Study Summary

Fuel Cells Hydrogen Trucks

Heavy-Duty's High Performance Green Solution

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List of abbreviations

BEV	Battery Electric Vehicles
CAPEX	Capital Expenditures
CO_2	Carbon Dioxide
EU	European Union
FCH	Fuel Cells and Hydrogen
FCH JU	Fuel Cells and Hydrogen Joint Undertaking
GHG	Greenhouse Gases
GVW	Gross Vehicle Weight
H_2	Hydrogen
HDT	Heavy-Duty Truck
HRS	Hydrogen Refuelling Station
NOx	Nitrogen Oxides
OEM	Original Equipment Manufacturer
OPEX	Operating Expenditures
R&I	Research and Innovation
RCS	Regulation, Codes and Standards
TCO	Total Cost of Ownership

Abstract

Fuel cell and hydrogen (FCH) technology is a very promising zero-emission powertrain solution for the heavy-duty trucking industry. The FCH 2 JU subcontracted this study to analyse the state-of-the-art of the technology, its surrounding policy and regulatory regime, ongoing trial and demonstrations projects, and its total cost of ownership and market potential. Furthermore, specific case studies and industry experts identified remaining technological and non-technological barriers for FCH technology in different trucking use cases.

The study projects a potential fuel cell trucks sales share of approx. 17% of new trucks sold in 2030 based on a strong technology cost-reduction trajectory. With scaled-up production of FCH trucks and hydrogen offered below 6 EUR/kg, FCH heavy-duty trucks (FCH HDT) provide the operational performance most comparable to diesel trucks regarding daily range, refuelling time, payload capacity and TCO. Nine case studies were developed as first tangible business opportunity blueprints for the industry. They also provide a view on current limitations of real-life operations. In conclusion, 22 barriers have been identified that, successfully tackled, will unlock the full commercial potential of FCH HDT for the trucking and logistics industry. The study proposes tailored R&I projects and policy recommendations that address such remaining barriers in the short-term.

Executive summary

In line with the EU Green Deal and its target to reach carbon neutrality by 2050, Europe is set to decarbonise its transport and mobility industry. EU legislation is already pushing for stricter emission and pollution standards to achieve a necessary 90% reduction of emissions by 2050. While being a backbone of the European economy, the road freight sector is also responsible for a significant amount of CO_2 emissions. Reducing the carbon footprint of heavy-duty trucking is therefore key to achieving the EU's ambitious climate protection targets.

The transition to zero- and low-emission vehicles based on alternative powertrain solutions, such as fuel cell and hydrogen (FCH) or battery-electric, is the main lever for meeting stricter emission standards. The study provides a comparison of alternative powertrain technologies for heavy-duty trucks (HDT), analysis the state-of-the-art of the technology and develops a total cost of ownership analysis (TCO). The comparison showed that FCH applications present a very promising zero-emission alternative. Due to their high operational flexibility and relatively short refuelling time, FCH HDT are particularly suited for long-haul operations.

From a TCO perspective, FCH HDT can become cost-competitive by 2027 if production volumes are ramped up swiftly, as shown in a comparison of FCH trucks with conventional diesel and other alternative powertrains. Preconditions are (i) scaled-up production of FCH trucks and that (ii) hydrogen is offered below 6 EUR/kg. At this scale, the study projects a potential FCH sales share of approximately 17% of new trucks sold in 2030 in a base scenario (~59,500 trucks). If achieved, the zero-emission FCH HDT provide the operational performance most comparable to diesel trucks regarding daily range, refuelling time and payload capacity at a better TCO than the incumbent technology from 2027 onwards.

On the short-term a cost premium of up to 22% for FCH trucks over diesel trucks is expected. The commercialisation of FCH technology for the HDT industry is still at an early stage and first truck products are just becoming available on the market. Today, low prototype production volumes result in relatively high production costs of both vehicles and hydrogen (H_2). In particular the powertrain (fuel cell module and tank system; CAPEX) and energy/fuel (OPEX) are the main cost drivers. Furthermore, H_2 refuelling infrastructure needs to be rolled out significantly and synchronised with FCH truck sales. Trial and demonstration activities will play a crucial role in providing real-life data and experience to pave the way for the market uptake.

FCH trucks show substantial market potential at scale as they are one of the most promising zero-emission alternatives for trucking. For this study, the market potential of FCH HD trucks in Europe has been analysed for three use case segments (long-, medium-, short-haul), which account for approximately 53% of HDT market sales in Europe and represent up to 70% emissions from the HD segment. For these use cases and three market uptake scenarios (conservative, base, optimistic), the study projects significant market potential for FCH HDT, with annual sales shares ranging between 16 and 51% in 2030. If this development can be realised, FCH HD trucks are poised to become a cornerstone for achieving Europe's CO_2 emission reduction targets by 2050. Industrial-scale production, affordable green hydrogen and the build-up of the associated hydrogen refuelling infrastructure are deemed to be key elements for FCH technology uptake. More importantly, achieving a high sales share of zero-emission solutions in the early 2030s is crucial to phase out the majority of diesel-powered trucks over their lifetime by 2050.

However, realising this market potential will depend on providing a financial and regulatory ecosystem that equally supports all stakeholders: truck operators and logistics users, truck OEMs, technology providers, fuel and infrastructure providers. While subsidies and tax exemptions are important tools for fostering the development of FCH technology for trucks, a key lever to cost competitiveness of zero-emission technologies lies in efficient CO_2 pricing. Implementation of emission-based road toll systems or exemptions from existing systems are further important instruments that could enable FCH business cases already in the short term. Already today, first business-driven projects are encouraging signs of a developing market for FCH HDT, e.g. in countries like Switzerland. In order to translate these first ventures into sustainable businesses and to realize their market potential, cost competitiveness on the supply-side and increased demand need to be generated through comparable targeted incentive schemes all over Europe.

Additionally, the study investigated the three use cases through case studies, in order to include the perspective of truck operators and logistics service providers building on information of real-life routes. In nine specific case studies, the economic and operational benefits of fuel cell and hydrogen technology within the transport industry were analysed. The case studies serve as tangible business opportunity blueprints while they also hint at remaining limitations as more FCH truck products and a more mature hydrogen supply chain are still to materialise.

FCH technology in the heavy-duty truck sector still faces several barriers before a commercial roll-out is possible. They are mainly related to the relative novelty of the technology for this application and initial support is needed to unlock its full market and decarbonisation potential. The study identified 22 technological and non-technological barriers. None of these barriers are deemed showstoppers for successful commercialisation. Policy adjustments and tailored R&I projects should be implemented to speed up and optimise a large-scale roll-out in the HDT sector in the next years. Four tailored R&I projects, with an estimated total budget of EUR 470 million, are suggested to overcome these remaining barriers in the short term. Work should especially be focused on improving technical and economic performance to allow commercial application. Especially standardisation of on-board hydrogen storage based on best lifecycle economics could speed-up FCH truck product development and hydrogen refuelling infrastructure roll-out. In the mid-term, developing this sector could also lead to export opportunities for European industry, as an increasing number of countries in other regions are transitioning to FCH transport and mobility solutions. This would also preserve highly qualified jobs and expertise in Europe.

The study shows that fuel cell and hydrogen technologies and applications are pivotal for a carbon-neutral future of the heavy-duty trucking and logistics industry. A concerted political and industrial push by a broad coalition of industry and public stakeholders is needed to deliver on this breakthrough moment. By transitioning to FCH heavy-duty trucks in the upcoming years, the trucking industry will embark on a journey towards competitive, clean, quiet and innovative mobility solutions in line with the EU's ambitious climate protection efforts and emission reduction targets.

Résumé

Conformément au "Green Deal" de l'UE et à son objectif d'atteindre la neutralité carbone d'ici 2050, l'Europe est prête à décarboner son secteur des transports et de la mobilité. La législation européenne préconise déjà des normes strictes en matière d'émissions et de pollution afin de parvenir à une réduction nécessaire de 90 % des émissions d'ici 2050. Le secteur du transport routier de marchandises, tout en étant un pilier de l'économie européenne, est également responsable d'un volume important d'émissions de CO_2. Il est donc essentiel de réduire l'empreinte carbone du transport routier lourd pour atteindre les objectifs ambitieux de l'UE en matière de protection du climat.

Le passage à des véhicules à émissions faibles ou nulles appuyés sur des solutions alternatives de propulsion, telles que la pile à combustible et l'hydrogène (FCH) ou la batterie électrique, est le principal levier pour respecter des normes d'émissions plus strictes. L'étude fournit une comparaison des technologies de propulsion alternatives pour les poids lourds (Heavy Duty Trucks, HDT), analyse l'état de l'art de la technologie et développe une analyse du coût total de possession (TCO). La comparaison a montré que les applications piles à combustible (FCH) présentent une alternative très prometteuse à émission zéro. En raison de leur grande flexibilité opérationnelle et de leur temps de ravitaillement relativement court, les HDT FCH sont particulièrement adaptés aux opérations longue distance.

Du point de vue du coût total de possession, le FCH HDT peut devenir compétitif d'ici 2027 si les volumes de production augmentent rapidement, comme le montre une comparaison des camions FCH avec le diesel classique et d'autres groupes motopropulseurs alternatifs. Les conditions préalables sont (i) la production à grande échelle des camions FCH et (ii) l'offre d'hydrogène en dessous de 6 EUR/kg. À cette échelle, l'étude prévoit une part potentielle des ventes de camions FCH d'environ 17 % des nouveaux camions vendus en 2030 dans un scénario de base (~59 500 camions). S'ils sont réalisés, les FCH HDT à zéro émission offrent les performances opérationnelles les plus comparables aux camions diesel en ce qui concerne l'autonomie journalière, le temps de ravitaillement et la capacité de charge utile, à un meilleur coût total de possession que la technologie actuelle à partir de 2027.

À court terme, on s'attend à une augmentation des coûts pouvant aller jusqu'à 22 % pour les camions FCH par rapport aux camions diesel. La commercialisation de la technologie FCH pour l'industrie des HDT n'en est qu'à ses débuts et les premiers produits pour camions sont tout juste disponibles sur le marché. Aujourd'hui, les faibles volumes de production de prototypes se traduisent par des coûts de production relativement élevés, tant pour les véhicules que pour l'hydrogène (H_2). En particulier, le groupe motopropulseur (module de pile à combustible et système de réservoir; CAPEX) et l'énergie/carburant (OPEX) sont les principaux facteurs de coût. En outre, l'infrastructure de ravitaillement en H2 doit être déployée de manière significative et synchronisée avec les ventes de camions FCH. Les activités d'essai et de démonstration joueront un rôle crucial en fournissant des données et des expériences réelles pour ouvrir la voie à l'adoption par le marché.

Les camions FCH présentent un potentiel de marché considérable à grande échelle, car ils constituent l'une des alternatives les plus prometteuses pour un transport routier sans émissions. Pour cette étude, le potentiel de marché des camions FCH en Europe a été analysé pour trois segments de cas d'utilisation (long, moyen et court courrier), qui représentent environ 53 % des ventes de camions HD en Europe et jusqu'à 70 % des émissions du segment HD. Pour ces cas d'utilisation et trois scénarios d'adoption par le marché (conservateur, de base, optimiste), l'étude prévoit un potentiel de marché important pour les FCH HDT, avec des parts de ventes annuelles comprises entre 16 et 51 % en 2030. Si cette évolution se concrétise, les camions FCH sont en passe de devenir une pierre angulaire pour atteindre les objectifs européens de réduction des émissions de CO_2 d'ici 2050. La production à l'échelle industrielle, l'hydrogène vert à un prix abordable et la mise en place de l'infrastructure de ravitaillement en hydrogène associée sont considérés comme des éléments clés pour l'adoption de la technologie FCH. Plus

important encore, il est essentiel d'atteindre une part élevée des ventes de solutions à émissions zéro au début des années 2030 pour éliminer progressivement la majorité des camions à moteur diesel au cours de leur durée de vie d'ici 2050.

Toutefois, la réalisation de ce potentiel de marché dépendra de la mise en place d'un écosystème financier et réglementaire qui soutienne de manière égale toutes les parties prenantes : les opérateurs de camions et les utilisateurs de logistique, les équipementiers de camions, les fournisseurs de technologie, les fournisseurs de carburant et d'infrastructures. Si les subventions et les exonérations fiscales sont des outils importants pour favoriser le développement de la technologie FCH pour les camions, un levier clé de la compétitivité des coûts des technologies à zéro émission réside dans une tarification efficace du CO_2. La mise en œuvre de systèmes de péage routier basés sur les émissions ou d'exemptions des systèmes existants est un autre instrument important qui pourrait permettre à FCH de parvenir à la rentabilité à court terme. Aujourd'hui déjà, les premiers projets d'entreprises sont des signes encourageants d'un marché en développement, par exemple dans des pays comme la Suisse. Afin de traduire ces premières initiatives en entreprises durables et de réaliser leur potentiel de marché, il est nécessaire de parvenir à la compétitivité coût du côté de l'offre et une augmentation de la demande grâce à des systèmes d'incitation ciblés comparables dans toute l'Europe.

En outre, l'étude a examiné les trois cas d'utilisation par le biais d'études de cas, afin d'inclure le point de vue des opérateurs de camions et des prestataires de services logistiques en s'appuyant sur des informations relatives à des itinéraires réels. Dans neuf études de cas spécifiques, les avantages économiques et opérationnels de la technologie des piles à combustible et de l'hydrogène dans le secteur des transports ont été analysés. Les études de cas servent de modèles d'opportunités commerciales tangibles tout en soulignant les limites qui subsistent, car il reste encore à mettre au point davantage de produits pour camions FCH et une chaîne d'approvisionnement en hydrogène plus mature.

La technologie FCH dans le secteur des poids lourds se heurte encore à plusieurs obstacles avant qu'un déploiement commercial ne soit possible. Ils sont principalement liés à la relative nouveauté de la technologie pour cette application et un soutien initial est nécessaire pour libérer tout son potentiel de marché et de décarbonation. L'étude a identifié 22 obstacles technologiques et non technologiques. Aucun de ces obstacles n'est considéré comme rédhibitoire pour une commercialisation réussie. Des ajustements politiques et des projets de R&I adaptés devraient être mis en œuvre pour accélérer et optimiser le déploiement à grande échelle dans le secteur des HDT au cours des prochaines années. Quatre projets de R&I sur mesure, avec un budget total estimé à 470 millions d'euros, sont proposés pour surmonter ces obstacles restants à court terme. Les travaux devraient en particulier se concentrer sur l'amélioration des performances techniques et économiques pour permettre une application commerciale. En particulier, la normalisation du stockage d'hydrogène à bord, basée sur la meilleure économie sur le cycle de vie, pourrait accélérer le développement de produits pour les camions FCH et le déploiement de l'infrastructure de ravitaillement en hydrogène. À moyen terme, le développement de ce secteur pourrait également créer des débouchés à l'exportation pour l'industrie européenne, car un nombre croissant de pays d'autres régions sont en train de passer aux solutions de transport et de mobilité FCH. Cela permettrait également de préserver des emplois et des compétences hautement qualifiés en Europe.

L'étude montre que les technologies et les applications des piles à combustible et de l'hydrogène sont essentielles pour un avenir neutre en carbone du secteur du transport routier et de la logistique. Une impulsion politique et industrielle concertée de la part d'une large coalition de parties prenantes de l'industrie et du secteur public est nécessaire pour réaliser cette avancée. En passant aux poids lourds FCH dans les années à venir, l'industrie du camionnage s'engagera sur la voie de solutions de mobilité compétitives, propres, silencieuses et innovantes, conformément aux efforts ambitieux de l'UE en matière de protection du climat et aux objectifs de réduction des émissions.

1. Introduction – Fuel cell and hydrogen trucks today

There is an increasing momentum behind the development and commercial use of fuel cell and hydrogen (FCH) trucks in the heavy-duty (HD) vehicle segment. In line with accelerating European and global efforts to combat climate change and reduce greenhouse gas emissions (GHG), decarbonisation and mitigation of emissions are necessary for all transport modes across Europe. Heavy-duty road transport contributes significantly to these emissions. Of the around 6.6 million medium- and heavy-duty trucks on European roads (ACEA, 2019)[1], around 3.3 million are of a weight higher than 15 tonnes (IEA, 2017)[2]. Together with other heavy-duty vehicles, these trucks account for approximately 27% of road transport related CO_2 emissions and around 5% of all European Union (EU) GHG emissions (EEA, 2018)[3]. FCH heavy-duty trucks (HDT) hold the promise of fulfilling the operational requirements of heavy-duty road transport currently carried out with mainly diesel trucks, while at the same time contributing to cleaner air and lower emissions. However, successful commercialisation and market integration will depend on lowering the total cost of ownership (TCO) of these vehicles.

This study, commissioned by the Fuel Cells and Hydrogen 2 Joint Undertaking, analyses the costs and market potential of FCH technology for heavy-duty trucks, comparing the technology to other competing low-carbon alternatives.[4] The results are based on extensive research and regular exchange with an Industry Advisory Board of 56 companies, institutions and associations. The FCH technology is currently in an early demonstration phase. Many new initiatives are being started, the first truck models are on the roads and new industry ventures and truck developments are being announced. In the coming years, real-life operational experience will further provide field data for zero-emission alternatives, especially for fuel cell and hydrogen-powered and battery-powered trucks. In order to develop an evidence-based perspective on the FCH market development for the heavy-duty transport and logistics industry, the study analyses the status quo of technology, the projected cost development and the market potential. It shows that fast technology development and increasing market uptake would need to become a reality for widespread uptake of FC trucks. Without it, the decarbonisation of the transport sector will be a challenge.

Based on a cost trajectory that considers increasing scale effects in production, the TCO and market analysis reveals that the FCH technology could have significant market potential in the investigated heavy-duty truck market segments. The study examines both the cost competitiveness and the technology acceptance rate of FCH HDT across three uses cases which represent approximately 53% of the total heavy-duty truck market in terms of new vehicle sales. It provides an overview of the state of the art of technologies in this sector, its surrounding policy and regulatory landscape as well as

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[1] European Automobile Manufacturers Association. (2019). *ACEA Report Vehicles in use Europe 2019*. Retrieved from https://www.acea.be/uploads/publications/ACEA_Report_Vehicles_ in_use- Europe_2019.pdf

[2] International Energy Association. (2017). *The Future of Trucks Implications for energy and the environment*. Retrieved from https://www.oecd.org/publications/the-future-of-trucks-9789264279452-en.htm

[3] European Environment Agency. (2020). *Carbon dioxide emissions from Europe's heavy-duty vehicles*. Retrieved from https://www.eea.europa.eu/themes/transport/heavy-duty-vehicles

[4] This study summary is the outcome of a study conducted by Roland Berger in close collaboration with an industry Advisory Board of 56 members from along the entire value chain. The study developed two main reports: The present summary ("Study Summary") and a comprehensive report ("Study Report"). Further information on the total cost of ownership and market potential analyses as well as the case studies is available in the separate Study Report, published by the FCH JU (https://www.fch.europa.eu/).

ongoing trial and demonstration projects for FCH HDT. Route- and industry-specific case studies explore how the technology would perform in real-life conditions. Based on these analyses and lessons learned, policy recommendations and potential research and innovation projects are suggested that could contribute to overcoming remaining technological and non-technological barriers to the widespread adoption of FCH technology in the transport and logistics industry.

1.1 State-of-the-art of the technology

A comparison of today's alternative powertrain technologies options for the HD road transportation sector – namely FCH, battery-electric vehicles (BEV), lower-carbon fuels, e-fuels and catenary – shows that FCH heavy-duty trucks offer a zero-emission alternative with high operational flexibility allowing for long-haul operation, while featuring a relatively short refuelling time. The comparison considers three indicators for a comprehensive overview of the technology state of the art:

> Technology Readiness Level of each technology measured on a scale from ideation to full commercial utilisation;

> Availability of refuelling and charging infrastructure;

> Emission reduction potential on a well-to-wheel basis.

