaseous refuelling LH_2 supply to gaseous refuelling LH_2 supply to LH_2 refuelling
Objectives of project	> Integrated technology development for optimised hydrogen storage for FCH HDT > Optimisation and standardisation of filling pressure, tank size, tank location, filling protocol, etc. > Analysis of total value chain TCO	> Development of prototypes in the area of truck and powertrain design to improve integration and standardisation of FCH technology in existing truck architecture > Design of new truck models optimised for FCH applications	> Large scale demonstration of 500 or more FCH HDT could accelerate the roll-out of fleet sized FCH truck deployment > Potential split in several sub-projects	> Development of refuelling protocols, storage optimisation, refuelling time and frequency for the roll-out of a comprehensive HRS network across Europe and/or several regional hubs, e.g. hydrogen valleys > Analysis of value chain and TCO calculations
Est. budget before funding	**EUR 10 m**	**EUR 100 m**	**EUR 350 m**	**EUR 5-10 m**

1) Cryo-compressed hydrogen

Source: Expert interviews; Roland Berger

The proposed R&I projects need to be set up to overcome the remaining technological barriers for FCH HDT commercialisation

Proposed Research and Innovation projects (1/2)

A **Technology development and optimisation for standardised on-board hydrogen storage systems for FCH heavy-duty trucks and refuelling protocol development**

In order to ensure a safe, efficient and fast refuelling process, the interface between the refuelling equipment and the truck needs to be standardised and ease of operation ensured. Today, further knowledge is needed on the implications of the heavy-duty refuelling process on station and vehicle and the requirements for both the refuelling station equipment and the truck technology (e.g. filling pressure, tank size, tank location, filling protocol, etc.). While refuelling protocols are currently being developed, the hardware and technology still need to be optimised for a safe truck-HRS communication. The suggested project addresses one of the main challenges related to the build-up of a comprehensive network of truck HRS with an approach of involving the whole value chain.

B **Development of FC truck and powertrain prototypes for integration and standardisation of FCH technology**

Integrating FCH technology into the existing truck architecture is a challenge that is being addressed by the industry – first FCH trucks have been developed by OEMs already. However, there need to be further efforts in developing more dedicated FCH truck products with truck models being optimised for FCH application. This project aims at the development of truck and powertrain prototypes for all transport and logistics use cases, covering long-, medium and short-haul operations. Such prototyping would also be instrumental in addressing remaining questions regarding restrictions on weights and dimensions of FCH trucks as well as payload implications depending on the applied H_2 storage systems. In this development process, further standardisation potential will be identified which will support efforts to bring down the costs of the truck (components). Involving the OEMs as well as the technology suppliers in this project also contributes to building up a European supply chain of FCH technology components for trucks.

Source: Roland Berger

The proposed R&I projects need to be set up to overcome the remaining technological barriers for FCH HDT commercialisation

Proposed Research and Innovation projects (2/2)

C **Cross-border multi-national demonstration of FCH heavy-duty fleets**

A cross-border multi-national large-scale demonstration project(s) is (are) suggested that includes a coalition of multiple stakeholders across the value chain in order to bring a high number of trucks on the road (up to 500 trucks in a scale-up scenario). Creating a project platform linking different industry players and supporting them with the target to bring the FCH trucks market into a pre-niche market scenario would speed up FCH truck product availability and provide further insights on reliability and durability of FCH trucks in real-life use. This type of project is needed in the short-term in order to build and expand the real-life experience with FCH trucks and gather field data for further technology development. Insights from ongoing projects (e.g. H2Haul) can be leveraged to build coalitions at a even larger scale. The project could also potentially be split in several sub-projects.

D **Technology development for hydrogen refuelling stations**

Linked to project A, it is also suggested to support the development of scaled refuelling stations (medium-, large-scale) in a dedicated project. Today's HRS are designed for passenger vehicles, yet they need to be adapted to service large trucks with higher refuelling demands. HRS for trucks will need to provide the required infrastructure solutions for transport operations, e.g. refuelling a larger fleet of trucks with a total of 1 tonne of hydrogen within a few hours at the end of the day. Research needs to cover HRS adaptions such as HRS size, storage solutions on site, hydrogen compression, optimisation of energy consumption, performance and throughput & utilisation requirements. Moreover, standardised refuelling protocols need to be developed to ensure the harmonisation of refuelling stations and processes across Europe and accelerate the development of a comprehensive roll-out of an HRS network, starting with designated regional hubs, such as hydrogen valleys.

Source: Roland Berger

Political initiatives and tailored programmes address non-technological barriers by providing funding and improving plannability

High-level proposition for political initiatives

Political initiatives

The short-term R&I projects must be accompanied by truck-specific political initiatives and tailored programmes that **specifically address the two identified non-technological high-priority barriers**, i.e. increase funding opportunities for FCH applications and improve plannability and long-term commitment towards the full commercialisation of FCH trucks

Public/private and private/private collaboration

- Coordinated interplay of public and private players as the prerequisite for a comprehensive transition along the entire value chain of heavy-duty trucks (e.g. public-private-partnerships to share business risks could be considered)
- Industry platforms to foster closer collaboration within the industry to enable consortia around commercial fleets
- Longer-term contracts between business partners to disperse uncertainty regarding market development and uptake of FCH applications, while providing both sides with increased plannability for a longer time horizon
- Large-scale projects including different OEMs, fuel cell providers and system integrators to stimulate the supply chain to decrease cost (e.g. increasing availability of trucks, parts and infrastructure)

- **CAPEX funds for production facilities**, e.g. direct financial support, such as grants, to set up facilities for new production lines to jump-start the industrialisation of FCH HDT production
- **R&D funding** to alleviate costs needed for continuing, accelerating and stepping up innovation research, prototype development and testing
- **Funding programmes targeting the entire truck life cycle** to provide incentives along the entire value chain – Such programmes need to be set up to cater to the specific needs and challenges of OEMs, suppliers, infrastructure providers and logistics users
- **Incentives for HRS providers targeting CAPEX and OPEX** to reduce market entry risks, e.g. through links to the station capacity (the funding amount is based on the size of the station's hydrogen storage[1])

Funding opportunites that improve plannability

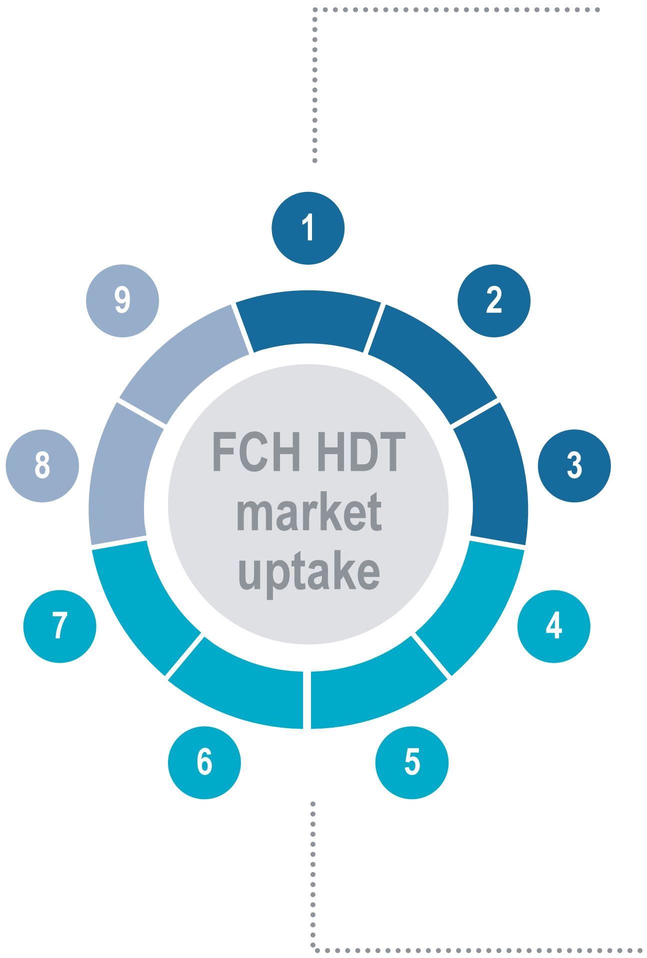
---

1) A successful example of this approach is the Low Carbon Fuel Standard's (LCFS) Hydrogen refuelling Infrastructure (HRI) credit provision programme in California; as of May 2020, this capacity-based funding instrument has supported the deployment of 48 hydrogen stations

Source: Roland Berger

The following instruments and levers complement the proposed R&I projects in order to accelerate FCH HDT market uptake

Concrete policy recommendations



EU

1. **Road toll exemption for zero-emission vehicles for longer time periods,** e.g. for 10 years, as well as considering road toll increases for higher emitting vehicles, such as in the Eurovignette Directive
2. **Government-driven base infrastructure coverage of countries,** e.g. as already in discussion as part of the Alternative Fuels Infrastructure directive
3. **Adjusted regulations on FCH heavy-duty truck dimension** to provide a legal framework for integrating alternative powertrains in trucks

National governments

4. **Exemption of levies and fees for production of green hydrogen** within an extended time period of up to 10 years and/or until binding targets of green hydrogen shares are fulfilled
5. **Subsidies for hydrogen refuelling station OPEX when stations are underutilised,** improving cost competitiveness of H_2 through higher plannability for station investors
6. **Tax breaks for logistics operators that transition to FCH HDT**, for example via stricter supply chain laws that incorporate provisions on CO_2 emission as an additional tax on logistics services and offerings
7. **Introduction of CO_2-related taxation in the logistics and delivery industry,** creating an additional incentive for logistics providers to speed-up a transition to zero-emission vehicles

Municipalities

8. **Preferred treatment for zero-emission vehicles,** e.g. through the establishment of lanes specifically dedicated to ZEV and guaranteed free parking zones for ZEV at refuelling stations and motorway rest stops
9. **Special permits for zero-emission vehicles to enter restricted areas,** e.g. city centre and urban areas during early morning or evening/night times

Note: Policy measures not in order of priority

Source: Roland Berger

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Manuscript completed in December 2020

First edition

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Berger

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Annex

This annex to the Study Report includes a detailed account of the TCO assumptions

Annex structure

1 General assumptions

- Utilisation [days/year]
- Duration of 1st/2nd life
- Battery costs
- Assumptions on range buffer (e.g. for batteries)
- Maintenance cost
- Motor vehicle tax
- Insurance cost

2 Use case specific assumptions (truck & tech.)

- Truck costs (w/o powertrain)
- Diesel powertrain costs
- E-drive costs
- Fuel cell cost
- H_2 tank costs
- Catenary equipment costs
- Battery capacity
- Lifetime of equipment [km]
- Road toll
- Consumption
- Ad-Blue system
- Weight and payload

3 Energy / fuel assumptions

- Fuel / energy cost[1]
  - Diesel (+ Ad-Blue cost)
  - e-Diesel
  - Electricity cost (charged)
- H_2 costs (refuelled)
- CO_2 emissions

---

1) Cost of energy includes infrastructure surcharges and taxes

Note: All assumptions were discussed with the Advisory Board members who contributed expert insights and orientation

Source: Roland Berger

TCO assumptions are made for all parameters in a base case scenario – General assumptions reflect this scenario

General assumptions

Days/Year		General
Input Parameter	days	250
User override	days	
RB Assumption	days	250

Duration of 1st life / 2nd life		1st life	1st&2nd
Input Parameter	years	5	10
User override	years		
RB Assumption	years	5	10

- All input parameters are introduced as a base assumption
- All assumptions can be overridden in order to reflect regional or user specific details
- The model is calculating TCO values for
  - 1st life of the truck
  - 1st and 2nd life combined
- Results for the study will be shown for 1st and 2nd life combined due to uncertainty around the residual value in light of limited secondary market in the early years of new technology introduction

Source: Roland Berger

Detailed breakdown of general assumptions for operation days and duration of first and second life

General assumptions – Details

Assumptions			Comments	Source
Days/Year		**General**		
Input parameter	days	250		
User override	days			
RB assumptions	days	250		

Comments:

- > The average truck operation is assumed to reflect the approximated number of working days within a year
- > Similar working day assumptions as for recent industry projects

Source: Assumption in line with RB OEM project experience

Duration of 1st life / 2nd life		1st life	1st & 2nd
Input parameter	years	5	10
User override	years		
RB assumptions	years	5	10

Comments:

- > The model is calculating TCO values based on the assumptions of the regular life cycle of a Diesel truck: 1st life ≈ 5 years; 1st and 2nd life combined ≈ 10 years
- > Uncertainty exists for (1) the life span of the 1st life of trucks with an alternative powertrain and (2) a possible market for used trucks (residual value uncertainty)
- > Results to be presented for a combined 1st and 2nd life in line with current utilisation of CNG/LNG trucks of truck operators to avoid distortion of results

Source: Assumption in line with RB OEM project experience, Methodology for results adjusted based on AB member feedback

Source: Roland Berger

Battery size is dynamically adopted based on case study specific model input

Battery assumptions

Large battery cost		2023	2027	2030
Niche	EUR/kWh	280	273	276
Rather Niche	EUR/kWh	208	202	197
Rather Mass	EUR/kWh	167	161	157
Mass	EUR/kWh	142	137	133
Energy density of large battery (to calculate payload reduction)	kWh/kg	0.176	0.199	0.233

Large battery buffer		Total	Reach	Lifetime
Buffer to assure reach and lifetime	%	33.3	20.0	90.0

Small battery cost		2023	2027	2030
Niche	EUR/kWh	364	355	348
Rather Niche	EUR/kWh	271	262	256
Rather Mass	EUR/kWh	216	209	204
Mass	EUR/kWh	185	178	173
Energy density of small battery (to calculate payload reduction)	kWh/kg	0.141	0.159	0.186

- BEV battery size is dynamically adopted to daily mileage based on user input
- Battery buffer in order to assure reach and to preserve lifetime
  - 90% of capacity are utilised to preserve lifetime of the battery (SO)
  - 20% additional battery capacity to assure necessary mileage after degradation and to avoid range anxiety
  - Homogeneity of driving pattern (flexible)
- Small battery is used as range extender in FCEV and catenary trucks
- Size of small battery dependent on use case

Source: Advisory Board expert interviews; Roland Berger

Detailed breakdown of assumptions for large battery cost

Battery assumptions – Details (1/2)

Assumptions | **Comments[1]** | **Source**

Large battery cost		2023	2027	2030
Niche	EUR/kWh	280	273	267
Rather Niche	EUR/kWh	208	202	197
Rather Mass	EUR/kWh	167	161	157
Mass	EUR/kWh	142	137	133
Energy density of large battery /to calculate payload reduction	kWh/kg	0.176	0.199	0.233

- The base case assumption is based on the assumed battery sales price:
  - Cell purchasing price: 80 EUR/kWh in 2023; 73 EUR/kWh in 2030
  - Price surcharges due to minor volumes to base cost: 50% in the NM; 10% in the MM
  - Manufacturing price for 'battery housing' 100 EUR/kWh in the NN, 30 EUR/kWh in the MM
  - Development/testing cost surcharge per truck: 13 EUR/kWh in the NM, 1 EUR/kWh in the MM
  - CV battery system cost: 233 EUR/kWh in the NM; 119 EUR/kWh in the MM
  - Sales, general and administrative expenses and margin: 20%
- A cycle life of > 1,400 cycles is assumed based on current specification in passenger car industry (assumption is that HDT use same cells)

Assumption in line with RB OEM project experience, RB battery cost analysis

Large battery buffer		Total	Reach	Lifetime
Buffer to assure reach and lifetime	%	33.3	20.0	90.0

- A battery buffer is included in order to assure reach and to preserve lifetime
  - 90% of capacity are utilised to preserve lifetime (State of Charge [SOC])
  - 20% additional battery capacity included to assure necessary mileage can be achieved (e.g. changed traffic conditions, air conditioning etc.)

Assumption in line with RB OEM project experience, RB battery cost analysis

1) NM = niche market; MM = mass market

Source: Advisory Board expert interviews; Roland Berger

Detailed breakdown of assumptions for small battery cost

Battery assumptions – Details (2/2)

Assumptions

Small battery cost		2023	2027	2030
Niche	EUR/kWh	364	355	348
Rather Niche	EUR/kWh	271	262	256
Rather Mass	EUR/kWh	216	209	204
Mass	EUR/kWh	185	178	173
Energy density of small battery /to calculate payload reduction	kWh/kg	0.141	0.159	0.186

Comments[1]

- The small battery is used as range extender in FCEV and catenary trucks
- Cost of small batteries are based on cost of large batteries, yet a premium of 30% is added to reflect that other costs (e.g. battery management system, housing) remain stable, additionally other cell chemistry is required to find a balance between high energy and high power of cell (i.e. higher cost expected)

Source

Assumption in line with RB OEM project experience, RB battery cost analysis

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[1] Further details on the size of the small battery are included in the section on truck specific assumptions on page 73

Source: Advisory Board expert interviews; Roland Berger

Operational costs like maintenance, motor vehicle tax and cost of insurance can be adapted for specific case studies

Operational cost assumptions

Maintenance cost		General
Diesel	EUR/km	0.12
Diesel E-Fuels	EUR/km	0.12
FCEV 350 bar	EUR/km	0.11
FCEV 700 bar	EUR/km	0.11
FCEV LH2	EUR/km	0.11
BEV	EUR/km	0.10
Catenary	EUR/km	0.10

Motor vehicle tax		2023	2027	2030
Diesel	% of vehicle cost	0.837%	0.906%	0.961%
Diesel E-Fuels	% of vehicle cost	0.837%	0.906%	0.961%
FCEV 350 bar	% of vehicle cost	0.837%	0.906%	0.961%
FCEV 700 bar	% of vehicle cost	0.837%	0.906%	0.961%
FCEV LH2	% of vehicle cost	0.837%	0.906%	0.961%
BEV	% of vehicle cost	0.837%	0.906%	0.961%
Catenary	% of vehicle cost	0.837%	0.906%	0.961%

Cost of insurance		Damage	Liability
Diesel	% of vehicle cost	0.5%	0.1%
Diesel E-Fuels	% of vehicle cost	0.5%	0.1%
FCEV 350 bar	% of vehicle cost	0.5%	0.1%
FCEV 700 bar	% of vehicle cost	0.5%	0.1%
FCEV LH2	% of vehicle cost	0.5%	0.1%
BEV	% of vehicle cost	0.5%	0.1%
Catenary	% of vehicle cost	0.5%	0.1%

> Electric drivetrains are expected to be less maintenance intensive, FCEV generally higher maintenance costs compared to BEV and catenary because of the complexity of equipment

> Motor vehicle tax is assumed equal for all technologies, but can be adapted to reflect different case study scenarios

> Cost of insurance is split into damage and liability
  - Cost of damage coverage is based on cost of truck
  - Liability is independent from cost of truck

Source: Roland Berger

Detailed breakdown of operational assumptions for maintenance cost and motor vehicle tax

Operational cost assumptions – Details (1/2)

Assumptions	**Comments**	**Source**

Maintenance cost		General
Diesel	EUR/km	0.12
Diesel E-Fuels	EUR/km	0.12
FCEV 350 bar	EUR/km	0.11
FCEV 700 bar	EUR/km	0.11
FCEV LH_2	EUR/km	0.11
BEV	EUR/km	0.10
Catenary	EUR/km	0.10

- Electric drivetrains are expected to be less maintenance intensive
- Higher maintenance costs are assumed for FCEV compared to BEV and catenary because of the complexity of equipment

Assumption in line with RB OEM project experience

Motor vehicle tax		2023	2027	2030
Diesel	% of vehicle cost	0.837	0.906	0.961
Diesel E-Fuels	% of vehicle cost	0.837	0.906	0.961
FCEV 350 bar	% of vehicle cost	0.837	0.906	0.961
FCEV 700 bar	% of vehicle cost	0.837	0.906	0.961
FCEV LH_2	% of vehicle cost	0.837	0.906	0.961
BEV	% of vehicle cost	0.837	0.906	0.961
Catenary	% of vehicle cost	0.837	0.906	0.961

- Motor vehicle tax is assumed equal for all technologies, but can be adapted to reflect different case study scenarios
- Vehicle taxes vary in real life depending on weight and emissions classes – Included base case assumptions reflect the use case scenarios of the TCO model on a higher level

Assumption in line with RB OEM project experience

Source: Roland Berger

Detailed breakdown of operational cost assumptions for insurance cost

Operational cost assumptions – Details (2/2)

Assumptions

Insurance cost		Damage	Liability
Diesel	% of vehicle cost	0.5%	0.1%
Diesel E-Fuels	% of vehicle cost	0.5%	0.1%
FCEV 350 bar	% of vehicle cost	0.5%	0.1%
FCEV 700 bar	% of vehicle cost	0.5%	0.1%
FCEV LH_2	% of vehicle cost	0.5%	0.1%
BEV	% of vehicle cost	0.5%	0.1%
Catenary	% of vehicle cost	0.5%	0.1%

Comments

- Cost of insurance is split into damage and liability
  - Cost of damage coverage is based on cost of truck
  - Liability is also calculated dependent on the cost of truck (proxy for real life liability costs)

Source

Assumption in line with RB OEM project experience

Source: Roland Berger

Fuel cell cost assumptions have been updated based on multiple expert interviews with Advisory Board members

Cost of truck and powertrain (1/2)

Vehicle type – Rated power		4x2 Tractor – 330 kW			6x2 Rigid – 270 kW			4x2 Rigid – 220 kW		
Truck chassis		2023	2027	2030	2023	2027	2030	2023	2027	2030
Truck w/o powertrain	EUR/unit	63,000	63,000	63,000	58,100	58,100	58,100	54,600	54,600	54,600
Diesel Powertrain		2023	2027	2030	2023	2027	2030	2023	2027	2030
Niche	EUR/unit	-	-	-	-	-	-	-	-	-
Rather Niche	EUR/unit	-	-	-	-	-	-	-	-	-
Rather Mass	EUR/unit	-	-	-	-	-	-	-	-	-
Mass	EUR/unit	24,000	26,500	26,500	19,500	21,550	21,550	17,500	19,325	19,325
E-Drive		2023	2027	2030	2023	2027	2030	2023	2027	2030
Niche	EUR/unit	37,401	35,959	34,877	34,341	33,161	32,276	31,791	30,830	30,108
Rather Niche	EUR/unit	20,689	19,650	18,871	18,486	17,636	16,999	16,650	15,957	15,438
Rather Mass	EUR/unit	13,539	12,731	12,125	11,825	11,165	10,669	10,397	9,859	9,455
Mass	EUR/unit	10,466	9,716	9,153	8,875	8,261	7,801	7,549	7,049	6,674
FC module at 120 kW (units p.a.[1])		2023	2027	2030	2023	2027	2030	2023	2027	2030
Niche (2,500 p. OEM)	EUR/kW	**430**	337	280	**430**	337	280	**430**	337	280
Rather Niche (5,000 p. OEM)	EUR/kW	240	**187**	155	240	**187**	155	240	**187**	155
Rather Mass (25,000 p. OEM)	EUR/kW	160	122	**100**	160	122	**100**	160	122	**100**
Mass (75,000 p. OEM)	EUR/kW	80	65	55	80	65	55	80	65	55

- Cost of chassis is kept constant over time
- Diesel powertrain is expected to always be a mass market application
- E-Drive permanent power is set to reflect diesel power
- Fuel cell stack capacity is adopted to use cases
  - 4x2 Tractor – 240 kW
  - 6x2 Rigid – 180 kW
  - 4x2 Rigid – 120 kW

[1] Assumptions: Truck production p.a.: Niche <5,000 units/year; Rather niche <10,000 units/year; Rather mass >50,000 units/year (~10% of market); Mass >150,000 units/year (~30% of market); e.g. Niche: 3 OEMs in market = ~ 1,666 FCH module units p.a. at 180 kW (avg.) or 2,500 units p.a. at 120 kW

▨ Used for TCO modelling

Source: Lastauto Omnibus; Advisory Board expert interviews; Roland Berger

Prices of alternative powertrain components are influenced by the assumption of market maturity from niche to mass scenario

Cost of truck and powertrain (2/2)

Vehicle type – Rated power			4x2 Tractor – 330 kW			6x2 Rigid – 270 kW			4x2 Rigid – 220 kW		
Truck chassis			2023	2027	2030	2023	2027	2030	2023	2027	2030
Truck w/o powertrain		EUR/unit	63,000	63,000	63,000	58,100	58,100	58,100	54,600	54,600	54,600
Diesel Powertrain			2023	2027	2030	2023	2027	2030	2023	2027	2030
Niche		EUR/unit	-	-	-	-	-	-	-	-	-
Rather Niche		EUR/unit	-	-	-	-	-	-	-	-	-
Rather Mass		EUR/unit	-	-	-	-	-	-	-	-	-
Mass		EUR/unit	24,000	26,500	26,500	19,500	21,550	21,550	17,500	19,325	19,325
E-Drive			2023	2027	2030	2023	2027	2030	2023	2027	2030
Niche		EUR/unit	37,401	35,959	34,877	34,341	33,161	32,276	31,791	30,830	30,108
Rather Niche		EUR/unit	20,689	19,650	18,871	18,486	17,636	16,999	16,650	15,957	15,438
Rather Mass		EUR/unit	13,539	12,731	12,125	11,825	11,165	10,669	10,397	9,859	9,455
Mass		EUR/unit	10,466	9,716	9,153	8,875	8,261	7,801	7,549	7,049	6,674
FC module at 120 kW (units p.a.[1])			2023	2027	2030	2023	2027	2030	2023	2027	2030
Niche	(2,500 p. OEM)	EUR/unit	🟦 103,200	80,764	67,200	🟦 77,400	60,573	50,400	🟦 51,600	40,382	33,600
Rather Niche	(5,000 p. OEM)	EUR/unit	57,600	🟦 44,866	37,200	43,200	🟦 33,650	27,900	28,800	🟦 22,433	18,600
Rather Mass	(25,000 p. OEM)	EUR/unit	38,400	29,356	🟦 24,000	28,800	22,017	🟦 18,000	19,200	14,678	🟦 12,000
Mass	(75,000 p. OEM)	EUR/unit	19,200	15,499	13,200	14,400	11,625	9,900	9,600	7,750	6,600