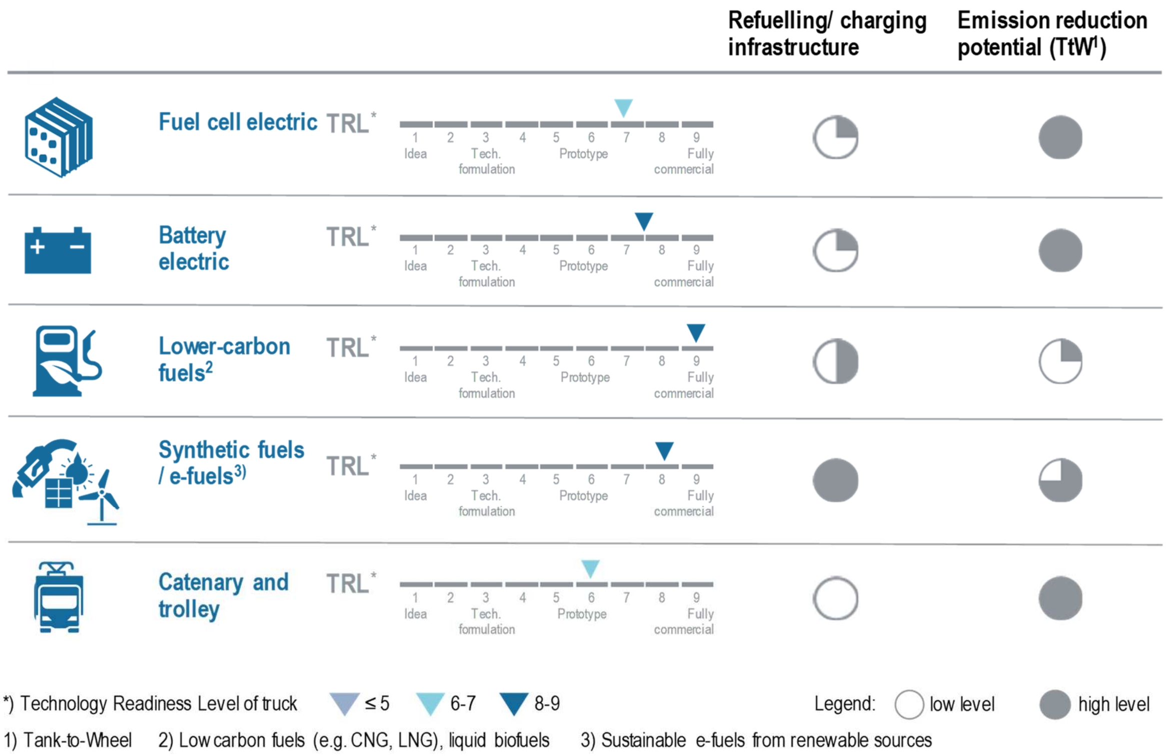

Figure 1: Comparison of alternative powertrain technologies for heavy-duty trucks

FCH HDT prototype trucks are beginning on-road demonstrations, however a market-ready vehicle offering, fully proven in an operational environment, is yet to be established in the market. Commercialisation is still at an early stage with relatively high vehicle and H_2 supply costs as well as a lack of sufficient HDT refuelling infrastructure. Similarly, BEV heavy-duty trucks face constraints regarding battery weight and price, which limits their range and payload for operations as well as charging time requirements and utilisation flexibility. However, BEV development benefits from industry experience in the passenger car and light-duty vehicle segments. As a result, battery heavy-duty trucks are already more established in operational environments.

On the other hand, lower-carbon fuel trucks, for example powered by LNG or CNG, have limited reduction potential of emissions, pollutants and particles. Yet these trucks have already found a market in Europe and are offered in transport and logistics offerings as an alternative to diesel trucks. Nevertheless, CNG/LNG also see limited refuelling infrastructure. Another alternative for diesel combustion engines are heavy-duty trucks fuelled by e-fuels, a CO_2-neutral alternative with medium-high range. Several e-fuel projects have shown technological readiness, but fuel production cost and limited scale of supply remain substantial hurdles for commercialisation.

Overall, the emission reduction potential of vehicles with alternative powertrains depends on the source of energy or fuel. If the electricity used for vehicle charging or the energy used for H_2 or e-fuel production does not stem from renewable energy, these alternatives cannot be counted towards a full CO_2 reduction. Furthermore, as e-fuel HDT are otherwise conventional trucks with an internal combustion engine, they emit NO_x and hence contribute to the emission of pollutants and particles. Catenary trucks compare to BEV with regard to their emission reduction potential if no auxiliary combustion engines are installed. As catenary trucks are charged while driving through the overhead connection to the electricity grid, they do not require a time-consuming battery charging process. Moreover, they offer a potentially high range. However, these trucks are highly dependent on the roll-out of a comprehensive, associated infrastructure network.

Comparing alternative powertrains is complex and inherent uncertainties should be considered. Technology adoption depends on different requirements in infrastructure, regional differences in regulations and incentives, varying customer preferences as well as the total cost of ownership. Overall, zero-emission powertrains for trucks have yet to reach full commercial readiness. Considering the lack of available truck products in the market, the key challenge remains the development of commercially competitive zero-emission heavy-duty trucks. From a technology competition standpoint, hydrogen and fuel cell technology competes against other heavy-duty road transport applications that are being pushed forward in parallel. While all alternative technologies are currently being tested in trials and demonstrations and first commercial roll-outs, these projects show the differing technology readiness levels. Larger demonstration projects are being rolled out for prototype-stage and pre-series-stage FCH and BEV applications in multi-coalition projects. At the same time, catenary and e-fuels are mostly being tested in smaller trials and demonstration activities. LNG/CNG powered trucks, on the other hand, are already being tested and integrated in regular operations across Europe, highlighting its advanced technology readiness.

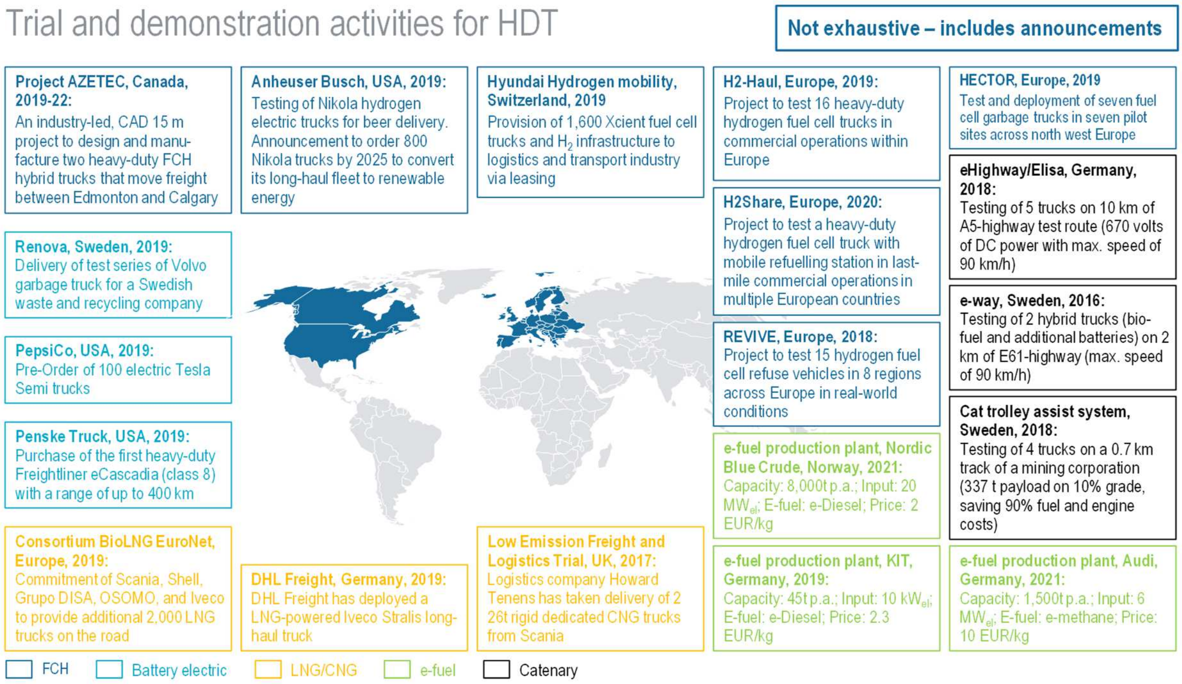

Figure 2: Overview of heavy-duty truck trial and demonstration activities

Fuel cells and hydrogen heavy-duty trucks need to be brought beyond demonstration status and reach higher production levels in order to enable a commercial market. First steps are being made as recent company announcements provide evidence of the increasing activities in the FCH sector that go beyond demonstration projects and pre-commercial market trials. As a prominent example in Europe, a joint venture of an OEM and infrastructure provider started in 2020 to deliver the first of a planned total of 1,600 FCH trucks to clients in Switzerland. In this partner network, the corresponding H_2 infrastructure is being set up in Switzerland in parallel. Such developments will provide further insights on the performance potential of FCH applications in the short term and highlight both the interest in alternative powertrain vehicles in the transport and logistics industry, and the need for a push to market of the heavy-duty truck products.

1.2 Policy and regulatory regime

Technological advancements in FCH heavy-duty trucks are driven by truck OEMs and component manufacturers. Yet also policy makers have an important part to play in unlocking the full potential of hydrogen technologies for the HDT industry. By setting ambitious policy goals combined with strong supporting legislation and support schemes, all relevant stakeholders can contribute to advancing and adapting FCH technology.

Policies and support and incentive schemes at the national and supra-national level provide the regulatory framework in which FCH applications for the heavy-duty truck sector are being developed. A comparison of key international markets shows that policies and regulatory approaches on low-emission HD trucks differ across markets and technologies. At the same time, the increasing knowledge and conscience regarding the importance of lower carbon solutions by the general public and policy makers have led to the introduction of CO_2 emission standards for HDT in all investigated key markets in North America, Europe and Asia, etc.:

- The EU set the direction of an ambitious decarbonisation agenda as part of the EU Green Deal in 2019. It includes a 90% reduction target for transport emissions by 2050 and, as such, is a driving force for low-emission vehicles, fuels, and the build-up of the related infrastructure – enhancing the long-term potential for FCH HDT;

- In California, a precedent was set regarding the implementation of the Clean Air Act as the key framework for stricter targets on air quality, setting the cornerstone for industry action. Furthermore, sales quota for zero-emission trucks are in place;
- At U.S. national level, the upcoming Cleaner Trucks Initiative (CTI) puts HD trucks in focus of general emissions reduction efforts. The Environmental Protection Agency is currently in the process of updating its NO_x emission standards through the CTI and is expected to issue a final rule by mid-2021;
- China offers a strong government incentive scheme consisting of subsidies and purchase tax exemptions for low-emission vehicles including HD trucks, which was recently prolonged until 2022;
- South Korea generally provides strong support for the take-up of hydrogen and fuel cell technology.

Markets		HDT CO_2 standards	Long-term target
North America	USA	**2027 GHG Phase 2 standards** [-15-27% compared to 2018 baseline]	n/a
North America	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
Asia	South Korea	Euro VI based overall emission standards (no specific CO_2 regulation)	**2050** Discussion on net-zero emission target
Asia	Japan	**2025 Fuel economy standards** [avg. -13% compared to 2015 baseline]	**2050** 80% reduction of transport emissions

Figure 3: Heavy-duty road freight decarbonisation trajectory[5]

While the key HD road freight markets – North America, EU and Asia – are set on a decarbonisation trajectory, the EU is aiming for the strictest emission targets. The EU's decarbonisation agenda is also guiding recent EU regulation for the transport sector, which needs to fulfil the long-term net emission reduction target of 90% by 2050. For the first time in Europe, the CO_2 Emission Standards Regulation ((EU) 2019/1242) has established manufacturer-specific tailpipe CO_2 emission standards for new HDT with reduction targets of -15% by 2025 and -30% by 2030. Furthermore, the Clean Vehicle

[5] Emission reduction targets refer to different baseline years and technologies and are as such not like for like.

Directive (2019/1161) introduced a definition of clean vehicles and national minimum public procurement targets for clean mobility solutions.

While EU legislation increasingly pushes for stricter standards in emission reduction and fuel quality, hydrogen applications as a key enabler are not yet the focus of existing policies. However, the European Commission envisages kick-starting a clean hydrogen economy with its Hydrogen Strategy and upcoming legislation. The ongoing review processes of selected legislation are particularly relevant for FCH technology uptake and central to current policy discussions at the EU and national levels, e.g.:

- General review of CO_2 Emission Standards Regulations in 2022, that will include a review of 2030 targets, an extension of scope to other HD vehicles and a review of the zero- and low-emission vehicle incentive mechanism;
- Reviewing the Alternative Fuels Infrastructure Directive, which expires in 2021, updating requirements for refuelling stations for alternative fuels as well as compulsory targets for EU member states for building a European H_2 network are in discussion;
- Review of the Eurovignette Directive, extending the scope of vehicles in the current legislation and introducing charging based on CO_2 standards, including a potential reduction for zero-emission vehicles.

Hydrogen is emerging as a central building block for a renewable energy system in the EU, as defined also in the EU Energy System Integration Strategy from July 2020. However, the European approach towards subsidies and tax exemptions is currently still fragmented. FCH heavy-duty trucks could benefit from a more cohesive approach across member states, e.g. with regards to HRS network roll-out, as well as from incentive schemes to support the general uptake of hydrogen applications and that of zero-emission FCH vehicles. For example, the support for hydrogen valleys and the FCH JU Regions and Cities Initiative provide first steps towards such a systemic approach for hydrogen application by the EU. These initiatives show that in order to effectively achieve the intended development in the targeted sectors, a more holistic approach should combine funding and incentives schemes on three levels:

- Support of the supply-side of FCH trucks through large-scale deployments;
- Strengthening of the demand side through measures such as purchase tax exemptions for new FCH HDT;
- Support for refuelling infrastructure with significant investments and targeted funding schemes to finance the build-up of a comprehensive network of refuelling stations, e.g. through mandates to develop HRS along major corridors with a distance of 150 km between stations (as suggested in the context of the review of the Alternative Fuels Infrastructure Directive).

The analysis of support schemes for zero- and low-emission vehicles at the national level shows that subsidies, tolls and tax exemptions have successfully been used to foster the uptake of electric vehicles. With increasing technology development and availability, these measures could also favour FCH technology. For instance, an impactful lever is road toll exemption for low- and zero-emission vehicles, an instrument successfully used in Norway, other Scandinavian countries or Switzerland. Another lever to stimulate cost competitiveness of zero-emission technologies lies in higher taxes for diesel and fossil fuels. While it increases the cost for the incumbent technology, it also provides financing for demand stimulation and tax exemptions in other areas. Germany, for example, will raise carbon prices to EUR 25 per tonne in 2021 and EUR 55 per tonne in 2025 – gradually improving cost competitiveness for FCH trucks.

The current policy landscapes in the EU and other key international markets show that due to the increasingly stricter stance on emissions, policy decisions are being made in favour of zero-emission vehicles. FCH heavy-duty trucks can benefit from this environment as the technology development and vehicle uptake are supported by various initiatives. However, they still need to be integrated into a more systemic approach across Europe, the EU and at member state level. The EU net zero emissions target in 2050 will only be possible if the legislation and support schemes are implemented. Considering a truck's lifetime of up to 15 years, European truck fleet operators need to ensure that from the years 2030 to 2035, all newly purchased trucks are zero-emission vehicles. Legislation constitutes the backdrop for a continued transition towards low-carbon alternatives. As such, supply and demand side, as well as infrastructure considerations are to be considered to continue the path towards zero-emission mobility in heavy-duty road transport.

1.3 Existing trial and demonstration activities

Trial and demonstration activities play a crucial role in paving the way for the commercialisation of FCH heavy-duty trucks. Interest and action in the technology are increasing and a growing number of projects around the world demonstrate that FCH heavy-duty trucks work. In Europe, multiple demonstration projects cover different vehicle types, operational settings and a broad variety of stakeholder groups. At the same time, heavy-duty demonstration projects are also taking place in North America, with a regional focus in the Los Angeles area in California.

While European projects are well positioned to push FCH technology in the truck sector forward, projects in other geographies offer important insights. Despite projects being usually tailored to local conditions, they often share similar success factors and provide learnings beyond specific regional regulations or local preferences for certain technologies. Such insights mainly refer to, e.g.:

- **Possibility to rely on public support schemes:** The Alberta Zero-Emissions Truck Electrification Collaboration (AZETEC) project in Canada – forged by a multi-partner industry coalition – receives substantial public funding through the BEST Challenge programme;
- **Existence of local hydrogen ecosystems:** Ecosystems make it possible to leverage synergies from different modes of FCH applications, for example, as in the multi-modal approach of the Zero and Near-Zero Emissions Freight Facilities Project (ZANZEFF) in the Californian Los Angeles basin region;
- **Strong backing by industry players:** Individual company commitments on zero-emission transport can create momentum for commercialisation, as found in the Anheuser Busch Zero-Emission Beer Delivery initiative in cooperation with the U.S. OEM Nikola Motors.

In recent years, the overall growth in trial and demonstration activities in the heavy-duty truck segment worldwide was driven by projects in Europe. The number of European FCH HDT trial and demonstration projects is now levelling up with earlier US efforts. In total, twelve projects in Europe, nine key projects in North America, and two projects in Asia were identified that have been finalised, planned or are ongoing since 2015. Many of the European projects are conducted cross-nationally by multi-partner coalitions. It is not only OEMs and component manufacturers participating in these projects, but also infrastructure providers and wholesale and retail companies. Funding comes from different sources, depending on the specific context and coalition (European, national or interregional level). In North America, on the other hand, projects often build on support and funding from regional governments, as has been the case in the FCH frontrunner state California.

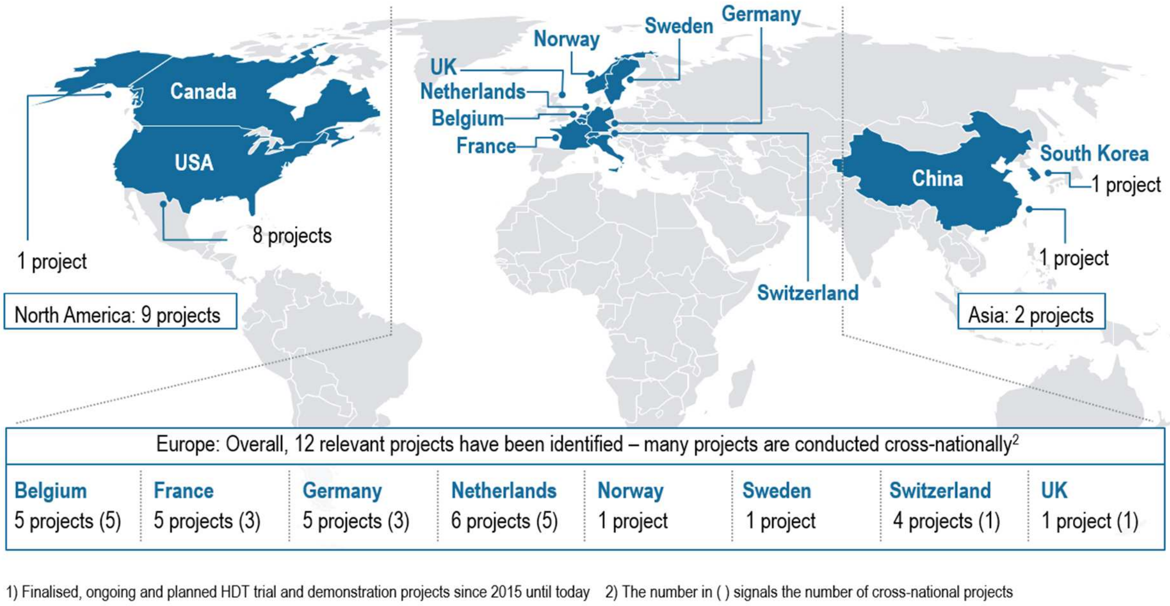

Figure 4: Overview of key fuel cell hydrogen heavy-duty truck trial and demonstration projects

For this study, the ten most relevant trial and demonstration activities were identified and analysed to provide a deeper understanding of where the industry stands today. The selected projects cover activities in Europe and North America and four relevant truck types (rigid 4x2, tractor 4x2, rigid 6x4, tractor 6x4).[6] A comparison of the selected projects shows high levels of transferability of European projects and lower overall transferability of projects from North America.[7] By definition, European projects usually share very similar technical features, regulatory frameworks, use cases, stakeholders and political motivation. Demonstration projects in North America draw on specific, mostly local factors, such as high industry ambition as identified in the cooperation between Nikola Motors and Anheuser Busch.

As a concrete example, the Hyundai Hydrogen Mobility (HHM) initiative in Switzerland can be differentiated from other projects. This joint venture between the OEM Hyundai Motor Company and the H_2 infrastructure provider H2Energy plans to bring 1,600 Xcient fuel cell trucks and the related H_2 infrastructure to the Swiss market. HHM is the first to offer FCH heavy-duty trucks to clients in Switzerland, generally and for commercial use in a pay-per-use model. The business model shows existing industry interest and the potential of the FCH HDT market.

Switzerland was chosen as the first country for the roll-out because local conditions are particularly favourable. Zero-emission vehicles are exempt from the Swiss heavy vehicle environmental duties per tonne and kilometre ("leistungsabhängige Schwerverkehrsabgabe", LSVA) and a strong hydrogen business community has built up over the last years. Furthermore, the regional approach allows for the possibility to scale up infrastructure and operations within a geographically defined ecosystem. HHM illustrates market readiness and cost competitiveness of FCH HDT under such circumstances and presents a lighthouse project for FCH technology in Europe. In building industry coalitions along the value chain of FCH trucks, the approach also

[6] For deep dives on the ten selected projects, please refer to the trial and demonstration project section in chapter B.2 of the Study Report.

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

addresses the chicken-and-egg dilemma of truck roll-out vs. refuelling infrastructure availability.

In line with the growing number of trial and demonstration projects, there is an increasing number of hydrogen refuelling stations (HRS) in Europe[8]. To date, most existing HRS are dedicated to the use of passenger vehicles and cannot be used by HD trucks due to different technological requirements for filling up the much larger truck tanks. However, the increasing number of stations is promising, and the existing foundation of HRS in Europe could partly be upgraded for truck-specific refuelling soon. As refuelling infrastructure is adjusted to meet the needs of heavy-duty trucks, more demonstration projects become feasible, providing a foundation for larger scale commercial deployment. The priority will be on building up infrastructure networks along major transport corridors (the European TEN-T corridors) and in proximity to demand centres, ideally in combination with evolving hydrogen hubs and valleys in Europe.

Trial and demonstration projects continue to provide important insights into the immediate trajectory of FCH heavy-duty trucks, as pertains to their technology development, cost competitiveness and implementation challenges. Thus, these projects advance the commercialisation of FCH HDT and are important steps towards unlocking the full market potential of FCH heavy-duty trucks in Europe. Business-driven projects, such as Hyundai Hydrogen Mobility in Switzerland and several OEM cooperations are encouraging signs of a developing market. However, in order to translate projects and first ventures into sustainable businesses and enable their market potential, cost competitiveness needs to be generated on the supply side (i.e. truck products, fuel supply, etc.), and demand has to be increased through targeted incentive schemes.

[8] More information on HRS network development to be found at: https://fchobservatory.eu/observatory/technology-and-market/hydrogen-refueling-stations/cumulative-data

2. Market potential for FCH heavy-duty trucks in Europe

The road freight sector is an important pillar of the European economy as 75% of goods are transported on wheels[9], but also a significant source of CO_2 emissions. As a zero-emission solution with a similar performance as conventional diesel-powered heavy-duty vehicles, FCH trucks have substantial market potential. This study analysed the market potential of FCH HD trucks in Europe by building on a comparison of total cost of ownership and a truck market forecast. The market potential analysis was conducted along three use cases, each representing a specific HD truck segment. Together, the three use cases account for approximately 53% of HDT sales in Europe – at the same time, they are responsible for the main share of CO_2 emissions being attributed to heavy-duty vehicles in the EU (EC, 2018).[10|11] In order to grasp their potential in the short term (2023) and the medium term (2030), a Total Cost of Ownership (TCO) analysis was conducted.[12] The developed cost trajectory demonstrates substantial potential for FCH heavy-duty vehicles. The TCO results also provide the foundation for estimating the market potential through cost advantages and technology acceptance rates.

Realising this market potential, however, will require the development of a favourable financial and regulatory ecosystem for both the demand side, e.g. truck operators and logistics users, and the supply side, e.g. truck OEMs, component manufacturers and fuel and infrastructure providers.

The three focus use cases investigated within the analysis are:

- ***Use Case I:*** 4x2 tractor (+ trailer) of 40 tonnes gross vehicle weight, used by international and national logistics companies and by companies in the manufacturing industry with their own trucking fleets. This use case represents the long-haul segment with an annual mileage of 110,000-160,000 km.
- ***Use Case II:*** 6x2 rigid trucks of 27 tonnes gross vehicle weight, used by wholesalers with their own trucking fleets. This use case represents the mid-haul segment with an annual mileage of 50,000-150,000 km.

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[9] European Commission. (2019). *Energy, transport and environment statistics — 2019 edition*. Retrieved from https://ec.europa.eu/eurostat/web/products-statistical-books/-/KS-DK-19-001

[10] The 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 referring to delivery vehicles: 6x2 tractor and rigid trucks (all weights) and 4x2 tractor and rigid trucks above 16 tonnes. The 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, with 4x2 tractors contributing the most, accounting for up to 38% of these emissions.

[11] European Commission. (2018). *Commission staff working document impact assessment - Accompanying the document Proposal for a Regulation of the European Parliament and of the Council setting CO2 emission performance standards for new heavy duty vehicles*. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=comnat:SWD_2018_0185_FIN

[12] The analysis builds on a projected cost trajectory for the main input factors, e.g. fuel cell module and hydrogen tank costs, battery costs and H_2 costs. The cost trajectory was developed in alignment with the study's industry Advisory Board and is based on expert input. The methodology and key assumptions can be found in the Annex of the Study Report.

> ***Use Case III:*** 4x2 rigid trucks of 18 tonnes gross vehicle weight that are used by regional logistics companies and retailers with their own trucking fleets and represents the short-haul, regional distribution segment with an annual mileage of 40,000-85,000 km.

	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 per year	~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

Figure 5: Use case characteristics

This study compares a total of seven different technologies. The incumbent diesel internal combustion engine serves as a reference case. It is compared to a zero-emission 'e-fuel' alternative and the zero-emission powertrain technologies of fuel cell and hydrogen electric (FCEV), battery electric (BEV) and catenary (overhead) lines. The business case analysis (TCO) differentiates between three H_2 onboard storage alternatives which are currently being used or researched for FCH vehicles. These storage technologies are for hydrogen storage at different pressure levels and conditions: compressed gaseous H_2 at 350 bar and 700 bar, as well as cryogenic liquid H_2 (LH_2) at -253 °C. All three storage technologies are potentially viable options for FCH truck uptake scenarios; however, the compressed gaseous options are currently more mature than the suggested liquid hydrogen route. Additionally, package constraints to carrying a sufficient amount of fuel in the trucks need to be considered. Liquid hydrogen could be a viable refuelling alternative by 2030, mainly due to this package advantage (i.e. high volumetric energy density translates into more fuel on the truck), scale of production and potentially lower refuelling infrastructure cost. However, hydrogen at 700 bar provides more flexibility for hydrogen sourcing, for example through pipeline supply or on-site electrolysis production. It potentially also offers compatibility with lower pressure levels of other vehicle types, enabling synergy effects for higher infrastructure utilisation. 350 bar technology on the other hand is only a solution for short-range operations with lower hydrogen on-board storage requirements. This technology is already deployed in existing FCH trucks today.

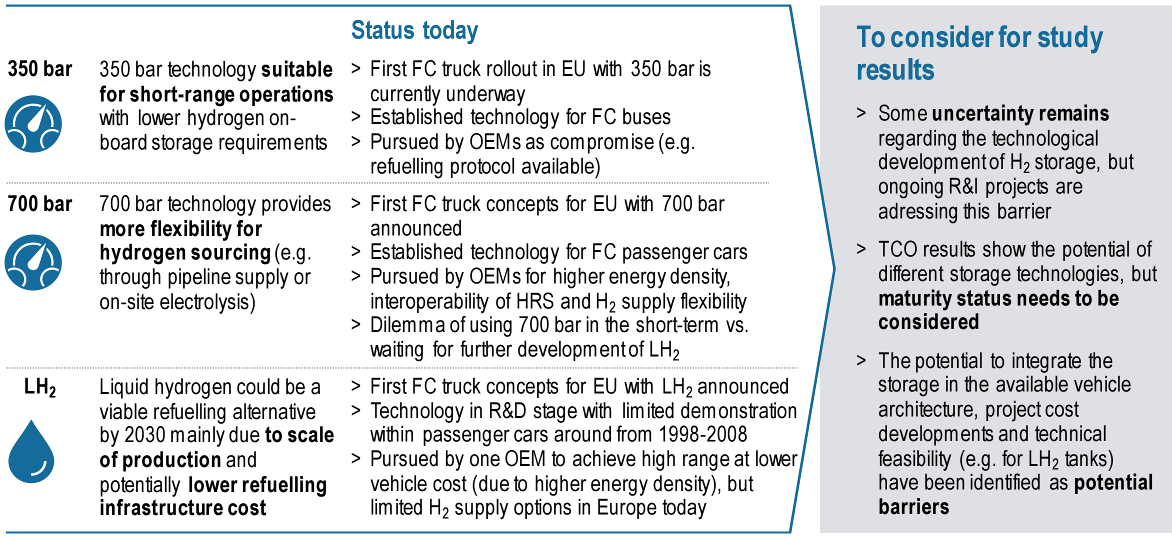

Figure 6: Main on-board hydrogen storage technologies

Comparing the total cost of ownership (TCO) of FCH trucks with conventional diesel and other zero-emission alternatives (e-diesel, battery electric, catenary) revealed a clear trend towards cost competitiveness of FCH technology – if production levels at scale can be reached.[13|14] It is shown that in 2030, the overall sales share of FCH heavy-duty trucks can increase to up to 17% in the investigated use cases. This demonstrates that FCH heavy-duty trucks are set to become a cornerstone of the European truck market. Furthermore, if this development materialises, the CO_2 emission reduction target could be reached by 2050.

2.1 Total cost of ownership analysis

The consideration of the total cost of ownership provides a comprehensive analysis for a truck's cost across its lifetime. In this chapter, the key findings illustrate the potential for FCH heavy-duty trucks to compete with other powertrain alternatives. A brief introduction of the methodology and an overview of the assumptions allow for a deeper understanding of the modelling process. Lastly, the discussion of results reflects the commercial potential of FCH technology across the three heavy-duty truck use cases.

Key findings: 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, looking at the time frame from 2023 to 2030. This applies to the three use cases developed for the analysis reflecting 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 of FCH heavy-duty trucks by 2030. This cost competitiveness is possible for all H_2 storage technologies. In comparison to battery electric trucks, FCH trucks show better TCO results across the years for the long- and medium-haul use cases. However, in the third use case on regional logistics, despite lower operational flexibility, battery electric trucks

[13] The TCO analysis compares seven propulsion alternatives: diesel, e-fuels, fuel cell (and hydrogen) electric vehicle technology (FCEV), battery electric vehicle technology (BEV) and catenary (overhead) lines.

[14] Production levels at scale refer to a fuel cell module production per year increasing from a niche scenario with <5,000 units/year to a rather mass scenario with >50,000 units/year.

may have a cost advantage compared to FCH technology. The TCO analysis identifies the cost of powertrain (CAPEX) and energy/fuel costs (OPEX) as the main cost drivers along the vehicle lifetime. Moreover, road toll is identified as a potential key lever to enable business cases already in the short term.

Overall, the total cost of ownership (TCO) modelling demonstrates that FCH technology for heavy-duty trucks can become cost-competitive with the incumbent diesel trucks by 2030. While the technology has already overcome many of its teething problems in the research and development phase, industrialised production and economies of scale will be key for ensuring this trajectory within the investigated time frame between 2023 and 2030. Hence, the TCO analysis illustrates that three factors will be crucial for FCH technology uptake in the heavy-duty truck segment:

- At-scale production for lower component costs and volume ramp-up due to automated manufacturing, improved purchasing processes and higher supply chain maturity/depth;
- Availability of 'affordable' green electricity for hydrogen production;
- Build-up of a sufficiently dense network of H_2 refuelling infrastructure and a supply chain for low-cost green hydrogen (e.g. through the exemption of electricity surcharges for hydrogen production).

Methodology: The Total Cost of Ownership (TCO) modelling methodology is based on the three use cases, comparing conventional and alternative powertrains on a like-for-like basis of truck performance. This means that truck operators would get a similar product as with a diesel truck today. In the model, input on the application scenario of a truck is introduced to yield results on what a specific truck will cost over its lifetime. Key assumptions on CAPEX and OPEX provide the basis, while all parameters can be adjusted to reflect specific operations and conditions. CAPEX parameters relate to the truck chassis and powertrain and infrastructure costs. OPEX parameters cover fuel and energy costs as well as operations and maintenance costs, e.g. vehicle tax and road toll. In addition, the current EU regulatory framework is considered. Niche to mass market scenarios are assumed to show the capabilities of FCH technology at different levels of industrial scale production.[15] As such, the analysis is not based on today's prototype cost.

The model offers two commercial perspectives: an analysis of the vehicle costs as they will arise over the vehicle lifetime (EUR/truck) and an analysis on the basis of payload considerations (EUR ct/tonne-km).[16] The latter reflects the weight-related factors that could impact the truck payload, e.g. the higher weight of the alternative powertrain. Another example would be the weight of the batteries on a battery electric truck that could potentially reduce the weight of goods to be transported due to overall weight restrictions. In addition, the model includes environmental metrics providing an estimation of CO_2 emissions savings on a well-to-wheel as well as tank-to-wheel basis.

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[15] The niche scenario refers to assumed fuel cell module production levels per year of <5,000 units/year. The rather niche scenario refers to <10,000 units/year. The rather mass scenario refers to >50,000 units/year and the mass scenario to >150,000 units/year.

[16] The EUR ct/tonne-km basis shows the TCO per EUR cents per tonne-km and reflects the costs of transporting one tonne payload on one kilometre of the route. For the calculation and based on current regulation in the EU, trucks with alternative powertrains are assumed to receive a payload gratification of 1 tonne compared to equivalent diesel trucks.

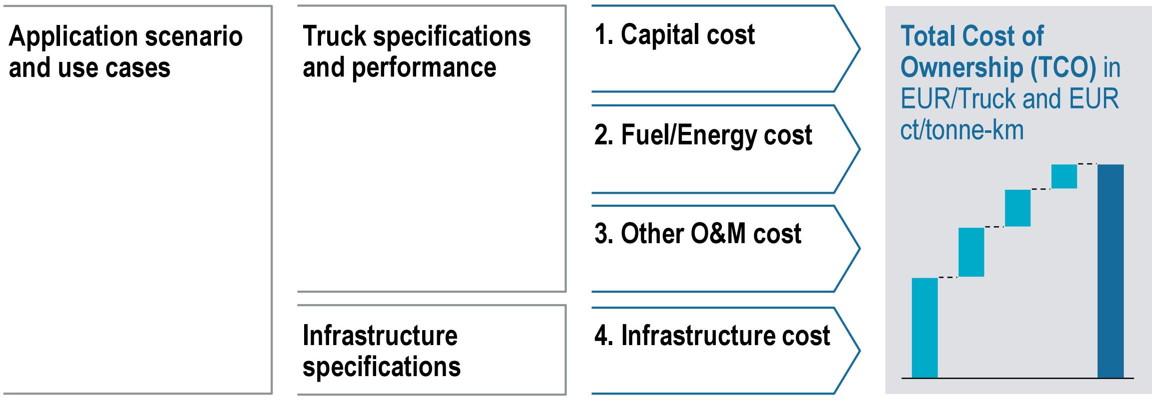


Figure 7: Schematic methodology of TCO modelling

Assumptions: The detailed parameter assumptions of the TCO model were developed in close cooperation with the study's Industry Advisory Board to provide the current state of costs and future cost and volume projections. The assumptions can be clustered into three main groups:

(1) General input on motor vehicle tax, insurance cost and road toll;

(2) Truck and technology-specific input, such as vehicle configuration and payload considerations, fuel cell and hydrogen tank costs, battery capacity and cost;

(3) Fuel/Energy and infrastructure input, such as refuelling and charging costs.

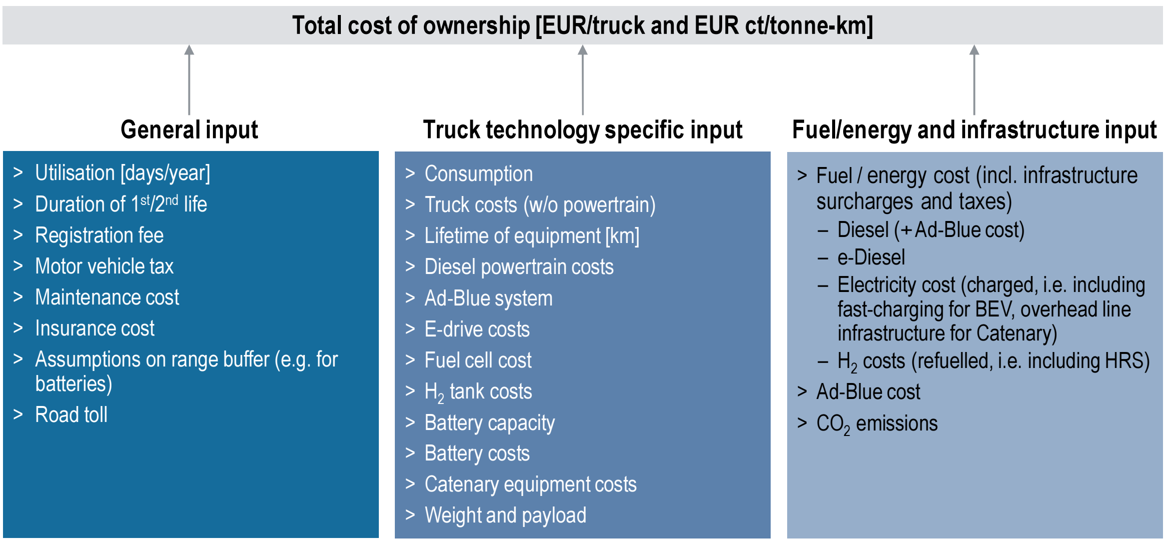


Figure 8: TCO model structure

In addition, the analysis was conducted reflecting further key assumptions:

- First and second life: The analysis differentiates between the first (5 years) and second life (10 years, combined with first life);
- Like-for-like comparability: FCH HDT trucks provide the same daily performance for operators as diesel trucks today (i.e. daily duty cycle can be performed without refuelling/recharging);
- Niche to mass market development: The cost development of FCH technology is not based on today's prototype cost but directed towards increasing production

levels at scale over time, from a niche technology in 2023 to a rather mass scenario in 2030;

- Current EU regulatory framework and incentive landscape.