- Cost of chassis is kept constant over time
- Diesel powertrain is expected to always be a mass market application – slight cost increase assumed due to further tightening emission regulation
- E-Drive permanent power is set to reflect diesel power
- Fuel cell stack capacity is adopted to use cases
  - 4x2 Tractor – 240 kW
  - 6x2 Rigid – 180 kW
  - 4x2 Rigid – 120 kW

1) Assumptions: Truck production p.a.: Niche <5,000 units/year; Rather niche <10,000 units/year; Rather mass >50,000 units/year (~10% of market); Mass >150,000 units/year (~30% of market); e.g. Niche: 3 OEMs in market = ~ 1,666 FCH module units p.a. at 180 kW (avg.) or 2,500 units p.a. at 120 kW

🟦 Used for TCO modelling

Source: Lastauto Omnibus; Advisory Board expert interviews; Roland Berger

Detailed breakdown of use case specific assumptions for truck chassis

Cost of truck and powertrain assumptions – Details (1/4)

Assumptions

Truck chassis

Truck w/o powertrain EUR/unit

4x2 Tractor – 330 kW

2023	2027	2030
63,000	63,000	63,000

6x2 Rigid – 270 kW

2023	2027	2030
58,100	58,100	58,100

4x2 Rigid – 220 kW

2023	2027	2030
54,600	54,600	54,600

Comments

- Numbers are based on a mature market and a stripped version of a truck, i.e. Diesel truck without engine, tank, etc.
- Truck chassis costs are assumed to be constant over the years

Source

Assumption in line with RB OEM project experience; Lastauto Omnibus

Source: Lastauto Omnibus; Advisory Board expert interviews; Roland Berger

Detailed breakdown of use case specific assumptions for Diesel powertrain

Cost of truck and powertrain assumptions – Details (2/4)

Assumptions

Diesel Powertrain

Mass EUR/unit

4x2 Tractor – 330 kW

2023	2027	2030
24,000	26,500	26,500

6x2 Rigid – 270 kW

2023	2027	2030
19,500	21,550	21,550

4x2 Rigid – 220 kW

2023	2027	2030
17,500	19,325	19,325

Comments

- Numbers comprise the cost of the ICE, after treatment, transmission and other:
  - E.g. EUR 24 k = EUR 10 k (ICE) + EUR 6 k (after treatment) + EUR 5 k (transmission) + EUR 3 k (others)
  - EUR VII standards are considered in the ICE and the after treatment
- Mass market is assumed for the four components across all use cases and years

Source

Assumption in line with RB OEM project experience and based on desk research

Source: Advisory Board expert interviews; Roland Berger

Detailed breakdown of use case specific assumptions for E-Drive

Cost of truck and powertrain assumptions – Details (3/4)

Assumptions

E-Drive

4x2 Tractor – 330 kW

		2023	2027	2030
Niche	EUR/unit	37,401	35,959	34,877
Rather Niche	EUR/unit	20,689	19,650	18,871
Rather Mass	EUR/unit	13,539	12,731	12,125
Mass	EUR/unit	10,466	9,716	9,153

6x2 Rigid – 270 kW

		2023	2027	2030
Niche	EUR/unit	34,341	33,161	32,276
Rather Niche	EUR/unit	18,486	17,636	16,999
Rather Mass	EUR/unit	11,825	11,165	10,669
Mass	EUR/unit	8,875	8,261	7,801

4x2 Rigid – 220 kW

		2023	2027	2030
Niche	EUR/unit	31,791	30,830	30,108
Rather Niche	EUR/unit	16,650	15,957	15,438
Rather Mass	EUR/unit	10,397	9,859	9,455
Mass	EUR/unit	7,549	7,049	6,674

Comments

- E-Drive permanent power is set to reflect diesel power
- E-Drive costs are assumed to be the same for FCEV, BEV and catenary
- Price surcharge vs. passenger cars due to minor volumes and commercial vehicle requirements[1] across all years:
  - 150% for the niche market
  - 30% for the mass market
- Development and testing cost e-powertrain and e-truck across all years:
  - EUR/truck 17,143 for the niche market
  - EUR/truck 1,429 for the mass market
- SGA[2] (incl. retail cost) and OEM margin across all years:
  - 20%

Source

Assumption in line with RB OEM project experience and based on desk research

[1] Accounting for the fact that CV have different requirements concerning scaling than passenger vehicles [2] Sales, general and administrative expenses

Source: Advisory Board expert interviews; Roland Berger

Detailed breakdown of use case specific assumptions for FC module

Cost of truck and powertrain assumptions – Details (4/4)

Assumptions

FC module at 120 kW net peak power (units p.a.)

4x2 Tractor – FC: 240 kW

			2023	2027	2030
Niche	(2,500 p. OEM)	EUR/kW	430	337	280
Rather Niche	(5,000 p. OEM)	EUR/kW	240	187	155
Rather Mass	(25,000 p. OEM)	EUR/kW	160	122	100
Mass	(75,000 p. OEM)	EUR/kW	80	65	55

6x2 Rigid – FC: 180 kW

			2023	2027	2030
Niche	(2,500 p. OEM)	EUR/kW	430	337	280
Rather Niche	(5,000 p. OEM)	EUR/kW	240	187	155
Rather Mass	(25,000 p. OEM)	EUR/kW	160	122	100
Mass	(75,000 p. OEM)	EUR/kW	80	65	55

4x2 Rigid – FC: 120 kW

			2023	2027	2030
Niche	(2,500 p. OEM)	EUR/kW	430	337	280
Rather Niche	(5,000 p. OEM)	EUR/kW	240	187	155
Rather Mass	(25,000 p. OEM)	EUR/kW	160	122	100
Mass	(75,000 p. OEM)	EUR/kW	80	65	55

Comments[1]

> Assumptions made for the typical size of a fuel cell (FC) module of 120 kW (net peak power)

> Costs FC module:
- 2023: EUR/kW 430 (NM) – 80 (MM)
- 2030: EUR/kW 280 (NM) – 55 (MM)

> FC stack power:
- 4x2 Tractor: 240 kW, 72.7% of vehicle power (330 kW)
- 6x2 Rigid: 180 kW, 66.7% of vehicle power (270 kW)
- 4x2 Rigid: 120 kW, 54.5% of vehicle power (220 kW)

> Assumed truck production p.a.:
- Niche <5,000 units/year
- Rather niche <10,000 units/year
- Rather mass >50,000 units/year (~10% of market)
- Mass >150,000 units/year (~30% of market)
- E.g. Niche: 3 OEMs in market = ~ 1,666 FCH module units p.a. at 180 kW (avg.) or 2,500 units p.a. at 120 kW

> FC module components consider a functioning FC system, e.g.:
- Fuel cell stack, hydrogen supply of the FC system (e.g. inlet valve), air compressor, cooling system, power electronics, control unit etc.

Source

Assumption in line with RB fuel cell project experience, multiple AB member feedback on assumptions, e.g. on volume production effects of modules

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1) NM = niche market; RN = rather niche market; RM = rather mass market; MM = mass market

🟦 Applied in TCO model for base case

Source: Advisory Board expert interviews; Roland Berger

H_2 tank systems are calculated dynamically taking into account fuel efficiency as well as buffers for range and route flexibility

Cost of hydrogen tanks

		4x2 Tractor – 330 kW			6x2 Rigid – 270 kW			4x2 Rigid – 220 kW		
		> ~ 560 km daily mileage			> ~ 380 km daily mileage			> ~ 250 km daily mileage		
H_2 tank capacity		2023	2027	2030	2023	2027	2030	2023	2027	2030
Capacity[1|2]	kg $_{H2}$	74	72	71	45	43	43	26	26	25
H_2 Tank – 350 bar		2023	2027	2030	2023	2027	2030	2023	2027	2030
Niche	EUR/unit	**52,198**	43,518	38,283	**31,633**	26,347	23,236	**18,600**	15,550	13,680
Rather Niche	EUR/unit	40,152	**33,475**	29,449	24,333	**20,267**	17,874	14,308	**11,962**	10,523
Rather Mass	EUR/unit	30,886	25,750	**22,653**	18,718	15,590	**13,749**	11,006	9,201	**8,095**
Mass	EUR/unit	21,620	18,025	15,857	13,102	10,913	9,624	7,704	6,441	5,666
H_2 Tank – 700 bar		2023	2027	2030	2023	2027	2030	2023	2027	2030
Niche	EUR/unit	**56,473**	47,369	41,861	**34,224**	28,678	25,408	**20,123**	16,926	14,958
Rather Niche	EUR/unit	41,988	**35,910**	32,201	25,446	**21,741**	19,545	14,962	**12,832**	11,506
Rather Mass	EUR/unit	33,773	28,157	**24,770**	20,467	17,047	**15,034**	12,034	10,061	**8,851**
Mass	EUR/unit	23,641	19,710	17,339	14,327	11,933	10,524	8,424	7,043	6,196
H_2 Tank – LH_2		2023	2027	2030	2023	2027	2030	2023	2027	2030
Niche	EUR/unit	**27,228**	20,918	17,307	**16,501**	12,664	10,505	**9,702**	7,475	6,184
Rather Niche	EUR/unit	18,152	**13,945**	11,538	11,001	**8,443**	7,003	6,468	**4,983**	4,123
Rather Mass	EUR/unit	12,101	9,297	**7,692**	7,334	5,629	**4,669**	4,312	3,322	**2,749**
Mass	EUR/unit	8,471	6,508	5,384	5,134	3,940	3,268	3,018	2,325	1,924

- > Tank capacity and cost enable average daily mileage per use case including a buffer
- > Requirements of driving profile (i.e. higher H_2 storage requirements) taken into account

1) Decrease in required tank capacity due to increasing efficiency of powertrain over time, including 33% capacity buffer equal to large battery and adjusted according to driving profile (e.g. heterogenous driving profile results in higher calculated tank capacity) 2) Efficiency improvements expected, reducing tank size, i.e. costs 🟦 Applied in TCO model for base case

Source: Shell International; Advisory Board expert interviews; Roland Berger

Detailed breakdown of use case specific assumptions for cost of hydrogen tanks – CGH_2 at 350 bar

Cost of hydrogen tanks – Details (1/3)

Assumptions

H_2 Tank – 350 bar

4x2 Tractor – 330 kW

		2023	2027	2030
Niche	EUR/unit	52,198	43,518	38,283
Rather Niche	EUR/unit	40,152	33,475	29,449
Rather Mass	EUR/unit	30,886	25,750	22,653
Mass	EUR/unit	21,620	18,025	15,857

6x2 Rigid – 270 kW

		2023	2027	2030
Niche	EUR/unit	31,633	26,347	23,236
Rather Niche	EUR/unit	24,333	20,267	17,874
Rather Mass	EUR/unit	18,718	15,590	13,749
Mass	EUR/unit	13,102	10,913	9,624

4x2 Rigid – 220 kW

		2023	2027	2030
Niche	EUR/unit	18,600	15,550	13,680
Rather Niche	EUR/unit	14,308	11,962	10,523
Rather Mass	EUR/unit	11,006	9,201	8,095
Mass	EUR/unit	7,704	6,441	5,666

Comments[1]

- Tank size is dynamically adopted to use case specific daily range requirements
- Tank size for use cases is based on daily range requirements and consumption assumptions
- A 33% buffer is included to assure sufficient range independent of driving profile
- A factor representing the driving profile requirements is included to calculate with an additional buffer reflecting higher required flexibility for some operations
  - 4x2 Tractor: Rather homogeneous = 1,25
  - 6x2 Rigid: Rather homogeneous = 1,25
  - 4x2 Rigid: Rather homogeneous = 1,25
- Tank costs are assumed at:
  - 2023: EUR/kg_{H2} 705 (NM) – 292 (MM)
  - 2030: EUR/kg_{H2} 542 (NM) – 225 (MM)

Source

Assumption in line with RB OEM project experience, Shell International Study, Advisory Board feedback

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[1] NM = niche market; RN = rather niche market; RM = rather mass market; MM = mass market

🟦 Applied in TCO model for base case

Source: Shell International; Advisory Board expert interviews; Roland Berger

Detailed breakdown of use case specific assumptions for cost of hydrogen tanks – CGH_2 at 700 bar

Cost of hydrogen tanks – Details (2/3)

Assumptions

H_2 Tank – 700 bar

4x2 Tractor – 330 kW

		2023	2027	2030
Niche	EUR/unit	56,473	47,369	41,861
Rather Niche	EUR/unit	41,988	35,910	32,201
Rather Mass	EUR/unit	33,773	28,157	24,770
Mass	EUR/unit	23,641	19,710	17,339

6x2 Rigid – 270 kW

		2023	2027	2030
Niche	EUR/unit	34,224	28,678	25,408
Rather Niche	EUR/unit	25,446	21,741	19,545
Rather Mass	EUR/unit	20,467	17,047	15,034
Mass	EUR/unit	14,327	11,933	10,524

4x2 Rigid – 220 kW

		2023	2027	2030
Niche	EUR/unit	20,123	16,926	14,958
Rather Niche	EUR/unit	14,962	12,832	11,506
Rather Mass	EUR/unit	12,034	10,061	8,851
Mass	EUR/unit	8,424	7,043	6,196

Comments[1]

- Tank size is dynamically adopted to use case specific daily range requirements
- Tank size for use cases is based on daily range requirements and consumption assumptions
- A 33% buffer is included to assure sufficient range independent of driving profile
- A factor representing the driving profile requirements is included to calculate with an additional buffer reflecting higher required flexibility for some operations
  - 4x2 Tractor: Rather homogeneous = 1,25
  - 6x2 Rigid: Rather homogeneous = 1,25
  - 4x2 Rigid: Rather homogeneous = 1,25
- Tank costs are assumed at:
  - 2023: EUR/kg_{H2} 763 (NM) – 319 (MM)
  - 2030: EUR/kg_{H2} 593 (NM) – 246 (MM)

Source

Assumption in line with RB OEM project experience, Shell International Study, Advisory Board feedback

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1) NM = niche market; RN = rather niche market; RM = rather mass market; MM = mass market

🟦 Applied in TCO model for base case

Source: Shell International; Advisory Board expert interviews; Roland Berger

Detailed breakdown of use case specific assumptions for cost of hydrogen tanks – LH_2

Cost of hydrogen tanks – Details (3/3)

Assumptions

H_2 Tank – LH2

4x2 Tractor – 330 kW

		2023	2027	2030
Niche	EUR/unit	27,228	20,918	17,307
Rather Niche	EUR/unit	18,152	13,945	11,538
Rather Mass	EUR/unit	12,101	9,297	7,692
Mass	EUR/unit	8,471	6,508	5,384

6x2 Rigid – 270 kW

		2023	2027	2030
Niche	EUR/unit	16,501	12,664	10,505
Rather Niche	EUR/unit	11,001	8,443	7,003
Rather Mass	EUR/unit	7,334	5,629	4,669
Mass	EUR/unit	5,134	3,940	3,268

4x2 Rigid – 220 kW

		2023	2027	2030
Niche	EUR/unit	9,702	7,475	6,184
Rather Niche	EUR/unit	6,468	4,983	4,123
Rather Mass	EUR/unit	4,312	3,322	2,749
Mass	EUR/unit	3,018	2,325	1,924

Comments[1]

- Tank size is dynamically adopted to use case specific daily range requirements
- Tank size for use cases is based on daily range requirements and consumption assumptions
- A 33% buffer is included to assure sufficient range independent of driving profile
- A factor representing the driving profile requirements is included to calculate with an additional buffer reflecting higher required flexibility for some operations
  - 4x2 Tractor: Rather homogeneous = 1,25
  - 6x2 Rigid: Rather homogeneous = 1,25
  - 4x2 Rigid: Rather homogeneous = 1,25
- Tank costs are assumed at:
  - 2023: EUR/kg_{H2} 368 (NM) – 114 (MM)
  - 2030: EUR/kg_{H2} 245 (NM) – 76 (MM)

Source

Assumption in line with RB OEM project experience, Shell International Study, Advisory Board feedback

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1) NM = niche market; RN = rather niche market; RM = rather mass market; MM = mass market

🟦 Applied in TCO model for base case

Source: Shell International; Advisory Board expert interviews; Roland Berger

Lifetime of powertrain components can be adapted to reflect technology developments

Further truck and technology specific assumptions

		4x2 Tractor – 330 kW			6x2 Rigid – 270 kW			4x2 Rigid – 220 kW		
Large battery		2023	2027	2030	2023	2027	2030	2023	2027	2030
Capacity of large battery	kWh	1,236	1,197	1,178	748	725	714	440	427	421
Small battery										
Capacity of small battery	kWh	127			114			106		
Catenary Equipment		2023	2027	2030	2023	2027	2030	2023	2027	2030
Niche	EUR/unit	48,468	45,600	45,600	48,468	45,600	45,600	48,468	45,600	45,600
Rather Niche	EUR/unit	40,390	38,000	38,000	40,390	38,000	38,000	40,390	38,000	38,000
Rather Mass	EUR/unit	36,351	34,200	34,200	36,351	34,200	34,200	36,351	34,200	34,200
Mass	EUR/unit	32,312	30,400	30,400	32,312	30,400	30,400	32,312	30,400	30,400
Lifetime in km and scrap value in %		km	scrap		km	scrap		km	scrap	
Diesel Drivetrain	km & %	1,400,000	10.0%		1,400,000	10.0%		1,400,000	10.0%	
E-Drive	km & %	1,400,000	10.0%		1,400,000	10.0%		1,400,000	10.0%	
FC Stack	km & %	1,400,000	10.0%		1,400,000	10.0%		1,400,000	10.0%	
Small Battery	km & %	1,400,000	10.0%		1,400,000	10.0%		1,400,000	10.0%	
H2 Tank 350 bar	km & %	1,400,000	0.0%		1,400,000	0.0%		1,400,000	0.0%	
H2 Tank 700 bar	km & %	1,400,000	0.0%		1,400,000	0.0%		1,400,000	0.0%	
H2 Tank LH2	km & %	1,400,000	0.0%		1,400,000	0.0%		1,400,000	0.0%	
Large Battery	km & %	700,000	10.0%		700,000	10.0%		700,000	10.0%	
Catenary Equipment	km & %	1,400,000	10.0%		1,400,000	10.0%		1,400,000	10.0%	
Road toll										
Cost of road toll	EUR/km	0.17			0.17			0.17		

- Large battery is the main powertrain of the BEV
- Small battery is used for FCEV and for catenary vehicles
- Cost of catenary equipment (pantograph) is expected to be equal for all use cases
- Road toll is set equal for each use case and technology but can be adapted via scroll bars to simulate regional or case specific settings

Source: ICCT; Mareev & Sauer 2018; Desk research; Roland Berger

Detailed breakdown of use case specific assumptions for large and small battery

Further truck and technology specific assumptions – Details (1/4)

Assumptions

Large battery	**Small battery**
Capacity of large battery[1] kWh	Capacity of small battery[1] kWh/100 km

4x2 Tractor – 330 kW

2023	2027	2030	
1,236	1,197	1,178	127

6x2 Rigid – 270 kW

2023	2027	2030	
748	725	714	114

4x2 Rigid – 220 kW

2023	2027	2030	
440	427	421	106

Comments

- The large battery is used in BEV
- The small battery is used for FCEV and for catenary vehicles
- The small battery is assumed to be sufficient to reach 100 km for all years and use cases
- The battery size can be dynamically adopted based on specific model input
- Assumed average consumption of BEV across all years:
  - 4x2 Tractor: 1.27 kWh/km
  - 6x2 Rigid: 1.14 kWh/km
  - 4x2 Rigid: 1.06 kWh/km

Source

Assumption in line with RB OEM project experience, Desk research

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1) The TCO model builds on the average of the consumption assumptions of the years 2023-2030

Source: Roland Berger

Detailed breakdown of assumptions for catenary equipment costs

Further truck and technology specific assumptions – Details (2/4)

Assumptions

Catenary Equipment for all use cases

		2023	2027	2030
Niche	EUR/unit	48,468	45,600	45,600
Rather Niche	EUR/unit	40,390	38,000	38,000
Rather Mass	EUR/unit	36,351	34,200	34,200
Mass	EUR/unit	32,312	30,400	30,400

Comments[1]

- Cost assumptions based on scientific literature for the pantograph/overhead vehicle grid connection
- Cost of catenary equipment is assumed equal for all use cases
- Decrease in costs assumed because of technology progress
- Price variation is assumed according to market size
  - NM: 120%
  - RN: 100%
  - RM: 90%
  - MM: 80%

Source

Assumption based on ICCT 2017, Mareev & Sauer (in Energies 2018, 11), Desk research

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[1] NM = niche market; RN = rather niche market; RM = rather mass market; MM = mass market

Source: ICCT; Mareev & Sauer 2018; Roland Berger

Detailed breakdown of assumptions for truck lifetime and scrap value

Further truck and technology specific assumptions – Details (3/4)

Assumptions

Lifetime in km and scrap value in % for all use cases

		km	scrap
Diesel Drivetrain	km & %	1,400,000	10.0%
E-Drive	km & %	1,400,000	10.0%
FC Stack	km & %	1,400,000	10.0%
Small Battery	km & %	1,400,000	10.0%
H2 Tank 350 bar	km & %	1,400,000	0.0%
H2 Tank 700 bar	km & %	1,400,000	0.0%
H2 Tank LH_2	km & %	1,400,000	0.0%
Large Battery	km & %	700,000	10.0%
Catenary Equipment	km & %	1,400,000	10.0%

Comments

> Assumptions for truck lifetime set at 1,400,000 km based on the Diesel drivetrain as incumbent technology

> Assumptions for final scrap value based on the Diesel drivetrain as incumbent technology

> Deviation for large battery due to limited number of possible charging cycles with fast charging (set at 1,400 cycles with assumed charging after 500 km)

> FC and H_2 tank lifetime are expected sufficient for 1st and 2nd life (FC: ~25,000 h, H2 tank: >5,000 cycles)

> Second life potential value for small and large battery assumed, after replacement (e.g. for use in stationary energy storage applications)

> H_2 tanks expected to last for first and second life with >5,000 cycles achievable but without scrap value; recoverable material gains assumed to cover waste deposition cost

Source

Assumption in line with RB OEM and fuel cell project experience

Source: Roland Berger

Detailed breakdown of assumptions for road toll

Further truck and technology specific assumptions – Details (4/4)

Assumptions	Comments	Source

Road toll

Cost of road toll EUR/km

4x2 Tractor – 330 kW

2023	2027	2030
0.17	0.17	0.17

6x2 Rigid – 270 kW

2023	2027	2030
0.17	0.17	0.17

4x2 Rigid – 220 kW

2023	2027	2030
0.17	0.17	0.17

> Cost of road toll included is based on a calculation of a sample of 14 European countries[1], approximating an European average

> Road toll is set equal for each use case and technology but can be adapted to simulate regional or case study specific settings

Desk research

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1) Austria, Belgium, Czech Republic, Denmark, France, Germany, Greece, Italy, Luxemburg, Netherlands, Poland, Portugal, Spain, Sweden

Source: Roland Berger

Assumptions are calculated based on Diesel fuel consumption – Efficiency improvement over time assumed for all powertrains

Consumption per km

		4x2 Tractor – 330 kW			6x2 Rigid – 270 kW			4x2 Rigid – 220 kW		
Consumption		**2023**	**2027**	**2030**	**2023**	**2027**	**2030**	**2023**	**2027**	**2030**
Diesel	l/km	0.320	0.310	0.305	0.288	0.279	0.275	0.271	0.263	0.259
Diesel E-Fuels	l/km	0.320	0.310	0.305	0.288	0.279	0.275	0.271	0.263	0.259
FCEV 350 bar	kg/km	0.080	0.077	0.076	0.071	0.069	0.068	0.066	0.064	0.063
FCEV 700 bar	kg/km	0.080	0.077	0.076	0.071	0.069	0.068	0.066	0.064	0.063
FCEV LH2	kg/km	0.080	0.077	0.076	0.071	0.069	0.068	0.066	0.064	0.063
BEV	kWh/km	1.324	1.283	1.262	1.182	1.145	1.128	1.101	1.069	1.052
Catenary	kWh/km	1.258	1.219	1.199	1.122	1.087	1.072	1.046	1.015	1.000
Ad-Blue		**2023**	**2027**	**2030**	**2023**	**2027**	**2030**	**2023**	**2027**	**2030**
Diesel	l/km	0.016	0.016	0.017	0.015	0.015	0.015	0.014	0.014	0.014
Diesel E-Fuels	l/km	0.016	0.016	0.017	0.015	0.015	0.015	0.014	0.014	0.014