Further information, guiding principles, methodology and details on the TCO assumptions developed for the study modelling can be found in the annex of the full version of the study (available at www.fch.europa.eu and via accessing the QR code).

Results: The TCO results across all use cases reveal a cost premium for FCH trucks of up to 22% compared to diesel trucks in 2023. While these results are still based on a niche scenario, a trend towards cost competitiveness can be observed from 2027 onwards.[17] In comparison with other zero-emission technologies, the results show a clear advantage for high daily and annual mileage. For instance, when compared to battery electric trucks, FCH trucks show a lower TCO across the years for the long- and medium-haul use cases (Use Case I and II).

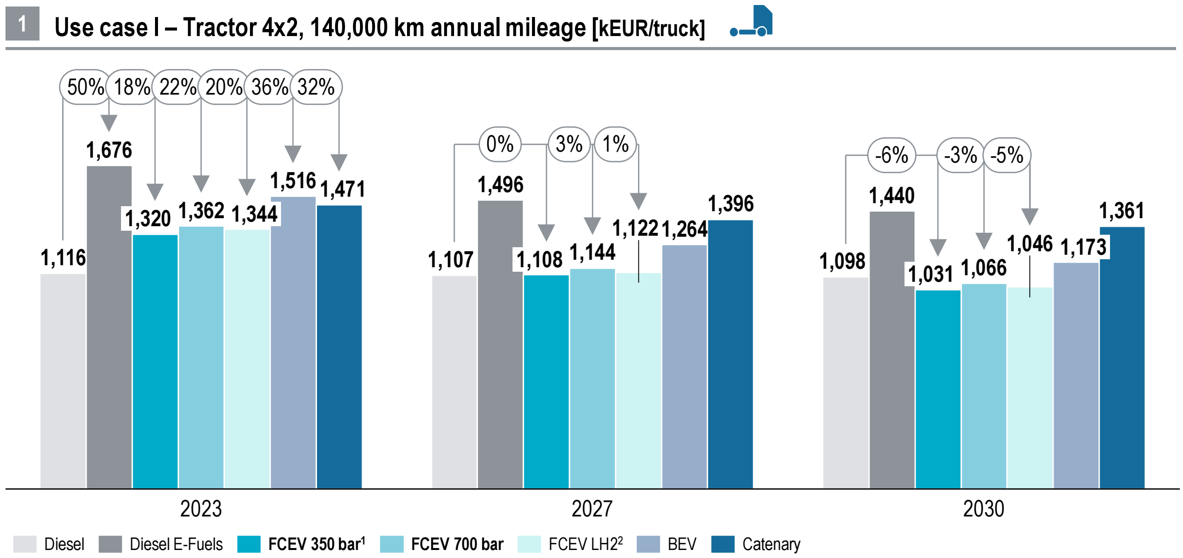
This analysis is confirmed also when considering the payload capacity of the trucks. As battery size and weight influence the maximum payload capacity of heavy-duty trucks, a large battery would mean a lower maximum payload.[18] As a result, a limited deployment of battery electric trucks in the medium- and long-haul segment is expected. However, in regional logistics (Use Case III), the results show that battery electric trucks can have a cost advantage compared to FCH technology – under the assumption that no additional power loads (e.g. for cooling the truck's cargo hold), higher payload or multi-shift operations are required. The breakdown by use cases further demonstrates the favourable TCO development for FCH technology on a more granular level:

Use Case I:

- In the long-haul use case, FCH technologies are projected to achieve a **lower TCO than conventional diesel** and other alternative powertrains in 2030. While a cost premium of 18%-22% remains for the niche market scenario in 2023, in 2027 the TCO of FCH heavy-duty trucks could already be at a similar level as diesel. Considering the current TCO gap to diesel trucks, specific incentives would have the potential to achieve cost parity even earlier.
- In comparison, **battery electric trucks show a higher cost premium of 36%** in 2023 when compared to diesel, mainly due to the battery costs. Moreover, as indicated before, the long-haul use case would **potentially see payload restrictions** due to the size and weight of the battery needed for kilometres driven. As a result, the TCO modelling reveals that battery electric trucks will not reach cost competitiveness with diesel-powered trucks by 2030.

[17] The niche scenario refers to fuel cell module production levels per year of <5,000 units/year.

[18] Batteries needed for long-haul routes add additional weight to the truck. In most cases, the integration of such additional weight would compromise the overall permissible payload as the maximum weight regulations still need to be considered.



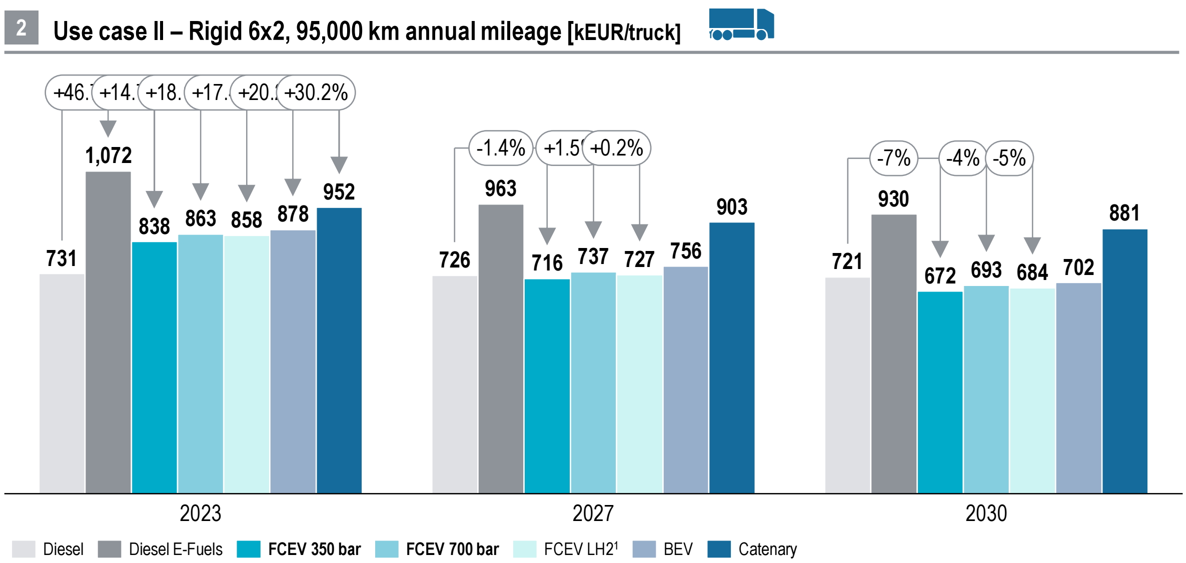
1) Under the assumption that sufficient hydrogen storage can be technically integrated in the current truck chassis architecture. Potential length regulation adjustments required.
2) The technical maturity is at a very early stage and needs to be demonstrated in a truck.

Figure 9: TCO assessment for Use Case I [kEUR/Truck; 1st & 2nd life]

Use Case II:

> In the mid-haul use case with an annual mileage of 95,000 km, FCH technology already **becomes cost competitive with diesel in 2027**, while it is still at a cost premium of up to 18% in 2023. In 2030, FCH heavy-duty trucks would provide a **better TCO than all other investigated alternatives.**

> Moreover, the different H_2 storage technologies show a **better TCO outlook in 2023 when compared to other zero-emission alternatives**. They also remain more cost competitive than the alternatives diesel e-fuels, BEV and catenary in 2027 and 2030. It can be noted that the results for battery electric trucks are only slightly higher than the TCO of FCH technology. However, payload considerations indicate again that a payload penalty would apply due to the battery size and weight for the required mileage.



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

Figure 10: TCO assessment for Use Case II [kEUR/Truck; 1st & 2nd life]

Use Case III:

> In the regional distribution use case with 60,000 km annual mileage, the TCO results show that FCH technology has a cost premium against diesel of as low as 11% in 2023. Due to a significant cost-down potential at scale in the short-haul segment, FCH heavy-duty trucks will generally **reach cost competitiveness with diesel trucks in 2027**, despite some variations across the different H_2 storage technologies.

> Due to the comparatively lower annual mileage, **battery electric trucks have a lower TCO** compared to FCH technology. In addition, the results indicate that the TCO for BEV will be lower than diesel in 2027 and 2030, indicating the potential for battery electric trucks on such routes that require lower overall range flexibility.

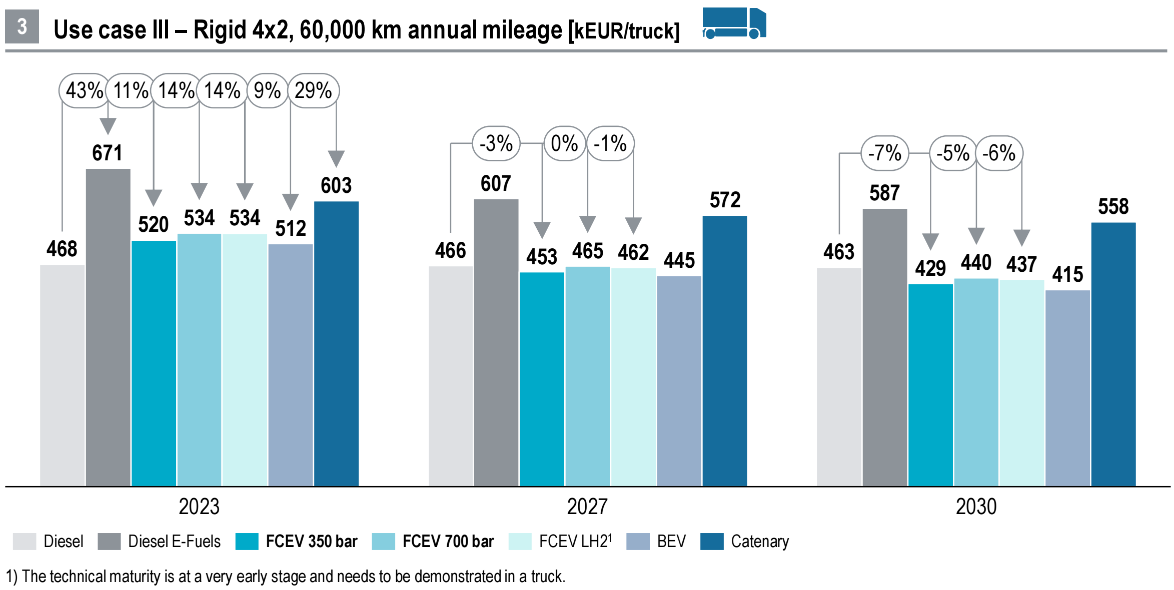


Figure 11: TCO assessment for Use Case III [kEUR/Truck; 1st & 2nd life]

The TCO analysis allows for two key learnings regarding FCH cost-reduction potential. Significant cost-down potential for FCEV at scale exists for all three use cases – demonstrating the TCO potential and the broad applicability of FCH technologies in the HDT market and its market potential towards 2030.[19] Furthermore, with a cost premium of 11%-22% in 2023 and the projected cost-down potential, FCH technology could be well within reach of cost competitiveness by 2030. In order to realise this projected cost-down scenario, a strong industry push towards economies of scale and supporting incentive schemes and regulations are needed. If vehicle demand is stimulated, infrastructure availability is ensured and the framework conditions provide a TCO advantage, the current momentum behind FCH technologies can be accelerated. Under

[19] While this Study Summary primarily compares the TCO of all three use cases on a kEUR/Truck basis, TCO modelling was also performed on a EUR ct/tonne-km basis. This second perspective considers potential payload gains and losses and shows that – also when considering payload capacity – FCH truck technology becomes more competitive than conventional diesel, e-fuels, BEV and catenary across all use cases as of 2027. Further information on the TCO analysis on EUR ct/tonne-km basis is available in chapter C.2 on TCO results in the Study Report.

these preconditions, the TCO of FCH technology will reach cost competitiveness with diesel before the end of this decade.[20]

2.2 Market potential

The TCO results provide the foundation for estimating the market of FCH heavy-duty trucks in Europe from 2023 towards 2030 and beyond. In this chapter, the key findings illustrate the potential for market penetration of FCH heavy-duty trucks based on the key assumption that cost advantages will lead to faster deployment. A brief introduction of the methodology includes three uptake scenarios that were developed reflecting potential truck adoption rates (conservative, base and optimistic scenario). Building on these scenarios, the view on the results per use case-specific market segment demonstrates that the TCO development will be key to more wide-spread adoption within the different segments.

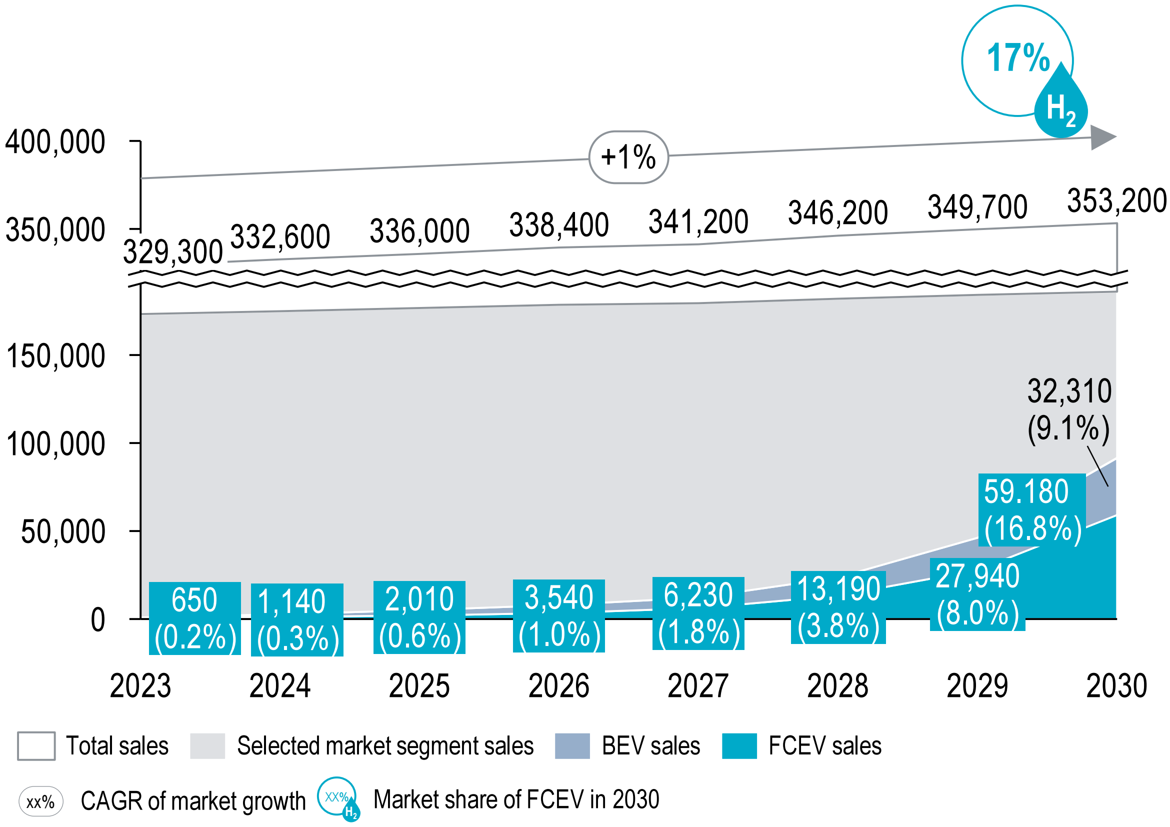


Figure 12: European market potential of FCEV [# of truck sales, rounded] – Base scenario

Key findings: The market model shows clear potential for zero-emission trucks, i.e. FCH and BEV heavy-duty trucks in all developed scenarios. For both technologies, increasing sales shares until 2030 are expected for the European market. After a moderate uptake until 2027, the market potential analysis indicates a significant FCH heavy-duty truck market penetration to an overall sales share of ~17% in 2030 in the base scenario (~9% sales share for battery electric trucks). Based on the heavy-duty truck market, this refers to approximately 59,500 new trucks in 2030. This represents roughly one third (~32%) of the annual sales in 2030 for the assessed use case specific

[20] Technological and non-technological barriers and derived recommendations for policy makers are discussed in chapter 4 of this Study Summary.

market segments. By 2030, it is estimated that an accumulated 110,000 heavy-duty fuel cell trucks are deployed on European roads (base scenario).

The base scenario for market potential of zero-emission trucks is in line with the necessary trajectory for reaching the CO_2 emission reduction targets for 2050. To achieve the EU's decarbonisation targets for transport, zero-emission trucks need to become the dominant technology of new truck sales in the decade starting 2030, to replace the majority of the EU truck fleet by 2050. However, the analysis shows that this will only be possible if the modelled growth rates for zero-emission technology are achieved. Currently, the market is still in a very early phase and needs to be developed now to allow for the market potential that will materialise. Cost competitiveness and market uptake can only be achieved through a concerted push to market and the set-up of required infrastructure.

Methodology: The market potential of FCH HD trucks in Europe is analysed along the three use cases, representing different road transport segments, operating patterns and truck types.[21] In these use cases, fuel cell and hydrogen as well as battery electric technologies (FCEV and BEV) are currently considered the two most relevant, commercially viable and technically advanced options. Hence, a specific focus is put on those two technologies. The market potential analysis itself considers the total cost of ownership development of heavy-duty trucks in different use cases and different combinations of daily range and annual mileage. In addition, it also considers that further external factors besides cost impact decision making. It is assumed that despite specific, calculated TCO results and technology development until 2030, only a share of trucks would be purchased as FCH trucks in earlier years and only become purely cost driven decision in a more mature market (e.g. technology is proven, more infrastructure is available, etc.).

Therefore, three uptake scenarios were developed reflecting that truck adoption rates in the future market are estimated based on clear criteria. These refer to the acceptance of a new technology as well as political, technological and vehicle availability parameters. Furthermore, market dynamics and infrastructure availability are considered.

- The **Conservative scenario** assumes that FCH and battery electric trucks mainly remain niche solutions in the selected leading market segments. In addition, a widespread risk aversion towards new technologies continues to hamper the technology uptake. Incentives and subsidies are reduced as the market develops.
- In the **Base scenario**, FCH and battery electric trucks achieve increasing market shares, and involved stakeholders show a higher degree of acceptance of business risks. Subsidies and incentives are put in place to ensure cost reductions at scale, while significant hydrogen infrastructure is being developed along main routes and near logistics trade hubs.
- The **Optimistic scenario** assumes that FCH and battery electric trucks see robust adoption across all considered market segments. Business risks are shared with other parties besides truck operators and a strong policy push supports the entire value chain, including OEMs, hydrogen and infrastructure providers, truck operators and logistics users.

[21] The market potential analysis refers to the specific market segments identified for this study: international logistics, national logistics, manufacturing industry, wholesale, retail and regional logistics.

Parameters based on Advisory Board expert input

TCO	Conservative scenario 2023	Conservative scenario 2027	Conservative scenario 2030	Base scenario 2023	Base scenario 2027	Base scenario 2030	Optimistic scenario 2023	Optimistic scenario 2027	Optimistic scenario 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)

Conservative scenario:
- 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

Base scenario:
- 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

Optimistic scenario:
- 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)

Figure 13: Market uptake scenarios [% of FCEV/BEV uptake]

Results: The study reveals strong FCEV market potential for the specific use cases with sales shares between 16-51% in 2030, depending on the uptake scenario. The conservative scenario shows a high growth rate of the sales share from 2027 until 2030 and an overall much slower development for BEV. The base scenario shows a higher uptake already for 2027 with a steep increase until 2030. In this scenario, FCEV sales surpass BEV sales already in 2023. The optimistic scenario predicts a total sale of over 95,000 FCH heavy-duty trucks in 2030, representing 51% of market sales in the considered market segments. It shows a higher uptake rate already for 2027 with a steep increase until 2030. The development of BEV trucks sales also increases, yet at a much lower level.