> Consumption values are based on project experience for Diesel consumption, respective alternative drive consumption calculated based on efficiency

> Adjustments made in line with Advisory Board member feedback

Source: Advisory Board expert interviews; Roland Berger

Detailed breakdown of use case specific assumptions for consumption per km

Consumption per km – Details (1/4)

Assumptions

Consumption

			2023	2027	2030
4x2 Tractor – 330k W	Diesel	l/km	0.320	0.310	0.305
	Diesel E-Fuels	l/km	0.320	0.310	0.305
	FCEV 350 bar	kg/km	0.080	0.077	0.076
	FCEV 700 bar	kg/km	0.080	0.077	0.076
	FCEV LH2	kg/km	0.080	0.077	0.076
	BEV	kWh/km	1.324	1.283	1.262
	Catenary	kWh/km	1.258	1.219	1.199

			2023	2027	2030
6x2 Rigid – 270 kW	Diesel	l/km	0.288	0.279	0.275
	Diesel E-Fuels	l/km	0.288	0.279	0.275
	FCEV 350 bar	kg/km	0.071	0.069	0.068
	FCEV 700 bar	kg/km	0.071	0.069	0.068
	FCEV LH2	kg/km	0.071	0.069	0.068
	BEV	kWh/km	1.182	1.145	1.128
	Catenary	kWh/km	1.122	1.087	1.072

Comments

- Numbers for diesel are set as given (real life driving consumption, confirmed by truck operating AB members)
- Consumption for Diesel E-fuels is assumed to be the same as for conventional Diesel trucks
- Consumption of FCEV, BEV and Catenary is calculated based on expected energy efficiency powertrains, e.g. power at wheel of diesel trucks calculated backwards for all electric powertrains (mainly based on limited real life energy consumption data for BEV, FCEV and Catenary)
- Catenary is assumed to be 5% more efficient than BEV due to charging losses for BEV but also taking into account additional air drag from pantograph
- Additional uncertainty remains about the seasonal power consumption of BEV & Catenary (e.g. energy consumption for heating in winter of driver cabin but also battery system during parking at cold temperatures)

Source

Assumption in line with RB OEM project experience; Adjusted based on AB member feedback, cross-checked with desk research

Source: Advisory Board expert interviews; Roland Berger

Detailed breakdown of use case specific assumptions for consumption per km

Consumption per km – Details (2/4)

Assumptions

Consumption

4x2 Rigid – 220 kW

		2023	2027	2030
Diesel	l/km	0.271	0.263	0.259
Diesel E-Fuels	l/km	0.271	0.263	0.259
FCEV 350 bar	kg/km	0.066	0.064	0.063
FCEV 700 bar	kg/km	0.066	0.064	0.063
FCEV LH2	kg/km	0.066	0.064	0.063
BEV	kWh/km	1.101	1.069	1.052
Catenary	kWh/km	1.046	1.015	1.000

Comments

- Numbers for diesel are set as given (real life driving consumption, confirmed by truck operating AB members)
- Consumption for Diesel E-fuels is assumed to be the same as for conventional Diesel trucks
- Consumption of FCEV, BEV and Catenary is calculated based on expected energy efficiency powertrains, e.g. power at wheel of diesel trucks calculated backwards for all electric powertrains (mainly based on limited real life energy consumption data for BEV, FCEV and Catenary)
- Catenary is assumed to be 5% more efficient than BEV due to charging losses for BEV but also taking into account additional air drag from pantograph
- Additional uncertainty remains about the seasonal power consumption of BEV & Catenary (e.g. energy consumption for heating in winter of driver cabin but also battery system during parking at cold temperatures)

Source

Assumption in line with RB OEM project experience; Adjusted based on AB member feedback, cross-checked with desk research

Source: Advisory Board expert interviews; Roland Berger

The fuel consumption figures were derived from a stepwise calculation based on drivetrain efficiency and energy consumption

Consumption per km – Details (3/4)

		2023					2027					2030				
		Fuel consump-tion	Energy content	Energy consump-tion	Drivetrain efficiency	Energy at wheel	Fuel consump-tion	Energy content	Energy consump-tion	Drivetrain efficiency	Energy at wheel	Fuel consump-tion	Energy content	Energy consump-tion	Drivetrain efficiency	Energy at wheel
			[kWh/l] [kWh/kg]	[kWh]	[%]	[kWh]		[kWh/l] [kWh/kg]	[kWh]	[%]	[kWh]		[kWh/l] [kWh/kg]	[kWh]	[%]	[kWh]
4x2 Tractor – 330 kW																
Diesel	l/100 km	32.00	9.80	313.60	38%	119.17	31.00	9.80	303.80	38%	115.44	30.50	9.80	298.90	38%	113.58
FCEV	kg/100 km	7.95	33.30	264.82	45%	119.17	7.70	33.30	256.54	45%	115.44	7.58	33.30	252.40	45%	113.58
BEV	kWh/100 km			132.41					128.27					126.20		
Catenary	kWh/100 km			125.79					121.86					119.89		
6x2 Rigid – 270 kW																
Diesel	l/100 km	28.80	9.80	282.24	36%	101.61	27.90	9.80	273.42	36%	98.43	27.50	9.80	269.50	36%	97.02
FCEV	kg/100 km	7.10	33.30	236.29	43%	101.61	6.87	33.30	228.91	43%	98.43	6.78	33.30	225.63	43%	97.02
BEV	kWh/100 km			118.15					114.45					112.81		
Catenary	kWh/100 km			112.24					108.73					107.17		
4x2 Rigid – 220 kW																
Diesel	l/100 km	27.10	9.80	265.58	34%	90.30	26.30	9.80	257.74	34%	87.63	25.90	9.80	253.82	34%	86.30
FCEV	kg/100 km	6.61	33.30	220.24	41%	90.30	6.42	33.30	213.74	41%	87.63	6.32	33.30	210.48	41%	86.30
BEV	kWh/100 km			110.12					106.87					105.24		
Catenary	kWh/100 km			104.61					101.52					99.98		

▨ Calculated result

Source: Roland Berger

Detailed breakdown of use case specific assumptions for consumption per km for Ad-Blue

Consumption per km – Details (4/4)

Assumptions

Ad-Blue

4x2 Tractor – 330 kW

		2023	2027	2030
Diesel	l/km	0.016	0.016	0.017
Diesel E-Fuels	l/km	0.016	0.016	0.017

6x2 Rigid – 270 kW

		2023	2027	2030
Diesel	l/km	0.015	0.015	0.015
Diesel E-Fuels	l/km	0.015	0.015	0.015

4x2 Rigid – 220 kW

		2023	2027	2030
Diesel	l/km	0.014	0.014	0.014
Diesel E-Fuels	l/km	0.014	0.014	0.014

Comments

> The increase in the assumed Ad-Blue valued refers to stricter emission targets over the coming years

Source

Assumption in line with RB OEM project experience

Source: Roland Berger

Reduced weight of alternative powertrains as well as regulatory alternative fuels payload incentive are considered

Use case specific payload assumptions

		4x2 Tractor – 330 kW			6x2 Rigid – 270 kW			4x2 Rigid – 220 kW		
Payload										
Maximum payload	t	27.0			14.5			10.5		
Avg. loading factor	%	90			80			70		
Share of empty runs	%	25			25			25		
Weight adaption w/o battery		2023	2027	2030	2023	2027	2030	2023	2027	2030
Diesel	t	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Diesel E-Fuels	t	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FCEV 350 bar	t	-1.90	-1.93	-1.95	-1.76	-1.78	-1.79	-1.71	-1.72	-1.72
FCEV 700 bar	t	-1.53	-1.58	-1.60	-1.53	-1.56	-1.57	-1.58	-1.59	-1.60
FCEV LH2	t	-2.49	-2.51	-2.52	-2.12	-2.13	-2.13	-1.92	-1.92	-1.93
BEV	t	-3.30	-3.30	-3.30	-2.66	-2.66	-2.66	-2.25	-2.25	-2.25
Catenary	t	-3.20	-3.20	-3.20	-2.56	-2.56	-2.56	-2.15	-2.15	-2.15

- Reduced weight of powertrain specific components is reflected, based on Tesla 3, Toyota Mirai and other benchmarks
- Weight of batteries is dynamically included in the calculation
- EU Weights and Dimension regulation is considered with additional + 1t GVW for alternatively fuelled vehicles following Directive (EU) 2015/719; assumption can be modified to reflect Regulation (EU) 2019/1242 with + 2t GVW for ZEV

Source: Lastauto Omnibus 2018; Eurostat; Desk research; Roland Berger

Detailed breakdown of use case specific assumptions for payload

Use case specific payload assumptions – Details (1/3)

Assumptions

Payload

4x2 Tractor – 330 kW

Maximum payload	t	27.0
Avg. loading factor	%	90
Share of empty runs	%	25

6x2 Rigid – 270 kW

Maximum payload	t	14.5
Avg. loading factor	%	80
Share of empty runs	%	25

4x2 Rigid – 220 kW

Maximum payload	t	10.5
Avg. loading factor	%	70
Share of empty runs	%	25

Comments

> Maximum payload refers to truck-specific numbers

> Average loading factors differ to reflect real-life utilisation patterns
  - Use case I (4x2 Tractor – 330 kW) – 90%
  - Use case III (6x2 Rigid – 270 kW) – 80%
  - Use case III (4x2 Rigid – 220 kW) – 70%

> Share of empty runs is based on Eurostat figures (not use case specific)

Source

Lastauto Omnibus 2018; Eurostat; Desk research; Assumption in line with RB OEM project experience, Advisory Board feedback

Source: Lastauto Omnibus; Eurostat; Desk research; Roland Berger

Payloads are calculated for each technology based on base case assumptions

Use case I – Payloads based on first base case assumptions

	Diesel	Diesel E-Fuels	FCEV 350 bar	FCEV 700 bar	FCEV LH2	BEV	Catenary
Base: Assumed payload of Diesel Truck	**27.0 t**	**27.0 t**	**27.0 t**	**27.0 t**	**27.0 t**	**27.0 t**	**27.0 t**
Payload gain from reduced weight of new PT components	0.0 t	0.0 t	0.9 t	0.5 t	1.5 t	2.3 t	2.2 t
Payload gain due to regulation[1]	0.0 t	0.0 t	1.0 t	1.0 t	1.0 t	1.0 t	1.0 t
Payload loss due to small battery	0.0 t	0.0 t	– 0.7 t	– 0.7 t	– 0.7 t	0.0 t	– 0.7 t
Payload loss due to large battery	0.0 t	0.0 t	0.0 t	0.0 t	0.0 t	– 7.0 t	0.0 t
Gross Payload	**27.0 t**	**27.0 t**	**28.2 t**	**27.8 t**	**28.8 t**	**23.3 t**	**29.5 t**
Avg. loading factor if truck is not empty [80%]	21.6 t	21.6 t	22.5 t	22.2 t	23.0 t	18.6 t	23.6 t
Share of empty runs [25%]	16.2 t	16.2 t	16.9 t	16.7 t	17.3 t	14.0 t	17.7 t
Net Payload	**16.2 t**	**16.2 t**	**16.9 t**	**16.7 t**	**17.3 t**	**14.0 t**	**17.7 t**
	no changes	no changes					

[1] Assumed is + 1 tonne GVW for alternatively fuelled vehicles following Directive (EU) 2015/719. This assumption can be modified to reflect Regulation (EU) 2019/1242 with + 2 tonnes GVW for zero-emission vehicles.

Source: Roland Berger

Payloads are calculated for each technology based on base case assumptions

Use case II – Payloads based on first base case assumptions

	Diesel	Diesel E-Fuels	FCEV 350 bar	FCEV 700 bar	FCEV LH2	BEV	Catenary
Base: Assumed payload of Diesel Truck	**14.5 t**	**14.5 t**	**14.5 t**	**14.5 t**	**14.5 t**	**14.5 t**	**14.5 t**
Payload gain from reduced weight of new PT components	0.0 t	0.0 t	0.8 t	0.5 t	1.1 t	1.7 t	1.6 t
Payload gain due to regulation[1]	0.0 t	0.0 t	1.0 t	1.0 t	1.0 t	1.0 t	1.0 t
Payload loss due to small battery	0.0 t	0.0 t	– 0.6 t	– 0.6 t	– 0.6 t	0.0 t	– 0.6 t
Payload loss due to large battery	0.0 t	0.0 t	0.0 t	0.0 t	0.0 t	– 4.3 t	0.0 t
Gross Payload	**14.5 t**	**14.5 t**	**15.6 t**	**15.4 t**	**16.0 t**	**12.9 t**	**16.4 t**
Avg. loading factor if truck is not empty [80%]	11.6 t	11.6 t	12.5 t	12.3 t	12.8 t	10.3 t	13.1 t
Share of empty runs [25%]	8.7 t	8.7 t	9.4 t	9.2 t	9.6 t	7.7 t	9.8 t
Net Payload	**8.7 t**	**8.7 t**	**9.4 t**	**9.2 t**	**9.6 t**	**7.7 t**	**9.8 t**
	no changes	no changes					

[1] Assumed is + 1 tonne GVW for alternatively fuelled vehicles following Directive (EU) 2015/719. This assumption can be modified to reflect Regulation (EU) 2019/1242 with + 2 tonnes GVW for zero-emission vehicles.

Source: Roland Berger

Payloads are calculated for each technology based on base case assumptions

Use case III – Payloads based on first base case assumptions

	Diesel	Diesel E-Fuels	FCEV 350 bar	FCEV 700 bar	FCEV LH2	BEV	Catenary
Base: Assumed payload of Diesel Truck	**10.5 t**	**10.5 t**	**10.5 t**	**10.5 t**	**10.5 t**	**10.5 t**	**10.5 t**
Payload gain from reduced weight of new PT components	0.0 t	0.0 t	0.7 t	0.6 t	0.9 t	1.3 t	1.2 t
Payload gain due to regulation[1]	0.0 t	0.0 t	1.0 t	1.0 t	1.0 t	1.0 t	1.0 t
Payload loss due to small battery	0.0 t	0.0 t	– 0.6 t	– 0.6 t	– 0.6 t	0.0 t	– 0.6 t
Payload loss due to large battery	0.0 t	0.0 t	0.0 t	0.0 t	0.0 t	– 2.5 t	0.0 t
Gross Payload	**10.5 t**	**10.5 t**	**11.6 t**	**11.5 t**	**11.8 t**	**10.2 t**	**12.0 t**
Avg. loading factor if truck is not empty [80%]	8.4 t	8.4 t	9.3 t	9.2 t	9.5 t	8.2 t	9.6 t
Share of empty runs [25%]	6.3 t	6.3 t	7.0 t	6.9 t	7.1 t	6.1 t	7.2 t
Net Payload	**6.3 t**	**6.3 t**	**7.0 t**	**6.9 t**	**7.1 t**	**6.1 t**	**7.2 t**
	no changes	no changes					

[1] Assumed is + 1 tonne GVW for alternatively fuelled vehicles following Directive (EU) 2015/719. This assumption can be modified to reflect Regulation (EU) 2019/1242 with + 2 tonnes GVW for zero-emission vehicles.

Source: Roland Berger

Detailed breakdown of use case specific payload assumptions for weight adaption without battery

Use case specific payload assumptions – Details (2/3)

Assumptions

Weight adaption w/o battery

			2023	2027	2030
4x2 Tractor – 330 kW	Diesel	t	0.00	0.00	0.00
	Diesel E-Fuels	t	0.00	0.00	0.00
	FCEV 350 bar	t	-1.90	-1.93	-1.95
	FCEV 700 bar	t	-1.53	-1.58	-1.60
	FCEV LH2	t	-2.49	-2.51	-2.52
	BEV	t	-3.30	-3.30	-3.30
	Catenary	t	-3.20	-3.20	-3.20

			2023	2027	2030
6x2 Rigid – 270 kW	Diesel	t	0.00	0.00	0.00
	Diesel E-Fuels	t	0.00	0.00	0.00
	FCEV 350 bar	t	-1.76	-1.78	-1.79
	FCEV 700 bar	t	-1.53	-1.56	-1.57
	FCEV LH2	t	-2.12	-2.13	-2.13
	BEV	t	-2.66	-2.66	-2.66
	Catenary	t	-2.56	-2.56	-2.56

Comments

> The weight of batteries is dynamically included in the calculation based on daily mileage and a buffer

> EU Weights and Dimension regulation is considered with an additional one tonne GVW incentive for alternatively fueled vehicles

> The considered hydrogen tank weight is assumed at:

- 350 bar: 15 kg/kg H_2
- 700 bar: 20 kg/kg H_2
- LH_2: 7 kg/kg H_2

> A payload reduction of BEV is reflected dynamically through the calculated battery weight (based on weight/kWh and size, changing according to daily mileage of the use case in the TCO model)

> Payload for catenary trucks is assumed to be 0.1 tonne higher compared to BEV due to the pantograph equipment (before considering the weight of the large battery, which is a separate and variable parameter in the TCO model)

Source

Lastauto Omnibus 2018; Desk research; Assumption in line with RB OEM project experience

Source: Lastauto Omnibus, Roland Berger

Detailed breakdown of use case specific payload assumptions for weight adaption without battery

Use case specific payload assumptions – Details (3/3)

Assumptions **Comments** **Source**

Weight adaption w/o battery

4x2 Rigid – 220 kW

		2023	2027	2030
Diesel	t	0.00	0.00	0.00
Diesel E-Fuels	t	0.00	0.00	0.00
FCEV 350 bar	t	-1.71	-1.72	-1.72
FCEV 700 bar	t	-1.58	-1.59	-1.60
FCEV LH2	t	-1.92	-1.92	-1.93
BEV	t	-2.25	-2.25	-2.25
Catenary	t	-2.15	-2.15	-2.15

- The weight of batteries is dynamically included in the calculation based on daily mileage and a buffer
- EU Weights and Dimension regulation is considered with an additional one tonne GVW incentive for alternatively fueled vehicles
- The considered hydrogen tank weight is assumed at:
  - 350 bar: 15 kg/kg H_2
  - 700 bar: 20 kg/kg H_2
  - LH_2: 7 kg/kg H_2
- A payload reduction of BEV is reflected dynamically through the calculated battery weight (based on weight/kWh and size, changing according to daily mileage of the use case in the TCO model)
- Payload for catenary trucks is assumed to be 0.1 tonne higher compared to BEV due to the pantograph equipment (before considering the weight of the large battery, which is a separate and variable parameter in the TCO model)

Lastauto Omnibus 2018; Desk research; Assumption in line with RB OEM project experience

Source: Lastauto Omnibus, Roland Berger

Energy costs are a major component of TCO – H_2 cost assumptions have been adjusted based on Advisory Board Member feedback

Energy/Fuel cost and emission assumptions

Fuel/Energy cost[1]		2023	2027	2030
Diesel	EUR/l	1.26	1.37	1.37
Diesel E-Fuels	EUR/l	3.18	2.65	2.17
FCEV 350 bar	EUR/kg	6.90	5.40	4.50
FCEV 700 bar	EUR/kg	7.30	5.74	4.80
FCEV LH2	EUR/kg	7.70	5.88	4.80
BEV	EUR/kWh	0.30	0.24	0.20
Catenary	EUR/kWh	0.51	0.50	0.50

Ad-Blue cost		2023	2027	2030
Cost of Ad-Blue	EUR/l	0.25	0.25	0.25

CO_2 emissions		WtW	WtT	TtW
Diesel	gCO_2e/l	3,240	570	2,670
Diesel E-Fuels	$gCOe_2/l$	-	-	-
FCEV 350 bar	gCO_2e/kg	-	-	-
FCEV 700 bar	gCO_2e/kg	-	-	-
FCEV LH2	gCO_2e/kg	-	-	-
BEV	gCO_2e/kWh	-	-	-
Catenary	gCO_2e/kWh	-	-	-

> Cost of energy includes infrastructure surcharges and taxes

> TCO model allows to differentiate between energy cost, taxes and infrastructure surcharges to reflect case specific circumstances

> Diesel and Diesel E-Fuels including taxation at the pump

> BEV charging electricity based on base electricity price, grid fees, tariffs and surcharges for fast charging infrastructure – Prices ultimately depend on the utilisation

> Catenary charging includes utilisation charges for catenary infrastructure (e.g. substation, grid connection, catenary wires)

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1) Fuel and energy costs also include additional infrastructure surcharges.

Source: Concawe; DLSV; Roland Berger

Detailed breakdown of assumptions for energy and fuel costs and emissions

Energy/Fuel cost and emission assumptions – Details (1/2)

Assumptions

Fuel/Energy cost		2023	2027	2030
Diesel	EUR/l	1.26	1.37	1.37
Diesel E-Fuels	EUR/l	3.18	2.65	2.17
FCEV 350 bar	EUR/kg	6.90	5.40	4.50
FCEV 700 bar	EUR/kg	7.30	5.74	4.80
FCEV LH2	EUR/kg	7.70	5.88	4.80
BEV	EUR/kWh	0.30	0.24	0.20
Catenary	EUR/kWh	0.51	0.50	0.50

Comments

> Cost of energy includes infrastructure surcharges and taxes where applicable
  - Diesel and Diesel E-Fuels include taxation at the pump
  - Catenary charging includes utilisation charges for infrastructure

> BEV charging electricity based on base electricity price, grid fees, tariffs and surcharges for fast charging infrastructure

> BEV electricity costs depend on infrastructure costs assumed at EUR 1.2 million per charging station unit (10 charging points) in 2023 and niche scenario and additional EUR 0.35 million other costs (e.g. set-up, maintenance)

> Catenary electricity costs depend on infrastructure costs assumed at 0.8 million EUR/km (incl. substations every 100 km, grid connection, catenary grid)

> Hydrogen cost calculated with separate supply chains and large scale production from electrolysis

Source

Desk research, assumption in line with RB OEM project experience, RB H2 cost model

Source: Concawe; DLSV; Roland Berger

Detailed breakdown of assumptions for energy and fuel costs and emissions

Energy/Fuel cost and emission assumptions – Details (2/2)

Assumptions **Comments** **Source**

Ad-Blue cost		2023	2027	2030
Cost of Ad-Blue	EUR/l	0.25	0.25	0.25

Source: Assumption in line with RB OEM project experience

CO_2 emissions		WtW	WtT	TtW
Diesel	gCO_2e/l	3,240	570	2,670
Diesel E-Fuels	$gCOe_2/l$	-	-	-
FCEV 350 bar	gCO_2e/kg	-	-	-
FCEV 700 bar	gCO_2e/kg	-	-	-
FCEV LH2	gCO_2e/kg	-	-	-
BEV	gCO_2e/kWh	-	-	-
Catenary	gCO_2e/kWh	-	-	-

> Diesel CO_2 emissions based on data triangulation from different sources and calculated in carbon dioxide equivalents

> Alternative powertrains are assumed to have zero emissions

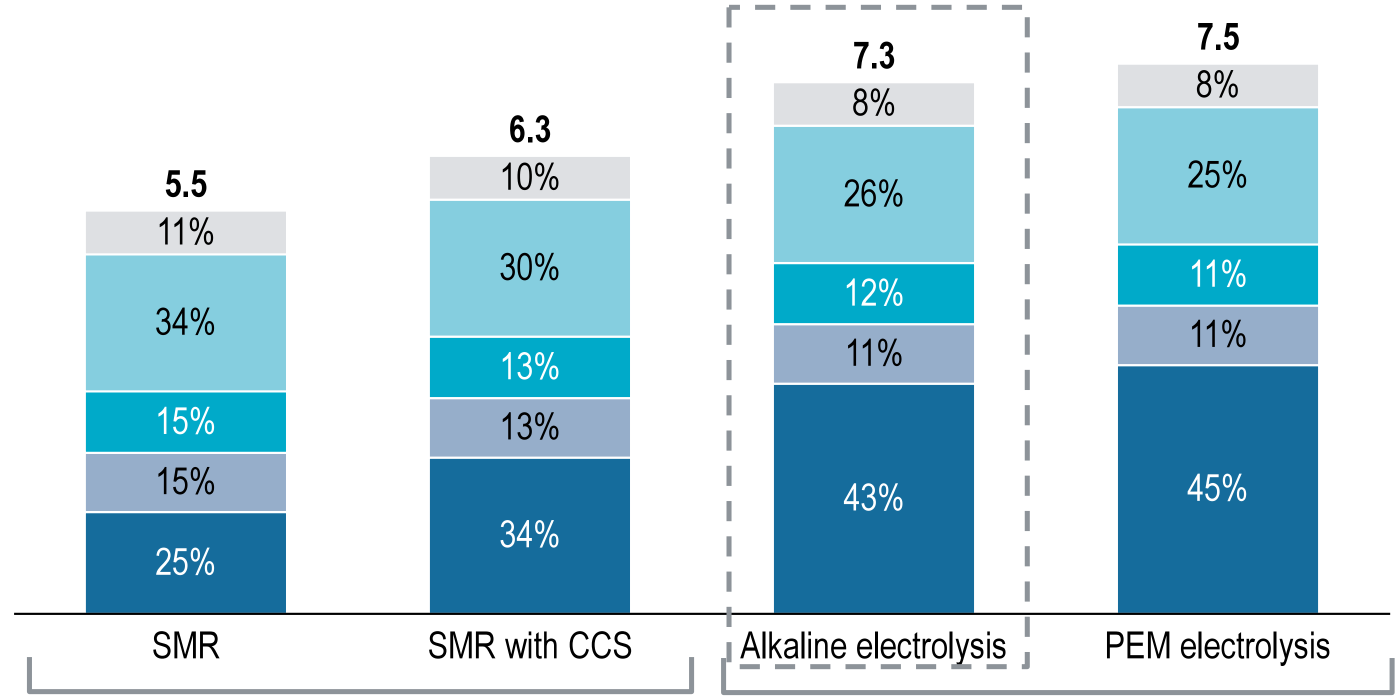
Source: Concawe; DSLV; Desk research; assumption in line with RB OEM project experience