The market potential analysis estimates that, following the base scenario, an accumulated total of 110,000 heavy-duty fuel cell trucks are deployed on European roads by 2030. This represents a 1.7% market share in a 6.6 million medium and heavy-duty truck market in Europe.

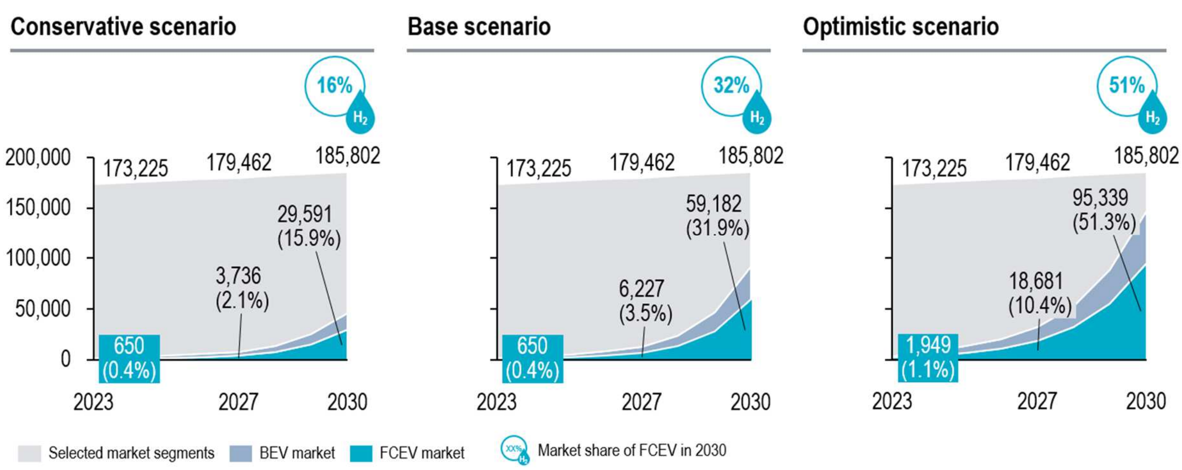


Figure 14: European market potential of FCEV [# of truck sales] – Market segments

Overall, the analysis shows that there is substantial market potential for FCH heavy-duty trucks in Europe. In the cost sensitive transport and logistics industry, commercial competitiveness of zero-emission vehicles with diesel will be crucial for the market uptake of FCH technology in the upcoming years. This was demonstrated in the TCO analysis as well as in the market potential analysis, building on three potential uptake scenarios. However, the analysis has also shown that it is not only the cost perspective that will be considered. Facing an overall growing demand for more sustainable operations and supply chains, the transport and logistics industry is responding. The deployment of zero-emission vehicles, pushed by political initiatives and market demand, is becoming more and more widespread. Against this background, FCH technology presents a good zero-emission solution with a promising trajectory for reaching cost competitiveness with the incumbent diesel trucks in the next decade.

Integrating FCH trucks into the fleet starting from 2023 will help to achieve the decarbonisation targets for the European truck industry. The predicted number of BEV and FCH heavy-duty trucks to enter the European market by 2030 will have significant CO_2 emission savings potential of up to 19 million tonnes CO_2e per year when they are refueled with zero-emission hydrogen. Due to its high share of the market potential, the impact of FCH technology on emission reduction going forward will be significant. Furthermore, FCH heavy-duty trucks offer reduction potential for other pollutants, such as the avoidance of NO_X and a reduction of particulate matter, e.g. by using regenerative braking. In addition, zero-emission FCH heavy-duty trucks contribute towards the reduction of health- and environment-related costs. Demonstrating such broader economic, environmental and social benefits of a truck industry fuelled by green hydrogen will help to unlock its full market potential and realise synergies between different applications along the FCH value chain.

Market development over the next 10 years is crucial for achieving the EU goal of climate neutrality by 2050. If the growth rate of zero-emission heavy-duty trucks materialises as projected by 2030, the CO_2 emission reduction target for transport for 2050 can be reached. However, new truck sales of currently mostly diesel trucks and other CO_2-intensive technologies need to be replaced by zero-emission alternatives from as early as 2030 onwards. Looking further ahead, the trajectory until 2050 would include replacing most of the diesel fleets with zero-emission vehicles, FCEV or other. This can be achieved if policy makers, OEMs, and end users enable the following drivers:

- Truck industrialisation with lower component costs and volume ramp-up;
- Push to market for zero-emission trucks to ensure scaling effects for cost competitiveness and market uptake;
- Improved availability of infrastructure to allow for widespread deployment;
- Policy and regulatory regime that targets all market actors;
- Widespread access to 'affordable' green hydrogen.

3. Case studies – FCH heavy-duty trucks in the transport & logistics ecosystem

Fuel cell and hydrogen trucks have the potential to become the zero-emission vehicle of choice for the transport and logistics industry, as both the total cost of ownership and market potential analysis have shown. However, only few FCH trucks have been deployed yet. OEMs and technology providers are working on scaling up the technology – supported by various research efforts and demonstration projects to gather operational experience, e.g. as in the H2HAUL project supported by the FCH JU. These projects also involve further key players for market uptake, namely the truck operators, logistics service providers and logistics users. They are deploying and operating the trucks to test for their specific requirements regarding, for instance, their performance, reliability and cost. In order to include the perspective of truck operators, logistics service providers and the end customer in this study, the three previously defined heavy-duty use cases were investigated further, building on information of real-life routes provided by the study's Advisory Board members. In specific case studies, the economic and operational benefits of fuel cell and hydrogen technology within the broader transport environment were tested. The case studies cover both typical logistics operations as well as specific application scenarios. Together with the previous use cases established in the TCO analysis, the findings represent a broader view on potential FCH heavy-duty truck deployment in the EU. Hence, the case studies can serve as tangible business opportunity blueprints for the industry, while they also give a first glance at current limitations as more commercial products and an established hydrogen supply chain are yet to materialise. Furthermore, important technological and non-technological barriers are identified that will be addressed in chapter four of this study.

The analysis of nine different case studies was conducted in order to gain a concrete perspective and apply the data driven TCO analysis to case specific scenarios. They explore potential opportunities of FCH technology and assess the economic and technological feasibility of specific routes, operations and business cases[22]. The case studies were selected along the three defined use cases of long-haul, medium-haul and regional distribution.

For the case studies, a balanced geographical spread across Europe was ensured to allow for a differentiated view on the potential of FCH technology in different national contexts. 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 case specific data.

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[22] The TCO results are based on assumptions taken in alignment with the study's Advisory Board as elaborated in chapter 2. In addition, case-specific information was included to reflect the real-life operations of the case study routes.

Use case		Location	Truck type	Country	Company
Use case I	1	Košice-Bratislava	Tractor 4x2, 40 t	SK	Bioway
Use case I	2	Alsace region	Tractor 4x2, 40 t	FR	FM Logistic
Use case I	3	Zwickau-Emden	Tractor 4x2, 40 t	DE	Schnellecke
Use case II	4	Hof-Kladno	Rigid 6x2, 27 t	DE/ CZ	DACHSER
Use case II	5	Valencia region	Rigid 6x2, 27 t	ES	DISFRIMUR
Use case II	6	Bolzano-Munich	Rigid 6x2, 27 t	IT/ DE	FERCAM
Use case III	7	Hatfield	Rigid 4x2, 18 t	UK	DHL
Use case III	8	Leoben-Göss region	Rigid 4x2, 18 t	AT	Brau Union
Use case III	9	Flen-Stockholm	Rigid 4x2, 18 t	SE	Unilever

Tractor 4x2, 40 t Rigid 6x2, 27 t Rigid 4x2, 18 t

Figure 15: Overview of geographical distribution of case studies in Europe

The case study analysis identified the following key learnings for the use of FCH technology in the heavy-duty trucking and logistics industry:

> FCH trucks can be cost competitive with diesel trucks across most case studies and use cases in 2030, only challenged by BEV in cases of short routes on a regular schedule;

> FCH trucks are especially well suited for routes with a high daily range, e.g. long-haul operations across regions and countries, needs for additional power requirements, e.g. transport of refrigerated goods, as well as high-frequency, multi-shift routes (availability of infrastructure along the route assumed);

> In comparison with other zero-emission alternatives, FCH trucks allow for operational performance most comparable to diesel trucks regarding daily range, refuelling time and payload capacity. While the overall range of a diesel truck can exceed 1,000 km with one tank fill, this type of performance is seldom required to fulfil a daily duty cycle and therefore does not necessarily have to be matched by FCH trucks[23];

> For most case studies, the investigated routes and rather small fleet sizes would not create sufficient demand to build separate large (private or public) hydrogen refuelling stations. The expected volumes would be challenging to make business cases for stations attractive. This could only be realised through higher demand and thus utilisation of infrastructure. However, while this study looked at a specific number linked to a certain route, in most cases there would be potential for higher demands if all vehicles of a depot would be converted to fuel cell and hydrogen technology. Hence, in the short- to mid-term when there will only be a limited number of FCH trucks on the roads, the setup of public infrastructure with a potential subsidy scheme would need to be in focus.[24] This would allow truck operators to gain experience with FCH trucks without having to manage the higher investment costs of both truck and infrastructure at the same time.

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[23] Information based on Advisory Board input.

[24] For a more detailed view on recommendations on future activities, see chapter 4.

FCH technology constitutes a good fit for a wide range of heavy-duty utilisation patterns. For example, in some 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 or busy daily operations) can be better ensured by FCH trucks.

3.1 Long-haul case studies linked to Use Case I

The long-haul truck segment usually involves operations of logistics companies transporting goods along long-distance routes in either international or national contexts or operations of companies with own trucking fleets, e.g. in the manufacturing industry. The high mileage routes are carried out with tractor-trailer vehicle combinations, amounting to a permissible gross vehicle weight (GVW) of typically 40 tonnes.[25] These large trucks are the most important pillar of the European transport fleet, carrying approx. 85% of EU road freight transport.[26] The case studies developed for the long-haul routes demonstrate the wide spectrum of deployment and show that real-life operations take different forms. The analysed case studies illustrate cross-border and cross-country logistics as well as high-mileage, multi-shift regional distribution.

In the case study of the Košice-Bratislava (Slovakia) cross-country route (total route length: 406 km), 15 trucks transport various lightweight, highly cubic goods (car parts, beverages) from the regional hub Košice in the Eastern part of the country to the capital Bratislava. The trucks then take up new load in Bratislava to either return to Košice or carry the new freight further to other countries in the EU.

The operation is volume restricted due to the heterogenous size of the loads. This means that the potential maximum payload of the trucks is most often not exceeded in terms of weight, but in volume capacity. At a first look at the TCO results, this plays in favour of a potential battery electric truck that needs to integrate the heavy additional battery suited to power the truck on a long route.[27] However, despite similar TCO results, payload considerations between FCH and battery technology indicate that BEV would not offer the same flexibility for a much bigger payload (e.g. heavier car parts) and longer ranges (e.g. cross-EU transport), which could restrict operations. This makes FCH technology the preferred zero-emission option, as it allows the necessary flexibility to potentially carry heavy loads for specific clients and operate longer ranges.

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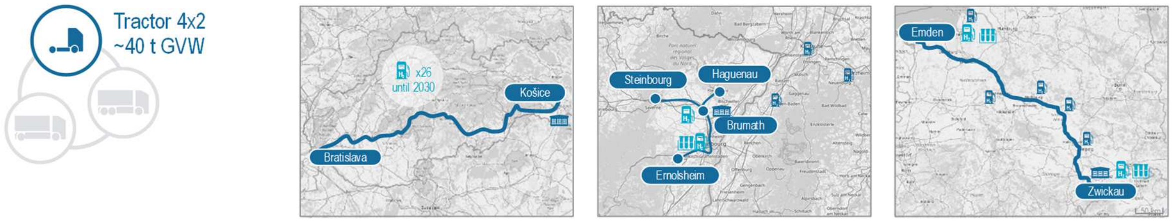
[25] The specific permissible gross vehicle weight in national transport varies from country to country, with further deviations due to regulations on certain vehicle combinations.

[26] A Eurostat analysis shows that in 2018, 85.4% of EU road freight transport was carried out by vehicles with a maximum permissible laden weight over 30 tonnes.
Eurostat. (2019). *Road freight transport by vehicle characteristics.* Retrieved from https://ec.europa.eu/eurostat/statistics-explained/index.php? title=Road_freight_transport_by_vehicle_characteristics#Road_transport_by_maximum_permissible_laden_weight_and_load_capacity_of_vehicle

[27] Batteries needed for long-haul routes add additional weight to the truck. In most cases, the integration of such additional weight would compromise the overall permissible payload as the maximum weight regulations still need to be considered.

Use case I – Case Studies	Kosice-Bratislava (SK)	Alsace region (FR)	Zwickau-Emden (DE)



	Kosice-Bratislava (SK)	Alsace region (FR)	Zwickau-Emden (DE)
Daily range	406 km	~270 km	607 km
Annual mileage	~130,000 km	~100,000 km	~130,000 km
Payload	10 t	26 t	~25 t
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	Cross-country route with further operation in other countries	24h warehouse logistics operation with refrigerated trailers	Long-haul automotive logistics service in a go-and-return route

Total cost of ownership [kEUR/truck; 1st and 2nd life]

	Kosice-Bratislava (SK) 2023	Kosice-Bratislava (SK) 2030	Alsace region (FR) 2023	Alsace region (FR) 2030	Zwickau-Emden (DE) 2023	Zwickau-Emden (DE) 2030
Diesel	908	892	575	563	955	945
FCEV 350 bar	1.102	836	774	582	1.253	985
FCEV 700 bar	1.140	868	802	605	1.293	1.017
FCEV LH_2	1.133	855	803	599	1.277	999
Battery	1.135	878	711	555 (Low probability to allow for charging time)	1.440	1.118
Catenary	1.269	1.162	909	830	1.395	1.292

Environmental analysis

	Kosice-Bratislava (SK)	Alsace region (FR)	Zwickau-Emden (DE)
CO_2 savings [tonnes p.a.]	135 t	109 t	135 t

Figure 16: Case studies for Use Case I – Long haul routes with 40 t trucks

In order to supply the trucks with hydrogen, public HRS are already planned along the main transport corridors in Slovakia, incl. an HRS near the depot in Košice. This push for hydrogen infrastructure is linked to the ongoing support and plans for the Central European 'Black Horse' project.[28] Access to public stations is required, because taken alone, the hydrogen demand of this specific fleet of 15 trucks would not be sufficient to make a business case for a private refuelling station.[29] The utilisation of the public HRS will be ensured by providing access to both 350 bar and 700 bar technology to service passenger vehicles, buses and trucks.

In the case study in the Alsace region in France, a regional distribution operation with 8 trucks servicing the same warehouse on three standard routes was investigated. The

[28] The Black Horse project will see the development, installation and operation of a hydrogen ecosystem in the Czech Republic, Hungary, Slovakia and Poland. A network of 270 HRS (for HDV, buses and passenger cars) will be set up to provide the infrastructure for the planned deployment of 10,000 FCH heavy-duty road transport vehicles. The project also foresees the installation of wind turbines, electrolyser facilities and hydrogen transport units. It is a candidate for the Important Projects of Common European Interest (IPCEI).

[29] A recommended station size and demand of at least 500 kg per day would generally be recommended by the study's Advisory Board members from the hydrogen infrastructure sector, in order to reach good scale effects.

three routes are rather short (between 30 and 88 km round trip), however, the involved trucks run on a very frequent schedule for up to 24 hours/day. The route involves the collection of food in three different factories with refrigerated trailers and the storage and coordination of these goods in a regional warehouse.

The refrigerated trailers have a separate engine, currently powered by diesel, which increases the overall fuel consumption of the vehicle. This is taken into account for the alternative powertrains, with TCO results showing that FCH technology is at a clear advantage in comparison with other zero-emission technologies. FCH technology would offer the necessary reach, required payload capacity and short refuelling time to allow for the almost 24-hour operation schedule. Battery electric trucks, which due to the relatively short route do not see payload reductions, would not offer the same flexibility. Especially the aspect of charging time would be crucial in this type of operation and could not be guaranteed in a fast-charging scenario as some trucks might carry out up to ten round trips per day (depending on seasonal patterns).

Also in this case, access to a public HRS close to the depot would be a good option to supply hydrogen to trucks. Besides, the logistics company linked to the case is considering the development of hydrogen hubs owned and operated by the company, including solar panels on the roof of warehouses, on-site electrolysis and in-house supply of hydrogen. If a sufficient amount of energy can be generated through this approach (0.5 MW electrolysis, considering the investigated fleet size in this case study), this could become an important initiative towards self-supply with green hydrogen.

In the case study of the cross-country route running from Zwickau to Emden in Germany, car parts are transported in a go-and-return operation. The logistics service provider first consolidates supplier goods at their hub in Zwickau and delivers them to the production plant in Emden. While this case study only considers the daily operation with two trucks (one starting on either end of the route), the operation can flexibly dispose over a pool of 41 vehicles that match the requirements for this route. In the meantime, the other 39 trucks service different operations on different routes. The operation is weight restricted with a >90% average weight loading factor, offering no leeway for payload reductions in alternative powertrain vehicles.

The TCO analysis showed that the FCH technology is the most cost-competitive zero-emission option on this route. This also becomes clear in the direct comparison with BEV. As the operation is linked to just-in-time delivery for automotive production, there is limited margin for different schedules. Hence, intra-day recharging of a battery would potentially not be possible. Furthermore, payload losses due to the heavy battery needed for the route have to be considered. Looking at the TCO results, diesel trucks are the cheapest option still in 2030 on a EUR/Truck basis). However, the analysis assumed public refuelling for the FCH trucks due to a low hydrogen demand for two trucks only, while considering the current practice of private refuelling for the diesel counterpart. This gives the TCO for diesel trucks a cost advantage due to the lower energy/fuel prices in private refuelling operations (without considering additional infrastructure investments in the case of diesel). Hence, the TCO potential of FCH trucks could become more prominent if cost parity of fuels can be achieved, e.g. through higher CO_2 driven taxation on diesel, increasing oil prices or a CO_2-driven road toll mechanism.

The Zwickau-Emden route further highlights potential for fuel cell and hydrogen synergies, linked to applications and hydrogen supply. Due to the proximity to port operations and automotive production in the North of Germany, FCH technology could be leveraged. There is potential access to renewable energy as well as an array of further potential FCH applications at the production site. Furthermore, the route is close to an existing H_2 production site in the chemical park in Saxony (i.e. in the City of Leuna), which could be used as a nearby hydrogen source to supply the trucks.

3.2 Medium/long-haul case studies linked to Use Case II

The medium/long-haul truck segment refers to operations similar to those described above: mid-to-long distance routes in national and cross-border (neighbouring countries) operations, often linked to wholesale. The routes are operated with larger rigid-type trucks with a permissible GVW of around 27 tonnes.[30] For higher-mileage routes, an additional trailer is connected to the truck in order to transport more goods in volume-restricted operations.

The case studies developed for this use case and truck type involve different shift operations with swap bodies, refrigerated equipment and night routes. This illustrates the versatile application of this vehicle type and the different needs truck operators and logistics users have regarding performance and flexibility.

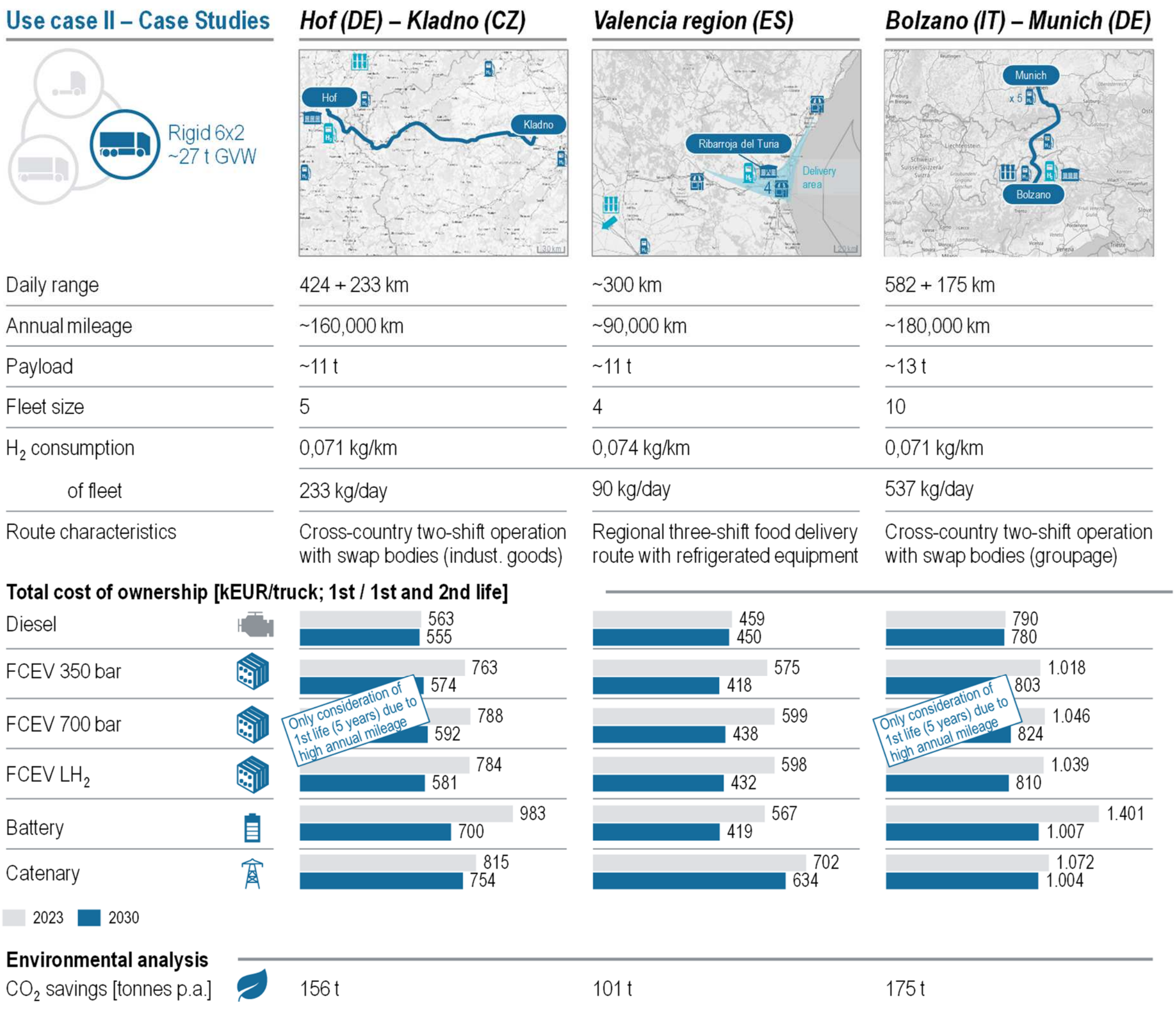


Figure 17: Case studies for Use Case II – Medium/long haul routes with 27 t trucks[31]

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[30] Please refer to chapter 2 for further information on the various truck types.

[31] The investigated case studies for use case II in part cover only the assumed first life period of the vehicle (approximately 5 years). This is due to the high mileage the respective trucks will accumulate over time. As it is assumed that the maximum lifetime of a vehicle amounts to 1.4 million kilometres, the investigated trucks would not be available for a full second life. For more information, please see the Annex of the Study Report.

In the case study of the cross-country route from Hof (Germany) to Kladno (Czech Republic), a double-duty operation for industrial groupage goods was investigated. The five trucks run on a line haulage operation at night that connects the regional depot in Hof with multiple branches in Eastern Europe. On this line, two swap bodies (one on the truck, one on a trailer) are transported from Hof to Kladno where they are exchanged with swap bodies coming from branches in Eastern Europe. Both trucks then return to their depot of origin with the new load. In a second shift with another driver during the day, the same trucks are used for regional operation around the depot. Operations on both shifts are volume restricted due to the heterogenous weights of groupage goods. Hence, there are no limitations regarding the permissible payload of 16 tonnes for both swap bodies.

The TCO analysis illustrated that on this two-shift operation with a relatively high total daily range, FCH would be the best zero-emission option. However, as diesel trucks are still the most cost attractive option in 2030, going for a zero-emission vehicle would still come at an extra cost by then if the circumstances do not change (e.g. energy and fuel prices). Nevertheless, the case study showed that if utilisation patterns are optimised for FCEV (e.g. allowing for intra-day refuelling between shifts), FCH technology could become cost competitive. This is due to the calculated size (and corresponding cost) of the hydrogen tanks to cover the whole daily range. If less hydrogen is required along the route because more frequent refuelling is possible, both tank size and related cost could be reduced. This possibility, however, would not work for BEV as there would not be sufficient time to charge the large battery.[32] Furthermore, the lifetime of trucks is set to a maximum of kilometres that can be driven over the years. Batteries generally have a lower expected lifetime than other alternative powertrains. This means that with a high mileage, the battery lifetime is consumed earlier, and a replacement battery will be needed for the truck. Hence, this increases the cost of powertrain and affects the overall TCO of the battery electric trucks.

In order to supply the trucks with hydrogen, access to a public HRS was considered, which is not yet available today. In order to ensure its commercial viability, the infrastructure would also need to be used with other applications in the area. A private refuelling station would only be cost effective if a large number of trucks linked to the depots are replaced by FCH trucks.

In the Valencia region case study in Spain, a regional depot connects various supermarket branches in the area. In a three-shift back-to-base operation with different drivers, food is delivered in trucks with refrigerated equipment. The individual operations of the trucks vary regarding route length and daily range, with the minimum one-way route being 30 km and the average daily range covering 300 km. The refrigeration equipment is run by an additional engine fuelled by off-road diesel, separate from the regular automotive diesel and taxed differently. This specific data was considered when including the overall consumption figures and the diesel cost.

The TCO analysis showed that FCH and BEV technology both present promising zero-emission options. However, FCH technology is more favourable as the TCO for BEV implies some limitations. The battery electric truck would imply a payload reduction due to the need for a larger battery to operate on all routes (maximum of 440 km daily range without the possibility for intra-day charging). Furthermore, the high mileage over lifetime is expected to require a battery replacement. This second replaced battery would still hold a relatively high residual value at the end of the ten-year timeframe considered in this study, because it was used to power the truck only for the last two years considered. However, there still is uncertainty around the second-life use of batteries and the corresponding value. The TCO result for BEV should be understood as implying

[32] Currently, ultra-fast charging stations at multi-MW scale needed for a very fast charging process do not exist. In addition, this would considerably increase the draw on the electricity grid that cannot be guaranteed in all local conditions.

such a limitation. The actual residual value of the battery could be lower, meaning an overall increased TCO result.

The relatively limited number of trucks in this case study would not generate enough hydrogen demand for the station to be cost effective: Hence, a potential HRS in Valencia (public or private) would need to service a larger number of trucks and other applications. At the same time, due to the strong ambition of the company linked to this case study, the installation of a private refuelling infrastructure is considered. This would be implemented first around the company's main hub, 200 km from the investigated route, but a further extension of the private network will be considered once the roll-out of further FCH trucks seems realisable. The option to go for an underutilised private refuelling station in the early days comes with a toll on the TCO of the first phase small fleet FCH trial.

The route from Bolzano (Italy) to Munich (Germany) offered another case study perspective on a cross-country route driven at night in a go-and-return operation. At night, the trucks drive from Bolzano to Munich on the heavily used Brenner route, passing Austria on the way. After the trucks return in the morning, they are used in regional distribution operations in a second shift during the day. This double duty of the trucks amounts to a daily mileage of approximately 750 km. Due to the transport of groupage goods, the operation is volume restricted as the loaded pallets have different weights, but the same size.

On this route, the TCO results indicate that FCH trucks would be the most cost-attractive zero-emission technology. In addition, FCH technology seems best suited to fulfil the operational requirements on this route, mainly the high daily range and the required flexibility. By comparison: Battery electric trucks would see a payload reduction due to the necessary battery size and weight on the route. Furthermore, the tight schedule of the two-shift operation would be a limitation for sufficient charging time. However, despite a clear cost-down potential at scale, FCH trucks are not yet cost-competitive with diesel in 2030. This is mainly due to the high daily range that requires a larger powertrain (fuel cell modules and hydrogen tank system) with high costs for zero-emission vehicles.[33] 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 the truck investment costs could be lower due to smaller tank sizes.

While the hydrogen demand of the trucks investigated in this case study might even enable the operation of a (small) private hydrogen refuelling station at the depot (0.5 tonnes/day), existing infrastructure could be leveraged. An HRS already exists very close to the depot that could potentially also provide the required hydrogen to fill up the trucks. Furthermore, the Tyrol region and local companies have ambitious plans for a hydrogen ecosystem (Hydrogen Valley South Tyrol), incl. deploying FCH trucks and transforming the Brenner route into a 'green corridor'.[34] In addition, various opportunities linked to the hydrogen infrastructure will potentially work in favour of FCH technology on this route in the future, increasing the possibilities of realising the FCH trucks investigated in this case study.

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[33] It is assumed that the daily range needs to be achieved without intermediate refuelling or charging. Hence, the TCO model considers a larger powertrain for the zero-emission vehicles which, in turn, increases the costs.

[34] The establishment of the Hydrogen Valley South Tyrol is considered a lighthouse project, being supported via various EU-funded projects such as CHIC, HyFIVE, REVIVE, Mehrlin, JIVE and LIFEalps.

3.3 Regional distribution case studies linked to Use Case III

The regional distribution segment usually involves operations of regional logistics and retail with trucks that have a more limited payload capacity. Mostly, these operations are plannable and run on a fixed schedule at depot and drop-off location. The shorter mileage routes are carried out with smaller rigid trucks with a GVW of around 18 tonnes. The case studies developed for this vehicle type include regional delivery operations in different geographies of rural and urban areas as well as routes with varying daily ranges.

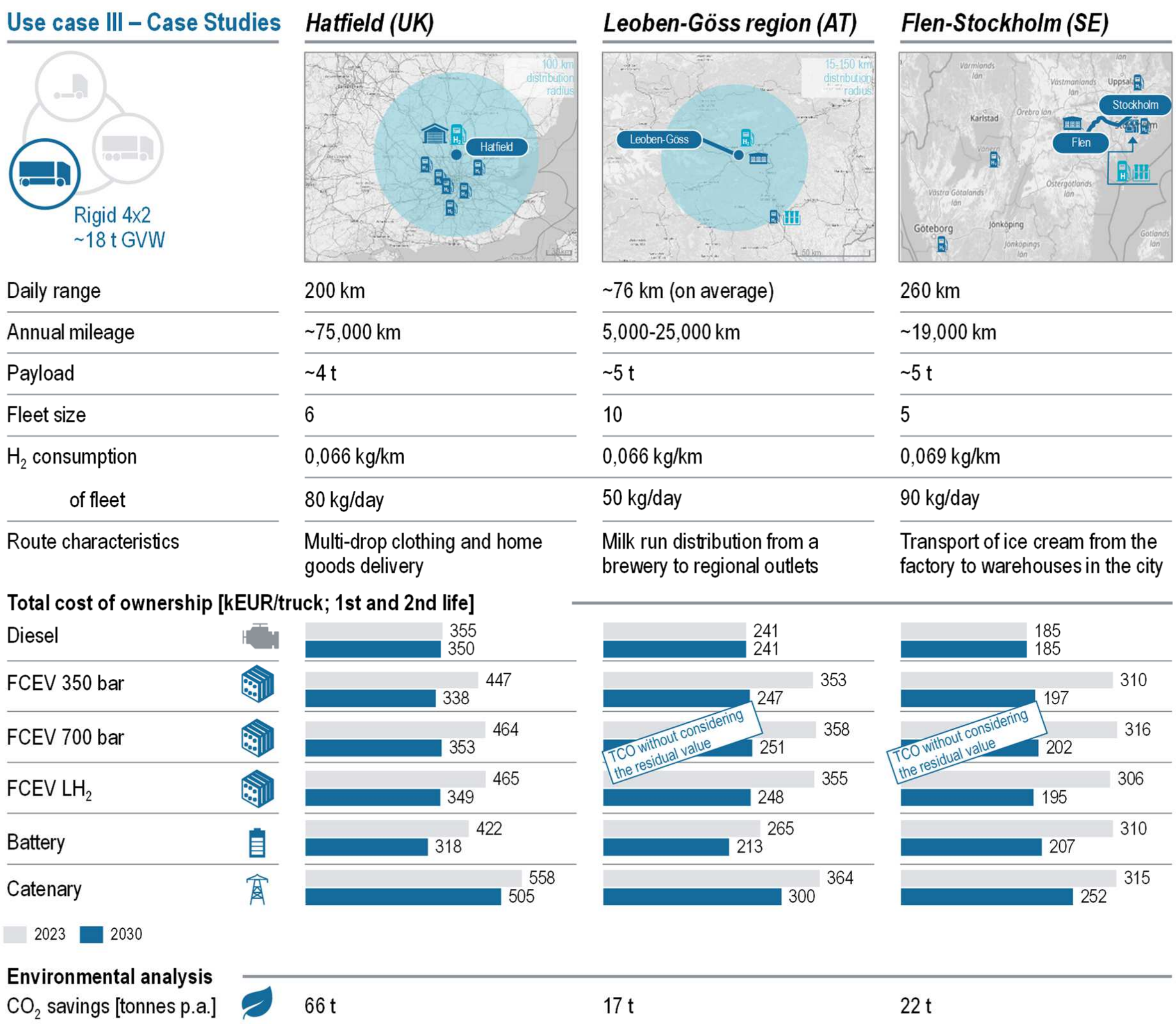

Figure 18: Case studies for Use Case III – Regional distribution routes with 18 t trucks

The case study on the Hatfield (United Kingdom) delivery route involves a fixed "bus stop" schedule to deliver clothing and home goods from the regional hub to the clients' stores. It is a multi-drop route of one or two deliveries per trip, operated in one or two shifts. The delivery area is within a radius of approx. 100 km from the regional hub, predominantly into inner-city London. The TCO analysis showed that BEV have a slight cost advantage over FCH trucks. The results revealed that battery technology overtakes diesel and FCH trucks as the cheapest technology option in 2030, demonstrating the increasingly positive commercial development of zero-emissi on technologies. However, when considering other factors besides the TCO results it becomes clear that this positive outlook must also be reflected in the operations. Here, (cost) advantages of FCH technology compared to BEV could become more prominent, e.g. when considering external influences such as higher energy needs in winter or the potentially very high demand on the electricity grid when charging a fleet of battery electric trucks.

On this route in today's diesel operation, one fuel stop per shift is carried out at a public station. As the hydrogen demand would not be sufficient for a private HRS, a public HRS would need to be installed close to the depot. Currently, the existing hydrogen refuelling stations in proximity of the route lie within the city of London and only provide access for cars and buses. A public HRS in Hatfield could not only provide the necessary infrastructure for the trucks linked to the specific delivery route but also service other FCH trucks passing the depot as well as potentially the fleets of other truck operators in the Northern London area. Furthermore, synergies with the existing HRS network could be realised for buses and passenger vehicles around London.

In the case study of Leoben-Göss (Austria), a local distribution operation in a rural area was investigated. For this milk-run-type, back-to-base operation of a local brewery within the same district, 15 trucks leave the production facility in the morning and, after visiting 10-20 outlets, return in the afternoon with empty crates and kegs. The deployed trucks generally have rather fixed routes, yet the stops on these routes differ over the weekdays. Hence, the specific routes vary from 15 to 150 km a day, with an average of approximately 76 km. The operation is volume restricted due to specific picking per route and different brands of crates/kegs, leading to limited floor space.

The TCO analysis for this case study showed that the potential for FCH technology is limited for these regional distribution routes, and BEV technology seems better suited. The results showed that battery electric trucks are the most cost competitive zero-emission option. In addition, the analysis illustrated that the residual value has a strong impact on the results – an inherent uncertainty today as almost no alternative powertrain trucks are being sold to operate in a second life yet. Consequently, the TCO results in this case study do not consider a potential residual value that would skew the results due to the very low mileage and the relatively low utilisation of this powertrain in terms of kilometres driven.[35] This consideration shows that there is some uncertainty that needs to be taken into account. At the same time, the model also illustrates that with a certain driving profile and mileage, a FCH truck lifetime of >10 years would be possible.

Despite good preconditions of the plannable route operated on a regular schedule, setting up the required hydrogen infrastructure for FCH trucks is another potentially limiting factor. As private infrastructure is not cost-effective for the limited number of trucks with low consumption, public refuelling infrastructure and further synergies in the region would be needed to build a case for FCH trucks. However, due to its setting in a rural area in Austria and a currently low demand for hydrogen that could only be increased as part of a country-wide technology change, the likelihood of a public HRS for trucks would be rather low.

The Flen-Stockholm (Sweden) case study investigated the potential of FCH trucks for regional ice cream delivery with refrigerated trucks. The ice cream pallets are collected from the production site in Flen, south of Stockholm, and delivered to warehouses in the Swedish capital with approximately 1-10 stops on the route. The go-and-return route covers approximately 260 km. Due to the nature of the transported goods (ice cream), the volume of the operation follows seasonal patterns.

The TCO results illustrated that this route offers potential for both FCH and battery electric trucks. Both technologies are at very comparable cost levels yet are not cost competitive with diesel trucks by 2030. Again, in this case study, a potential residual value is not considered as results could be skewed due to the very low mileage (see above). Nevertheless, FCH technology allows for operations closer to the current diesel performance. Further advantages of FCH technology could make FCEV better suited for the operation. In comparison with BEV, this could be the case if, for example, there is no space to charge vehicles at the depot during the required time slots. Another example

[35] For further information on the aspect of the residual value, please refer to the Study Report.

could be charging a fleet of BEV that leads to high energy costs and a (potentially too) high demand on the electricity grid. Furthermore, external influences can play a role, such as cold winters in Sweden. Here, more heating would be required, which could be supplied by excess heat from a fuel cell's thermo-management system without raising fuel consumptions levels.

The installation of a hydrogen infrastructure would be required, with higher potential for setup in Stockholm. Based on the investigated demand, a private refuelling station at the factory would only be commercially beneficial if high utilisation was ensured, e.g. through other types of trucks linked to the production process. In Stockholm, refuelling infrastructure for trucks could build on existing HRS for passenger vehicles. Furthermore, they could also provide hydrogen to a larger number of trucks, carrying out operations in the city area. However, it would need to be ensured that refuelling stops can be integrated into the route.

3.4 Findings on FCH application for real-life heavy-duty trucks application

The case studies provide an additional perspective on the potential of FCH application for heavy-duty trucks in Europe. On the one hand, they highlight the diverse operating patterns of heavy-duty trucks and show the key role of hydrogen refuelling infrastructure for various routes. On the other hand, they illustrate the industry views and uncover potential enablers and constraints. The total cost of ownership remains the potential key decision-making factor; however, operational considerations are important, too. Most prominently, truck operators and logistics users frequently highlight that the performance and usage of alternative powertrains should be as close to diesel trucks as possible. Hence, while the TCO perspective on the cost competitiveness of technologies will differ on a case-by-case basis, the assessment of the case studies shows that when looking at operational advantages, FCH trucks indeed present the best suited zero-emission technology in most cases.