Source: Concawe; DLSV; Roland Berger

Dispensed H_2 cost estimates – Production of green H_2 assumed based on renewable energy sources via Guarantees of Origin

Example for 2023 @ 700 bar refuelling [EUR/kg]

Input variables not exhaustive



Margin & contingency
Refuelling
Transport
Conditioning
Production

Production

- H_2 Capacity: 100,000 Nm³/h or ~ 205 tonnes/day
- Natural gas: ~ 0.025 EUR/kWh
- Utilisation: 8,500 hours p.a.
- CAPEX: EUR 130 m
- OPEX: 3% of CAPEX

- H_2 Capacity: 22,000 Nm³/h or ~ 45 tonnes/day (max)
- Electricity: 50 EUR/MWh (incl. GoO)
- Utilisation: 7,500 hours p.a.
- CAPEX: EUR 70 m (alkaline), EUR 85 m (PEM)
- OPEX: 3% of CAPEX

Margin & contingency
- Estimate

Refuelling
- Capacity: 1.2 tonnes/day
- CAPEX: EUR 3.5 m
- OPEX: 3% of CAPEX

Transport:
- Capacity: 1.1 tonnes/day @500 bar
- Distance: 150 km one-way
- CAPEX: EUR 1.1 m
- OPEX: 3% of CAPEX

Conditioning (trailer filling)
- Capacity: 8.8 tonnes/day
- CAPEX: EUR 10.0 m
- OPEX: 3% of CAPEX

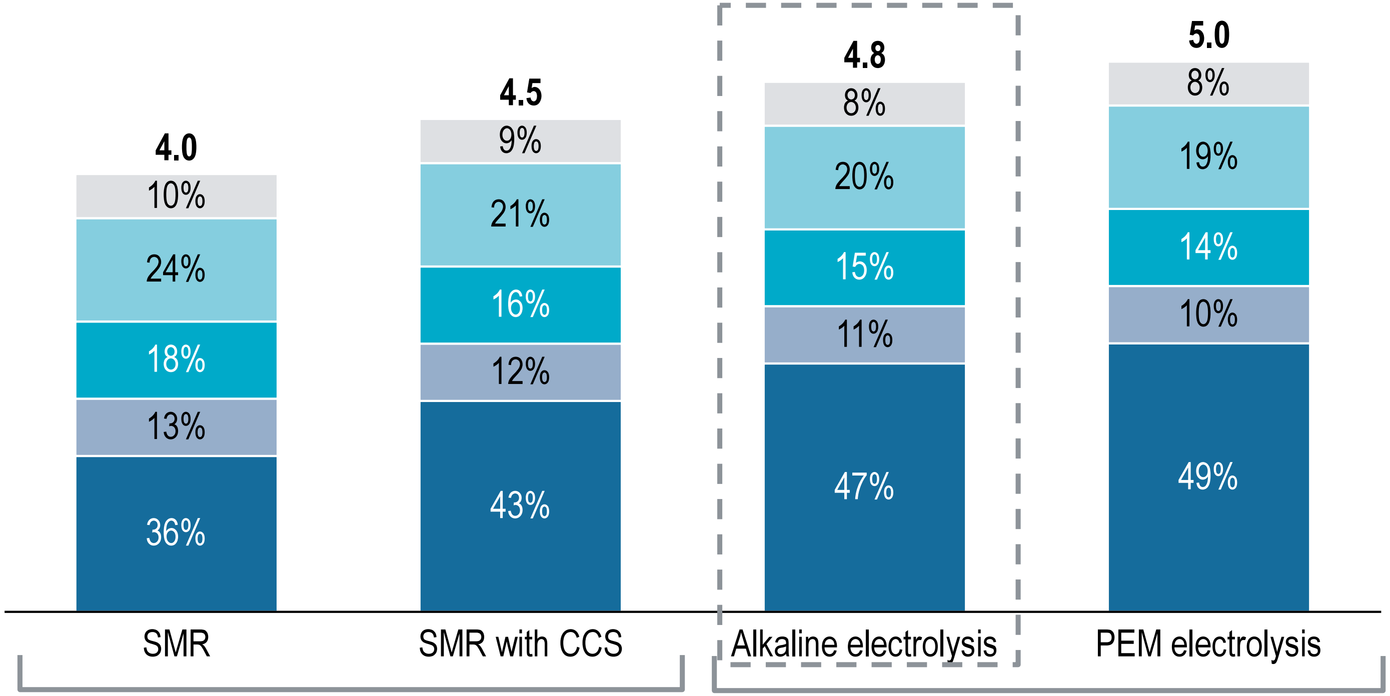
⬚ Used for TCO modelling

Source: Roland Berger

Dispensed H_2 cost estimates – Production of green H_2 assumed based on renewable energy sources via Guarantees of Origin

Example for 2030 @ 700 bar refuelling [EUR/kg]

Input variables not exhaustive



Production

- H_2 Capacity: 100,000 Nm³/h or ~ 205 tonnes/day
- Natural gas: ~ 0.025 EUR/kWh
- Utilisation: 8,500 hours p.a.
- CAPEX: EUR 130 m
- OPEX: 3% of CAPEX

- H_2 Capacity: 22,000 Nm³/h or ~ 45 tonnes/day (max)
- Electricity: 35 EUR/MWh (incl. GoO)
- Utilisation: 7,500 hours p.a.
- CAPEX: EUR 50 m (alkaline), EUR 65 m (PEM)
- OPEX: 3% of CAPEX

Margin & contingency
- Estimate

Refuelling
- Capacity: 6.0 tonnes/day
- CAPEX: EUR 6.5 m
- OPEX: 3% of CAPEX

Transport:
- Capacity: 1.1 tonnes/day @500 bar
- Distance: 150 km one-way
- CAPEX: EUR 0.75 m
- OPEX: 3% of CAPEX

Conditioning (trailer filling)
- Capacity: 8.8 tonnes/day
- CAPEX: EUR 3.5 m
- OPEX: 3% of CAPEX

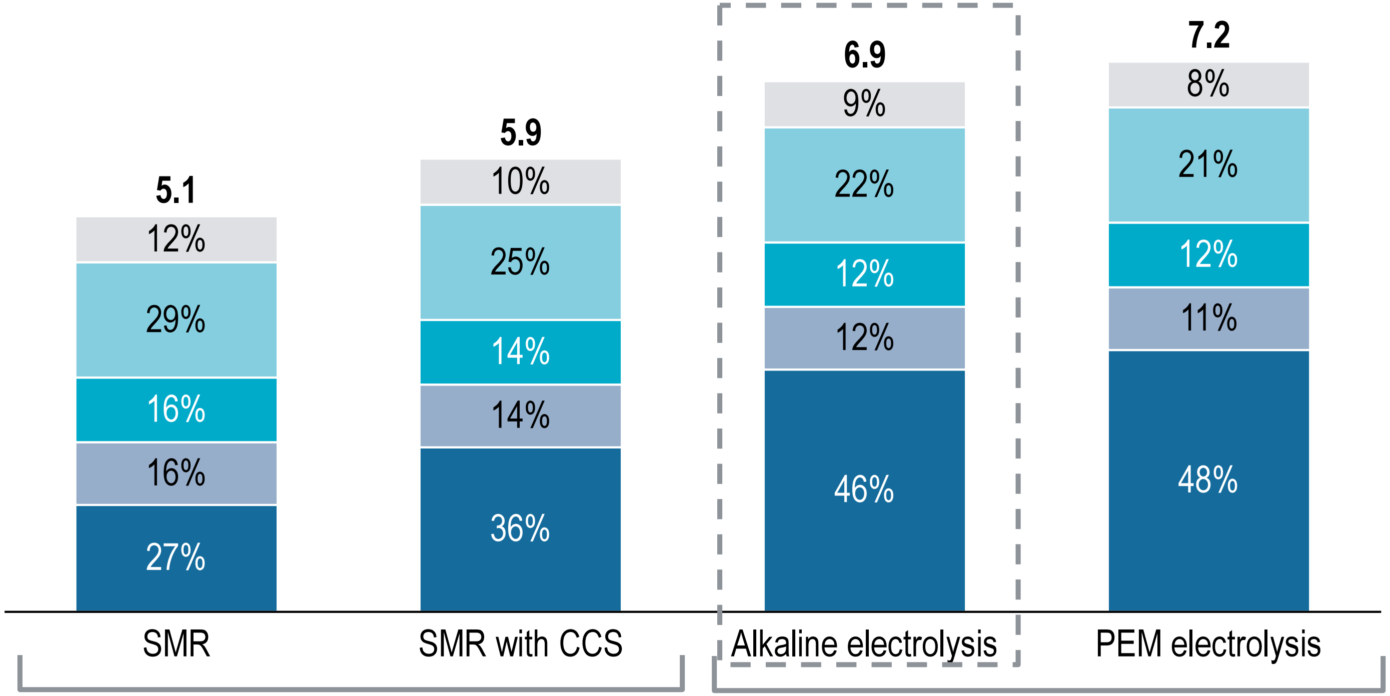
⬚ Used for TCO modelling

Source: Roland Berger

Dispensed H_2 cost estimates – Production of green H_2 assumed based on renewable energy sources via Guarantees of Origin

For 2023 @ 350 bar refuelling [EUR/kg]

Input variables not exhaustive



- ▨ Margin & contingency
- ▨ Refuelling
- ▨ Transport
- ▨ Conditioning
- ▨ Production

Production

SMR / SMR with CCS:
- > H_2 Capacity: 100,000 Nm³/h or ~ 205 tonnes/day
- > Natural gas: ~ 0.025 EUR/kWh
- > Utilisation: 8,500 hours p.a.
- > CAPEX: EUR 130 m
- > OPEX: 3% of CAPEX

Alkaline electrolysis / PEM electrolysis:
- > H_2 Capacity: 22,000 Nm³/h or ~ 45 tonnes/day (max)
- > Electricity: 50 EUR/MWh (incl. GoO)
- > Utilisation: 7,500 hours p.a.
- > CAPEX: EUR 70 m (alkaline), EUR 85 m (PEM)
- > OPEX: 3% of CAPEX

Margin & contingency
- > Estimate

Refuelling
- > Capacity: 1.2 tonnes/day
- > CAPEX: EUR 3.0 m
- > OPEX: 3% of CAPEX

Transport:
- > Capacity: 1.1 tonnes/day @500 bar
- > Distance: 150 km one-way
- > CAPEX: EUR 1.1 m
- > OPEX: 3% of CAPEX

Conditioning (trailer filling)
- > Capacity: 8.8 tonnes/day
- > CAPEX: EUR 10.0 m
- > OPEX: 3% of CAPEX