Advantages: The analysis of case studies shows that the presumed advantages of FCH technology in heavy-duty truck application become more evident in real-life business settings and would be highly valued by a majority of the truck users. FCH trucks allow long daily ranges, routing flexibility, fast refuelling and a payload capacity comparable to diesel vehicles. Compared to other zero-emission technologies, namely battery electric trucks, FCEV are at an advantage. Also, in case of a high energy need (e.g. for refrigerated equipment or in harsh winter conditions), FCH trucks offer a good option of providing additional energy without drawbacks for payload or performance. Looking at the TCO development across the case studies, a cost-down potential is expected over the years.[36] In some case studies, cost-competitiveness with diesel trucks was indicated in the mid-term from 2027 onwards if mass manufacturing of FCH HD trucks is stimulated today. Furthermore, like other zero emission trucks, FCH trucks have positive environmental potential beyond a significant CO_2 reduction, e.g. reducing pollution from particulate matter and avoiding NO_x.

Enablers: Across all case studies, it became clear that the FCH technology uptake heavily depends on local hydrogen refuelling infrastructure. Currently, without a Europe-wide network of HRS, the prospects for FCH trucks to be deployed in the near future are most favourable for fleets. For example, plannable route conditions with a regular

[36] The TCO results are based on TCO model assumptions taken in alignment with the study's Advisory Board as elaborated in Chapter 2. In addition, case-specific information was included to reflect the real-life operations of the case study routes.

schedule, line haulage routes or back-to-base operations could enable separate, dedicated HRS infrastructure with a daily consumption of more than 500 kg of hydrogen[37] on a case-by-case basis. Furthermore, existing H_2 infrastructure (e.g. for cars or buses) in close proximity to the route is a supporting factor that can be leveraged, as supply network and local know-how already exist. Existing 350 bar HRS for buses could support FCH trucks with the same pressure level for regional operation with shorter hauls. However, upgrades of the existing HRS technology for passenger vehicles and the capacity of the HRS to fill the larger tanks of the FCH trucks will need to be implemented in most cases. In addition, ongoing and planned FCH projects provide support in preparing the integration of FCH technology into regular transport operations, from setting the framework conditions of demonstration projects to larger-scale deployment (e.g. backing by coalition of different industry stakeholders and government).

At the level of truck deployment, a strong company interest in more sustainable transport solutions can fast-track the uptake of FCH trucks and, in part, the set-up of infrastructure. Leveraging their market positions, companies can create market demand for trucks and infrastructure on the one hand and push for higher compensation from subcontractors and customers, on the other. Another supporting factor at company level can be previous experience with LNG, (bio-)CNG or battery trucks that can be leveraged in preparing employees, subcontractors, and customers for handling the new technologies.

> **Long ranges, fast refuelling** and **payload capacity** comparable to diesel vehicles
> Clear **cost-down potential** over the years
> Potential in case 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 rollout 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 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

> High **dependence on local hydrogen refuelling infrastructure**
> High **cost of powertrain** for FCH trucks and **uncertainty on second life use** and **value today**
> High **cost of hydrogen** – Fuel costs (OPEX) would be especially expensive
> **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)

Figure 19: Overview of main findings on real-life business cases for FCH technology

[37] Industry experts suggest a daily consumption of 400-500 kg of hydrogen per day as a suitable consumption to consider private refuelling which is equivalent to c. 10 FCH long-haul trucks with 50 kg of hydrogen per tank fill.

Opportunities: The opportunities identified in the case studies relate to existing favourable conditions for FCH technology in the current industry environment that can be further developed and leveraged. They mainly concern access to energy and infrastructure, supporting regulation and partnership possibilities:

> First, regulations put in place that favour low and zero emission vehicles can be an effective lever for FCH trucks, if rolled out on a larger scale across Europe (e.g. road toll exemption already in place in some countries);

> Second, the proximity of the route's depot to a renewable energy source and power plant provides direct potential for green hydrogen production (e.g. wind parks, solar power plants). The renewable energy derived through the power plant can be used for water electrolysis to enable a supply with green hydrogen;

> Third, multi-modal use of hydrogen infrastructure creates synergies with other applications (e.g. cars, forklifts, buses, garbage trucks, further trucks at the depot that are operating on other routes, other logistics companies in the area). Multiple other collaboration opportunities could be identified that also relate to longer-term plannability;

> Fourth, these opportunities, in turn, can also offer potential for local/regional partnerships to set up refuelling infrastructure that can be used by multiple companies and users (e.g. as realised in projects linked to hydrogen valleys and hubs).[38] As such, the higher utilisation of the HRS provides for a better commercial perspective and a better chance of realisation;

> Furthermore, if partnerships and collaborations were oriented at a longer time frame (e.g. customer contracts), this would ensure plannability of investments and therefore increase possibilities of FCH truck purchases by truck operators;

> Lastly, an aligned cross-border rollout of both FCH trucks and HRS with EU standards offers the chance for a concerted uptake and no interoperability problems.

Constraints and barriers: While the case study analyses showed that there is a multitude of supporting factors for the uptake of FCH trucks, there are still important barriers and constraints that need to be overcome first for the potential to materialise. As one of the main cost drivers, the cost of the powertrain for FCH trucks is today high compared to the incumbent diesel engine technology. Currently, there is no certainty on the second life use and value of FCH trucks, which might cause reluctance among truck operators to make a purchase decision as early movers. Furthermore, the energy and fuel costs today (especially for green hydrogen) are rather high. As it is not yet certain how the cost of green hydrogen will develop, and clear decisions on support mechanisms have not been made, not for the mid-to-long-term either, other powertrain options might be favoured in the meantime. These concerns are currently actively being addressed in political discussions on the structure of support and incentive mechanisms, e.g. as part of the role attributed to hydrogen in the EU Recovery Plan.

Moreover, when directly compared to today's diesel trucks, further development of FCH technology is needed in order to systematically match the performance of diesel in all aspects. More flexibility regarding operations and business practices would be needed to adapt specific utilisation patterns, e.g. to allow for the possibility of intra-day refuelling for multi-shift operation. In addition, in-house depot HRS in a 'business as usual' manner

[38] The emerging EU approach supports integrated hydrogen projects across sectors and along the entire value chain (so-called hydrogen valleys). These projects do not only serve the transport industry, but also other industries as well as the energy sector and offer opportunities for collaboration along the value chain. For further details, please refer to e.g. the HEAVENN project in the Netherlands, the first sectorally integrated hydrogen valley to obtain funding by the FCH JU.

would only be a commercially attractive option if many trucks were to run on hydrogen and be supplied by the same station. A minimum utilisation (assumption of at least 10 trucks consuming the 500 kg per day as per industry expert recommendation) would need to be serviced per HRS (for both private and public HRS installation) to allow for a sufficiently attractive business case.

View on industry development: Besides the assessment and illustration of potential opportunities of FCH technology in the heavy-duty market in Europe, the case studies offer a detailed view into the transport and logistics industry. While operations might appear similar at first glance, there are differences that are not easily grasped by looking at the route data only. For example, the ownership structures of trucks can be set up in multiple ways: e.g. owned and operated; leased and operated; owned, operated but managed by the customer with trucks at their full disposal.

With this understanding in mind, the specific case studies can be evaluated from another perspective. It becomes evident that current utilisation patterns might often prevent the successful integration of alternative powertrains in existing fleets as they have been optimised based on diesel engine technology in respect to operation and business cases. Nevertheless, truck operators, logistic service providers and logistics users show some acceptance for compromise to adjust these patterns to enable zero-emission trucking. For instance, short intra-day refuelling stops for FCH trucks could be considered, while battery charging in a two-shift operation could be nearly impossible due to a lack of time to fully recharge the vehicle.

Generally, it can be observed that the transport and logistics industry is willing – and in part is already active - to engage in projects with alternative powertrain vehicles. While LNG trucks are the most often referenced alternative to date, this starting point offers high potential for FCH trucks as it provides a reference case for implementing a new gaseous fuel in the logistics industry. It is often expressed by truck operators, however, that a commitment from all partners in the value chain would be needed in order to minimise business risks, e.g. via long-term contracts, H_2 floaters, guarantees on residual value calculations (or buy-back clauses), as well as encompassing service and maintenance contracts. Nevertheless, the most decisive factor for logistics operators remains the total cost of ownership and the question of whether the logistics customer has a higher willingness to pay for a zero-emission option that is certainly more expensive in the short term. Currently, this seems to still be up for debate as the decision on the vehicle used in operations is most often based on the best business case from a purely financial point of view.

4. Recommendations for successful implementation of FCH technology in the heavy-duty truck sector

Fuel cells and hydrogen applications are clean, safe and innovative technologies that are key for a future of decarbonised mobility and transport solutions. The EU is pushing to advance the technology, leveraging many globally leading FCH heavy-duty market development activities in Europe. This constitutes significant upside potential for the European FCH industry and truck OEMs. Nevertheless, FCH technology for the heavy-duty truck application faces some challenges and barriers. These mainly originate from the current development stage of the technology, as FCH technology for HD trucks is still a relatively novel application in comparison to other FCH uses where commercial products are a reality. Therefore, initial strong/targeted support is needed to unlock its cost-reduction potential and full market potential to realise its decarbonisation promise.

Of the current technological and non-technological barriers identified in this study, none are 'showstoppers' for the successful commercialisation of FCH heavy-duty trucks. However, large-scale roll-out of FCH technology in the heavy-duty truck sector can be sped up in the upcoming years. In the short term, dedicated research and innovation (R&I) projects are needed to continue the development of FCH components and applications for trucks, promote the market maturity of truck products and refuelling infrastructure, and establish industry standards that enable cost reduction for the entire industry. If the market development gains traction globally, European companies will also benefit from a growing FCH heavy-duty truck market in other regions that also transition to FCH transport and mobility solutions.

4.1 Barriers to the widespread adoption of FCH in heavy-duty transport

Based on insights shared by members of the study's Industry Advisory Board, expert interviews with representatives of key industry stakeholders and additional comprehensive desk research, 12 technological and ten non-technological barriers to the widespread adoption of FCH technology for heavy-duty trucks have been identified. The barriers have been analysed and clustered based on a set of criteria to derive a list of barriers that present need for action today. These prioritised fields of action must be addressed successfully soon, to pave the way for FCH technology to unfold its market potential in the heavy-duty road transport industry.

Criteria for prioritisation:[39]

> Relevance for most truck types and models;
> Urgency for technology commercialisation;
> Number of technical areas concerned;
> Frequency with which they were named in the stakeholder responses and expert interviews.

Based on these criteria, the study pinpoints six barriers of high priority, nine barriers of medium priority and seven low priority barriers. Expert interviews showed that none of the barriers are roadblocks for the wider implementation, as fuel cell and hydrogen technology

[39] Prioritisation, especially with regards to safety and emergency measures, does not reflect the overall importance of the topic, but the perspective on the main needs for action in the heavy-duty truck sector

itself has already reached a high level of maturity.[40] However, their application in the heavy-duty setting is still at the early stage.

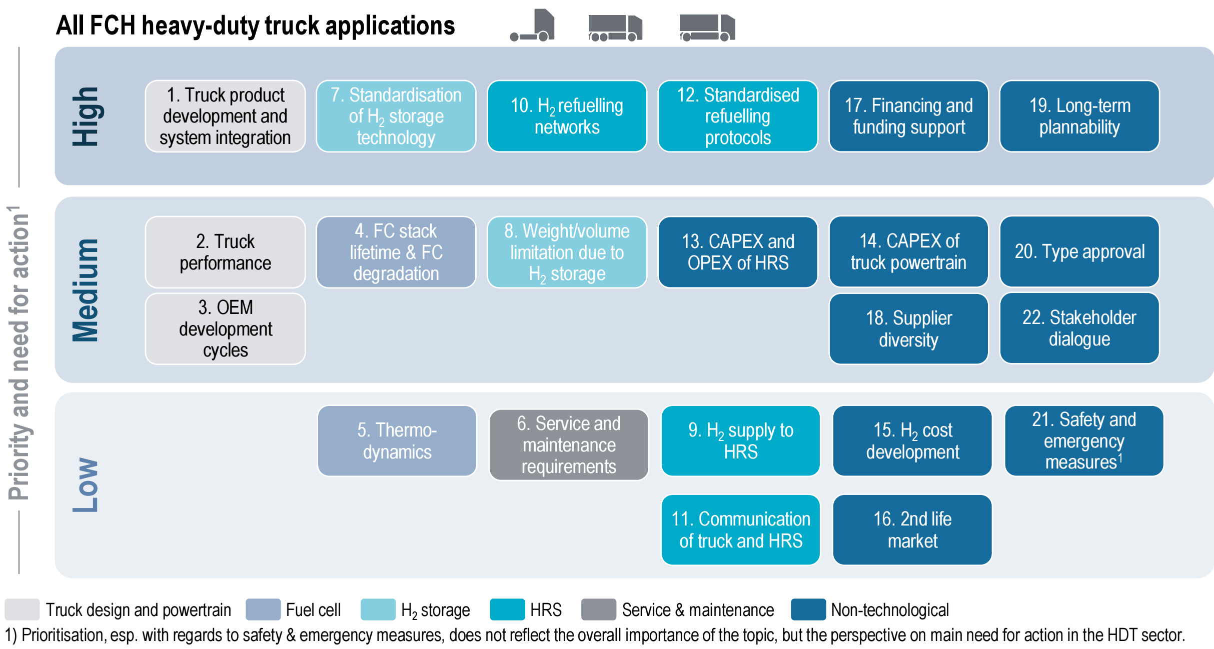

Figure 20: Overview of barriers for FCH heavy-duty trucks and priority for short-term R&I

As shown in current trial and demonstration projects, FCH technology for heavy-duty trucks is increasingly being tested. Progress in research and industrial development aims to bring FCH trucks closer to fulfilling the operational requirements of the heavy-duty transport and logistics industry in terms of range, refuelling time and payload capacity. However, further technical optimisation and adjustments are needed to overcome remaining barriers. The analysis found 12 technological barriers mainly related to technical challenges and optimisation potential along the FCH heavy-duty value chain:

- **Truck design and powertrain** encompassing barriers on integrating the FCH powertrain in existing truck chassis while optimising weight and dimensions, overall cost and reliability of the vehicles;
- **Fuel cell powertrain** related barriers regarding fuel-cell specific challenges, such as stack lifetime, improved thermodynamics and optimisation of fuel cell integration;
- **H_2 onboard storage** barriers such as the lack of standardised H_2 onboard storage technology, as regards the various options 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, and combinations such as cryo-compressed hydrogen storage);
- **Hydrogen refuelling infrastructure** related challenges regarding high space requirements for H_2 storage on-site at the HRS, sufficient network coverage for future rollouts and uncertainty about the widespread availability of green/low-carbon H_2;
- **Service & maintenance** barriers, such as a lack of standardised service and maintenance requirements, spare part availability in early rollout markets and FCH-ready truck workshop density.

[40] For instance, the large-scale production of green hydrogen is a prerequisite for CO_2 savings for all end users. However, in this study, it is attributed a lower need for action due to its limited direct impact on FCH heavy-duty truck deployment. Nevertheless, its importance for FCH technology in general is fully acknowledged.

Most of the identified technological barriers are directly linked to the optimisation potential of FCH technology, in particular of the FCH truck powertrain itself, the individual fuel cell and hydrogen tank components (e.g. H_2 onboard storage) and the hydrogen refuelling infrastructure and its interoperability with the trucks. Overcoming these technological issues can bring FCH heavy-duty to similar operational performance as incumbent diesel trucks. Especially truck operators and logistics service providers require that FCH technology be able to fulfil their daily duty cycles before considering a transition of their existing trucking fleets. However, some operational adjustments are still to be expected. Diesel trucks can rely on a fuel with a very high energy density that can achieve ranges of more than 1,500 km on a single tank fill. This benchmark can currently not be matched with any zero-emission powertrain technology. Therefore, the study focuses on powertrain configurations that would allow truck drivers to perform one full daily duty cycle without refuelling.

Overcoming the following four technological high-priority barriers are deemed particularly necessary for short- and medium-term research and innovation projects.

A key technological barrier for broad market adoption is the **integration and standardisation of FCH technology components into existing truck architecture.**[41] Progress related to truck design and system integration is also determined by the product development process and production cycles of OEMs and component providers. Today's truck chassis designs are developed around diesel engines and diesel tanks. Innovation is a continuous process, but OEMs are bound to their development and production cycles. The truck OEM industry develops truck models to last up to 20 years until a new model takes its market position. Currently, political decision-makers demand that technology changes are introduced much faster in these development cycles. As a consequence, there is a mismatch between the time needed for the design of a truck optimised for FCH technology and the regulatory demand. While truck designs are being optimised for FCH technology, some of today's heavy-duty trucks are already being retrofitted to integrate the fuel cell system and hydrogen tanks. However, development and optimization are still ongoing and require time. In particular, the different onboard storage requirements for different types of H_2 pressure levels are a frequent topic of the current technological debate. In addition, there is no standardised fuel cell module yet, that would allow easier integration into various truck architectures. This challenge has also been identified by the FCH JU in its 2020 annual work plan. The resuming innovation project aims to develop standard sized FC modules for heavy-duty applications going forward.[42]

Another important barrier is the current **lack of standardisation of available H_2 onboard storage technology for heavy-duty trucks**. This barrier affects the whole value chain from truck development to hydrogen production and storage, and on to refuelling equipment. Existing and planned options, such as hydrogen at 350, 500 and 700 bar, liquid hydrogen and cryo-compressed hydrogen each provide a range of advantages and disadvantages, depending on the use case and potential synergies with existing applications.[43] However, there is currently no coordinated industry-wide approach as

[41] In addition to the integration of fuel cell powertrains, another area of development is the retrofitting of conventional internal combustion engines (ICE) with hydrogen ICEs that can run on dual fuel or a blended mix.

[42] The FCH JU provides funding for the project 'FCH-01-4-2020: Standard Sized FC Module for Heavy Duty Applications with an indicative budget of EUR 8 million. The project start is expected for early 2021.

[43] For example, hydrogen at 350 bar can be sufficient for lower range use cases but would not provide a viable solution for long-haul trucks. The lower energy density of the fuel would require large H_2 tanks to provide sufficient fuel for long routes. But due to their size, these tanks could not be integrated into today's truck chassis architecture. Furthermore, although H_2 at 500 bar technology has not been investigated as a focus technology for this study, it represents a viable

different OEMs are pursuing different solution routes.[44] Resolving the question of H_2 onboard storage technology, however, is a crucial factor for the commercial rollout of FCH heavy-duty trucks, in particular with regard to refuelling infrastructure. On the one hand, in some respects the development of different onboard storage solutions might provide specific use cases with optimised solutions. On the other hand, however, higher levels of certainty on the on-board storage technology for heavy-duty trucks in the short-term would accelerate at-scale technology production and HRS build-up. Specifically, refuelling processes might become more complex if several options were to be offered at refuelling stations. Different storage technologies require different refuelling protocols and different refuelling equipment. A common standard for the industry is prerequisite to delivering the required infrastructure for truck refuelling and allow for future-proof investments. Hence, a joint industry effort and a systemic perspective on truck technology, operation, refuelling station networks and hydrogen generation is required to identify the most suitable option for commercialisation, e.g. in terms of cost, customer requirements, viability at scale and potential to meet 2050 targets. While these questions are partly already being addressed, and some truck manufacturers are moving ahead with technology that already exists, an industry compromise in the short term is paramount to achieve the 2030 and 2050 CO_2 emission targets.

The study has identified **the lack of a connected (inter)national network of H_2 infrastructure** as the third main technological barrier. Refuelling stations would need to be implemented along EU transit routes, national and regional logistics centres and important urban nodes in order to make FCH heavy-duty trucks a viable alternative for the transport and logistics industry. It is also imperative to tap into synergies with existing HRS for passenger vehicles and buses when extending the refuelling infrastructure to provide for the requirements of heavy-duty trucks.