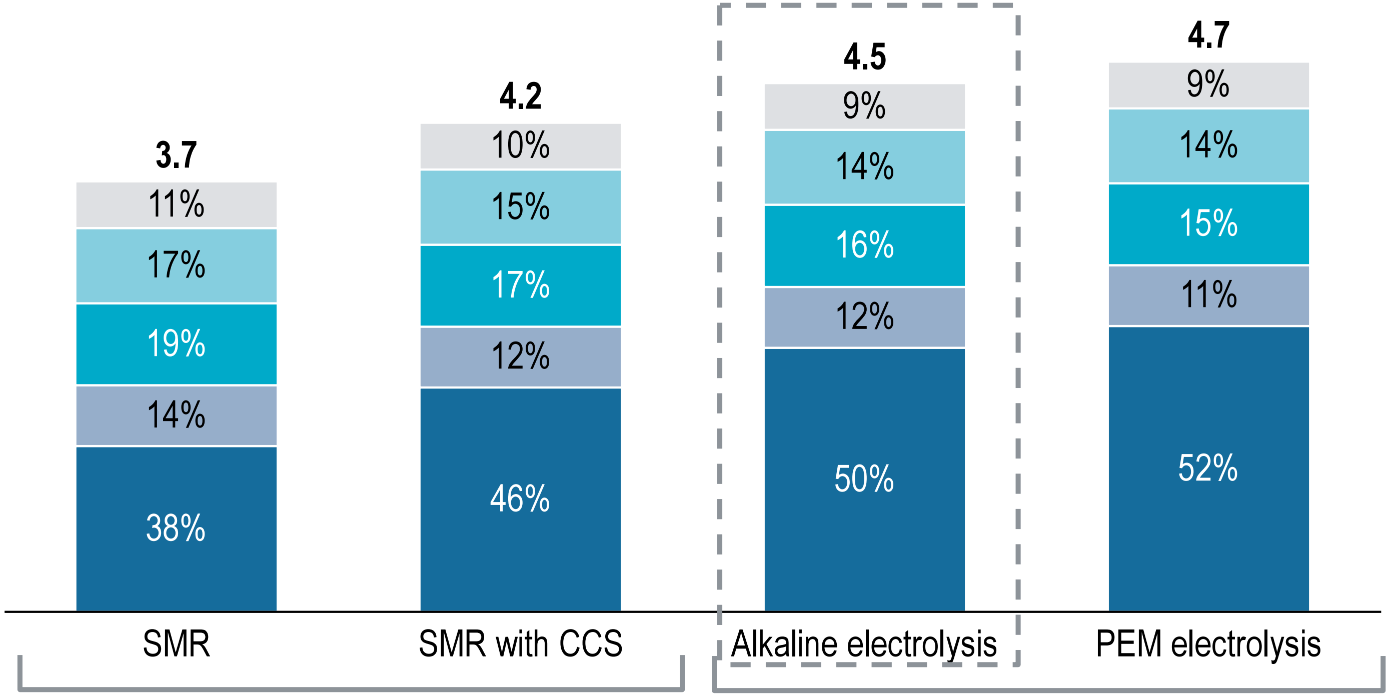
⬚ Used for TCO modelling

Source: Roland Berger

Dispensed H_2 cost estimates – Production of green H_2 assumed based on renewable energy sources via Guarantees of Origin

For 2030 @ 350 bar refuelling [EUR/kg]

Input variables not exhaustive



Margin & contingency
Refuelling
Transport
Conditioning
Production

Production

SMR / SMR with CCS:
- H_2 Capacity: 100,000 Nm³/h or ~ 205 tonnes/day
- Natural gas: ~ 0.025 EUR/kWh
- Utilisation: 8,500 hours p.a.
- CAPEX: EUR 130 m
- OPEX: 3% of CAPEX

Alkaline / PEM electrolysis:
- H_2 Capacity: 22,000 Nm³/h or ~ 45 tonnes/day (max)
- Electricity: 35 EUR/MWh (incl. GoO)
- Utilisation: 7,500 hours p.a.
- CAPEX: EUR 50 m (alkaline), EUR 65 m (PEM)
- OPEX: 3% of CAPEX

Margin & contingency
- Estimate

Refuelling
- Capacity: 6.0 tonnes/day
- CAPEX: EUR 5.0 m
- OPEX: 3% of CAPEX

Transport:
- Capacity: 1.1 tonnes/day @500 bar
- Distance: 150 km one-way
- CAPEX: EUR 0.75 m
- OPEX: 3% of CAPEX

Conditioning (trailer filling)
- Capacity: 8.8 tonnes/day
- CAPEX: EUR 3.5 m
- OPEX: 3% of CAPEX

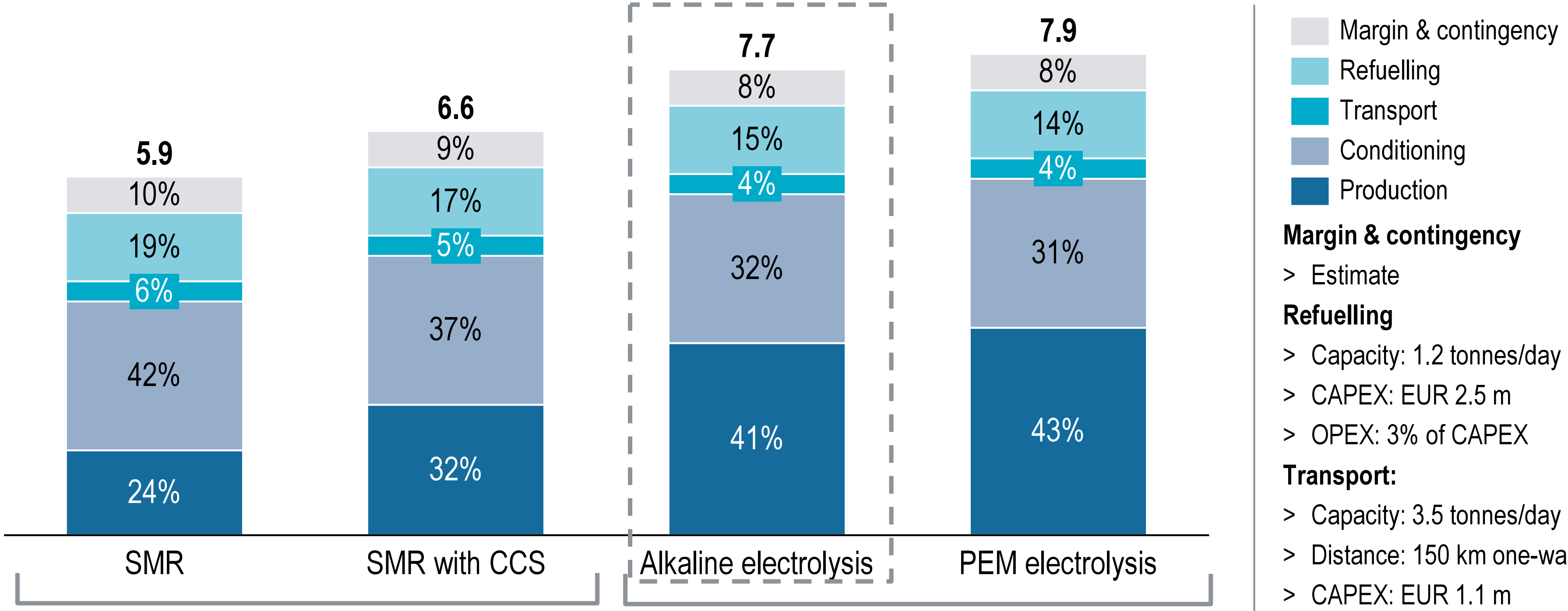
Used for TCO modelling

Source: Roland Berger

Dispensed H_2 cost estimates – Production of green H_2 assumed based on renewable energy sources via Guarantees of Origin

For 2023 @ LH_2 refuelling [EUR/kg]

Input variables not exhaustive



Production

- > H_2 Capacity: 100,000 Nm³/h or ~ 205 tonnes/day
- > Natural gas: ~ 0.025 EUR/kWh
- > Utilisation: 8,500 hours p.a.
- > CAPEX: EUR 130 m
- > OPEX: 3% of CAPEX

- > H_2 Capacity: 22,000 Nm³/h or ~ 45 tonnes/day (max)
- > Electricity: 50 EUR/MWh (incl. GoO)
- > Utilisation: 7,500 hours p.a.
- > CAPEX: EUR 70 m (alkaline), EUR 85 m (PEM)
- > OPEX: 3% of CAPEX

Margin & contingency
- > Estimate

Refuelling
- > Capacity: 1.2 tonnes/day
- > CAPEX: EUR 2.5 m
- > OPEX: 3% of CAPEX

Transport:
- > Capacity: 3.5 tonnes/day LH_2
- > Distance: 150 km one-way
- > CAPEX: EUR 1.1 m
- > OPEX: 3% of CAPEX

Conditioning (LH_2 plant)
- > Capacity: 5.0 tonnes/day
- > CAPEX: EUR 30.0 m
- > OPEX: 3% of CAPEX
- > Energy cons.: 13 kWh/kg

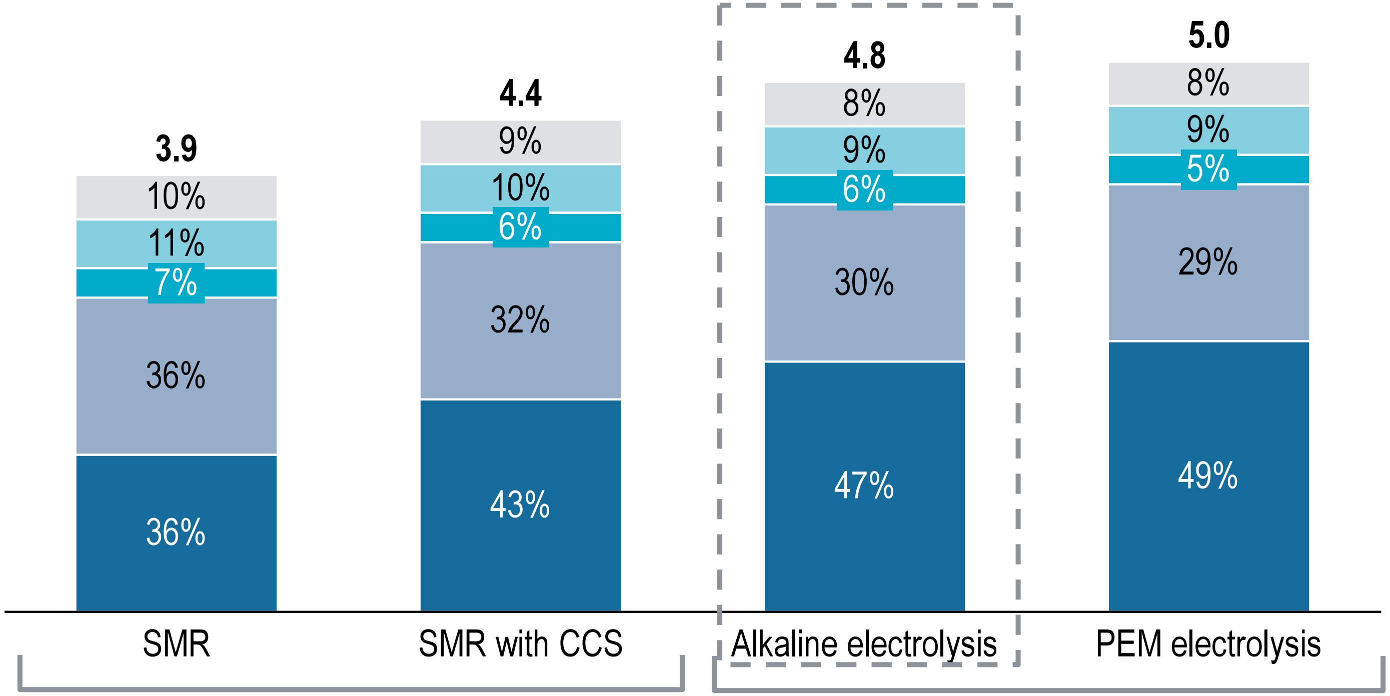
⬚ Used for TCO modelling

Source: Roland Berger

Dispensed H_2 cost estimates – Production of green H_2 assumed based on renewable energy sources via Guarantees of Origin

For 2030 @ LH_2 refuelling [EUR/kg]

Input variables not exhaustive



Production

- H_2 Capacity: 100,000 Nm³/h or ~ 205 tonnes/day
- Natural gas: ~ 0.025 EUR/kWh
- Utilisation: 8,500 hours p.a.
- CAPEX: EUR 130 m
- OPEX: 3% of CAPEX

- H_2 Capacity: 22,000 Nm³/h or ~ 45 tonnes/day (max)
- Electricity: 35 EUR/MWh (incl. GoO)
- Utilisation: 7,500 hours p.a.
- CAPEX: EUR 50 m (alkaline), EUR 65 m (PEM)
- OPEX: 3% of CAPEX

Margin & contingency

- Estimate

Refuelling

- Capacity: 6.0 tonnes/day
- CAPEX: EUR 4.0 m
- OPEX: 3% of CAPEX

Transport:

- Capacity: 3.5 tonnes/day LH_2
- Distance: 150 km one-way
- CAPEX: EUR 0.75 m
- OPEX: 3% of CAPEX

Conditioning (LH_2 plant)

- Capacity: 35.0 tonnes/day
- CAPEX: EUR 120.0 m
- OPEX: 3% of CAPEX
- Energy cons.: 11 kWh/kg

Used for TCO modelling

Source: Roland Berger

Roland
Berger

THINK:ACT