The **lack of industry-wide standardised refuelling protocols** is another main technological barrier. It is closely linked to the lack of standardisation of available H_2 onboard storage technology and the build-up of refuelling infrastructure. This interconnection of technological barriers underlines the importance of a joint development timeline of OEMs, hydrogen suppliers and HRS providers.

Beyond the abovementioned high priority barriers, further technological barriers are related to the durability of the fuel cell itself on the truck side[45]. On the HRS side, there is a need to improve the interface communication between trucks and refuelling stations. On the operational side, another important challenge that needs to be addressed is the development and implementation of industry-wide service and maintenance standards, as well as corresponding protocols to allow for efficiency through standardisation.

In addition to the technological barriers, the study identified ten non-technological barriers. These relate to economic, political, social and legal aspects within the hydrogen ecosystem that should be addressed to speed up the commercialisation of FCH heavy-duty trucks:

> **Economic 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 sooner;

> **Political barriers** relate to limited planning security on the 'leading technology of the future' that leads to reservations in business decisions and affects a potentially faster development of the market;

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compromise between 350 and 700 bar technology in terms of cost and functionality. Various technological aspects of different storage technologies, such as pre-cooling, are currently investigated in the PRHYDE project.

[44] The FCH JU-funded PRHYDE project investigates different storage and refuelling technologies and different refuelling protocol requirements for medium- and heavy-duty hydrogen trucks, addressing remaining uncertainties through the development of such standards and protocols.

[45] This aspect is addressed as part of a project currently set up by the FCH JU.

> **Legal barriers** concern the limited harmonisation across European countries within their respective legal and regulatory frameworks, affecting international transport operations due to different regulations, codes and standards (RCS) 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 barriers** consider the limited experience and security concerns on hydrogen technology, both within the concerned industries and among the public, causing hesitation regarding technology acceptance.

Among the identified non-technological barriers, two are considered to have a high need for action to be addressed through targeted political initiatives. First, the lack of adequate financing and funding support for the commercialisation of FCH technologies and components is an important barrier, in particular in the market entry phase. Currently, most available funding and financing instruments are project related and directed at short-term projects. To accelerate the broad adoption of FCH technologies in the heavy-duty truck industry, more long-term programmes and support mechanisms need to be implemented at national and EU level. Existing support schemes are the Connecting Europe Facility (CEF) funding framework and the German National Innovation Programme for Hydrogen and Fuel Cell Technology (NIP II). For example, the CEF funding framework has provided match funds for hydrogen infrastructure for FCH buses. Similar programmes would also provide support for the transport and logistics industry. On the national level, the German NIP II follows a two-sided approach with support for research and development programmes and investment grants to directly target market activation.

Direct CAPEX grants are deemed efficient funding schemes particularly suited to supporting initial market ramp-up. The market potential analysis illustrated that FCH heavy-duty trucks sales will only evolve once better cost competitiveness is achieved. This will only happen through FCH truck production at scale. In the short term, public support will be required to ensure such market uptake, in order to reach scale economies. However, existing public funding schemes often include lengthy bureaucratic procedures. Overall, the regulatory framework for incentive systems needs to be stable, transparent and harmonised on a European level in order to provide funding opportunities along the entire truck value chain. This would cover the production of FCH components and trucks as well as the operation and maintenance of FCH heavy-duty trucks in real-life operations.

Secondly, limited long-term policy commitment and plannability for FCH technology is leading to reservations in business decisions and hindering a potentially faster development of the market. The EU has committed to the decarbonisation of road transport with the goal to reach a 90% reduction in greenhouse gas emission from transport. Policy and industry efforts are set in motion to work on future solutions. However, despite setting binding CO_2 emission targets for heavy-duty trucks, the way forward regarding the technology is still to be defined. FCH technology for heavy-duty trucks is considered one of several viable zero-emission alternatives to diesel. Its advantages are recognised, but due to the limited maturity of the application and the market, it is not yet established as the 'leading technology for road transport of the future'. Different zero-emission technologies see differing levels of political attention, with some players strongly supporting battery technology, and others the development of hydrogen technologies. To improve the overall plannability within the FCH ecosystem, national governments and the EU would need to highlight their specific support towards FCH-based solutions for the transport and mobility industry. Several national hydrogen strategies, e.g. those published by governments in Germany, France, the Netherlands and Portugal in 2020, point in the right direction. Other countries in Europe should follow suit, while the mentioned forerunners need to demonstrate their commitment by implementing what they envision. This would provide orientation for OEMs, component manufacturers and providers of refuelling infrastructure to focus on specific investments and accelerate the development of an FCH heavy-duty truck market.

Further non-technological barriers mostly relate to costs and regulation. Due to FCH technology being a new application for heavy-duty trucks, there still is a lack of long-term and field data on the durability of the trucks. Also, uncertainty prevails regarding the residual value of vehicles. Due to the young age of the zero-emission truck market, with very limited re-sales, there is a general uncertainty as to the residual value of trucks, which creates uncertainty for truck operators when making purchasing decisions. In practice, this will be reflected in higher total cost of ownership calculations for trucks. Moreover, FCH truck leasing contracts, used very regularly by logistics companies, will initially be less favourable compared to diesel trucks. This is because truck dealers need to factor-in the uncertainty on the vehicle's residual value when trucks are returned. However, it is expected that most of the cost-related issues observed today will be resolved through technological advancements and optimisation. Additionally, a de-risking facility that provides a guarantee on the residual value until more data and experience on the market uptake could help overcoming this barrier. Furthermore – as with every emerging technology – the development of the FCH heavy-duty truck industry is currently still constrained by the lack of regulatory structures, such as standardised and efficient truck approval processes or standardised safety procedures.

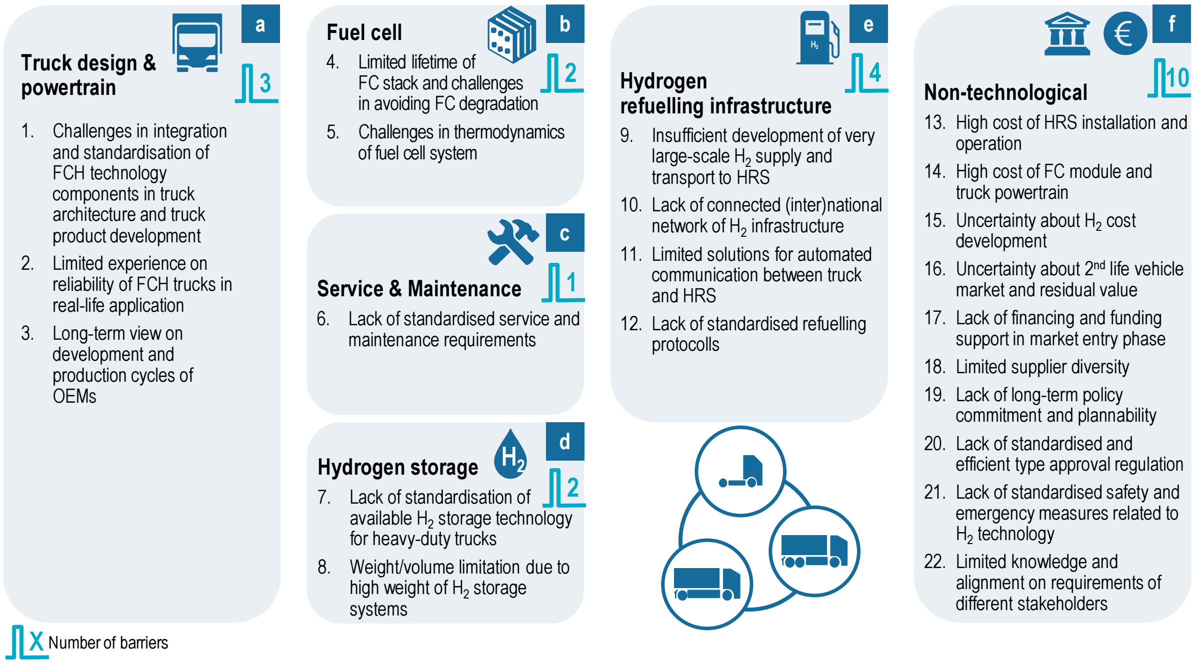

Figure 21: Barriers to FCH technology in the heavy-duty truck ecosystem

The analysis of technological and non-technological barriers demonstrated that there are still challenges to be resolved in order to establish the required conditions for an accelerated FCH heavy-duty truck market uptake. However, it also should be highlighted that none of the identified barriers are roadblocks to further market development. In addition, the analysis identified levers that enable and promote widespread FCH truck deployment. These levers can also act as pillars of orientation for future measures. Firstly, in order to address the chicken-and-egg dilemma of the hydrogen ecosystem, it is imperative for all stakeholders to move along on the same concerted and sequenced timeline. Furthermore, the politically driven decarbonisation agenda should be reflected in industry commitments, in order to align the levels of ambition on both sides. Secondly, stringent and harmonised long-term policy frameworks are needed that are consistent with other policy and industry goals, such as standards on safety, weights and dimensions for heavy-duty transport.[46] Thirdly, financial and funding support mechanisms are required to provide funding and incentives tailored to the needs of the players along the value chain. Both unilateral and multilateral funding is needed in the short term, e.g. for technology

[46] Expert interviews referenced regulation regarding the EU General Safety Regulation as a potentially decisive element for truck dimensions. This could have implications for the available space for alternative powertrains, as it might require adjustments of the installation space in the truck architecture. As such, it might also require a redesign of current truck chassis.

rollouts by multi-partner and potentially international consortia. At the same time, funding for smaller scale projects should become accessible more swiftly at EU and national level.

4.2 Potential synergies of widespread FCH technology implementation

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 buses, taxis, trains, forklifts and ships. Overcoming the barriers for FCH adoption in the heavy-duty trucking industry can result in positive synergies for other industries and vice-versa. Using multimodal synergies along the entire hydrogen value chain creates spill-over effects for the commercial and operational deployment of FCH technology. Five overarching potential synergies were identified that should be explored further to accelerate the implementation of FCH technologies:

- **Decreasing production costs:** Increasing production of FCH components and parts in general generates economies of scale and thereby also contributes to lower production costs for specific FCH HDT components. For instance, volume production of fuel cells for passenger vehicles will positively influence the cost reduction for heavy-duty trucks;
- **Transferring experience:** Existing data on real-life operations and related service and maintenance procedures from other transport applications, such as passenger vehicles and public transport buses, provide valuable insights and knowledge for truck operators and OEMs;
- **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;
- **Optimised production, transport and use 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;
- **Demand for renewable hydrogen:** Increasing the deployment of FCH HDT will increase the demand for renewable hydrogen, i.e. providing a value pool for hydrogen with relatively good cost competitiveness compared to incumbent taxed fossil fuels, in contrast to large-scale industrial use. This would at the same time also decrease the import dependency of other forms of (fossil) energy.

In order to realise the effects of these potential synergies it is necessary to increase dialogue and collaboration across industry sectors and stakeholders within the hydrogen ecosystem. The provision of transparent and long-term regulatory frameworks for various FCH applications within an overarching hydrogen strategy, as for example in the EU Hydrogen Strategy, is crucial. The case study analysis in chapter 3 offered insights on how such synergies could be leveraged in real-life operations:

- 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. This would also have positive effects on the existing HRS, as a capacity utilisation above 80% could reduce the OPEX of HRS by up to 25%;[47]
- Proximity to industrial hubs, such as port operations, large production sites or transport hubs increases chances of multi-partner hydrogen collaborations, as multiple applications could benefit from the eco-system. Moreover, they provide

[47] Information based on industry expert interviews.

access to other hydrogen applications and the respective infrastructure, e.g. rail or maritime transport;

> 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 due to the high potential they provide for the use of HRS, enabling a constant demand for larger amounts of H_2;
> Setting up (mostly regional) hydrogen ecosystems 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;
> Access to renewable energy production or existing H_2 production close to the depot or operations can lead to a facilitated set-up of an H_2 supply chain. This offers the potential of earlier truck refuelling infrastructure availability, as investigated with on-site H_2 hubs for a logistics service provider in France.

In addition, technology know-how spill-over from hydrogen applications in adjacent industries such as passenger vehicles, buses, trains or forklifts can lead to further cost reduction for FCH technology. Another lever lies in optimising FCH vehicle operations. For instance, a higher density of the refuelling station network would offer the possibility of reduced tank sizes, as it enables intra-day refuelling, e.g. during breaks. Moreover, hydrogen supply could be optimised through large on-site electrolysis, lower delivery distances or the supply of refuelling stations through future H2 pipeline networks. This also relates to future developments in the field of hydrogen storage technologies, in particular regarding the different maturity levels of LH_2 and 700 bar storage methods. There is a co-dependency between the development of FCH heavy-duty trucks and the roll-out of refuelling infrastructure (chicken-and-egg dilemma). The current uncertainty on the storage technology to be established impacts both OEMs and infrastructure providers alike, as a change in technology is not easily realised. As a consequence, without industry-wide standards on storage technologies, infrastructure investments will not be made without strong support through public funding.

4.3 Recommendations for research and innovation

Ambitious research and innovation projects can jump-start the transition of the transport and logistics industry to FCH technology. Such projects can be set up in reference to the identified technological and non-technological barriers. As part of a proposed heavy-duty sector R&I roadmap, it is suggested to address the main technological barriers in research & innovation (R&I) projects, while policy recommendations are provided for the non-technology barriers with the highest need for action. Four tailored R&I projects, with an estimated total project budget of EUR 470 million before public funding, are suggested to swiftly address the identified barriers in the short- and medium-term. These projects refer to the technological development and optimisation of 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 demonstrations 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 rollout of FCH heavy-duty trucks and provide a strong foundation for setting standards 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 lifecycle 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.

The suggested R&I projects are designed to ensure a wide scope to potentially also address the identified medium and low priority barriers to FCH truck deployment. Therefore, the projects are ambitious in terms of both size and timeline.

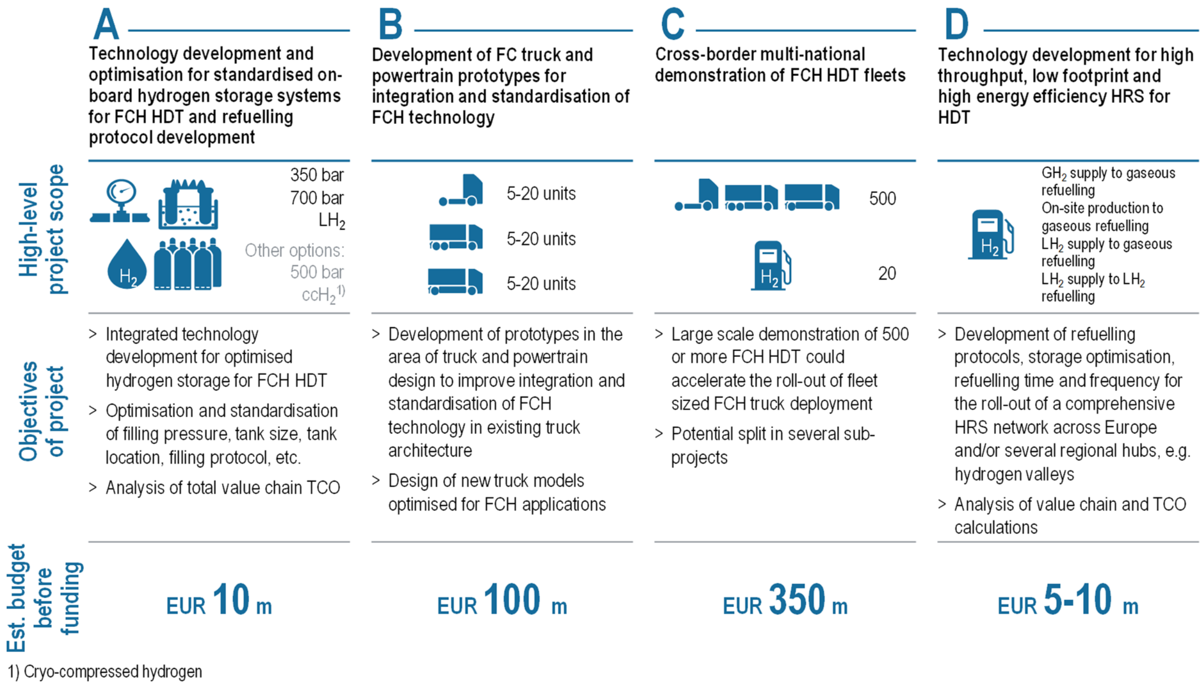

Figure 22: Overview of short-term R&I projects to address high-priority barriers

> **Technology development and optimisation for standardised on-board hydrogen storage systems for FCH heavy-duty trucks and refuelling protocol development (Project A)**

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 stations and vehicles, 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 (e.g. through the FCH JU-funded PRHYDE project), the hardware and technology still need to be optimised for 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.

> **Development of FC truck and powertrain prototypes for integration and standardisation of FCH technology (Project B)**

Integrating FCH technology into the existing truck architecture is a challenge that is being addressed by the industry – OEMs have already developed first FCH trucks. However, further efforts re required in developing more dedicated FCH truck products, with truck models being optimised for FCH application. This project aims to develop 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 of the applied H2 storage systems. In this development process, further standardisation potential will be identified, which will support efforts to bring down the costs of the truck and its components. Involving the OEMs and technology suppliers in this project also contributes to building up a European supply chain of FCH technology components for trucks.

> **Cross-border multi-national demonstration of FCH heavy-duty fleets (Project C)**

Cross-border multi-national large-scale demonstration projects are suggested that include a coalition of multiple stakeholders across the value chain in order to get a high number of trucks on the road (up to 500 trucks to facilitate scale-up scenarios). Creating a project platform linking different industry players and supporting them with the target of bringing 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 an even larger scale. The project could also potentially be split into several sub-projects.

> **Technology development for hydrogen refuelling stations (Project D)**
  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, and 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 within a few hours at the end of the day, with a total of 1 tonne of hydrogen. Research needs to cover HRS adaptations such as HRS size, on-site storage, hydrogen compression, optimisation of energy consumption, performance, throughput and 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 rollout of an HRS network, starting with designated regional hubs, such as hydrogen valleys. Future projects can also build on already ongoing projects like COSMHYC XL or the projected financed under the call FCH-01-08-2019.

In addition, a coordinated interplay of public/private and private/private players is required for a comprehensive transition along the entire value chain of heavy-duty trucks. For example, this can be set out in joint ventures to share business risks when transitioning to this new technology. Furthermore, closer collaboration within the industry is crucial, e.g. through industry platforms. Longer-term contracts between business partners, for example between OEMs and logistics users, could 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 would also result in increased competition, enhanced negotiating power and consequently in lower prices for all involved stakeholders. Furthermore, political initiatives and tailored programmes can provide funding and improve plannability and long-term commitment on the deployment of FCH heavy-duty trucks:

> CAPEX funds for production facilities, e.g. direct financial support, such as cash grants, to set up facilities for new production lines to jump-start the industrialisation of FCH heavy-duty 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 hydrogen life cycle to provide incentives along the value chain. Such programmes were to be set up to cater to the specific needs and challenges of OEMs, parts suppliers, infrastructure providers and logistics users in each country. For example, a de-risking facility that provides guarantees to leasing companies that absorbs the residual value risk and allows them to provide sound financial solutions to FCH truck operators;
> 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 and refuelling capacity)[48].

[48] A successful example of this approach is the Low Carbon Fuel Standard's (LCFS) Hydrogen Refueling Infrastructure (HRI) credit provision programme in California. As of May 2020, this capacity-based funding instrument has supported the deployment of 48 hydrogen stations.

Besides programmes and initiatives that specifically focus on improving cost- and funding-related barriers, the analysis of the identified barriers showed that they should ideally be complemented by concrete policy recommendations. A concerted push on from the European Union, national governments and municipalities is required in order to accelerate FCH HD truck commercialisation.

Figure 23: Overview of concrete policy recommendations

In order to optimise the impact of these proposed instruments, the policy and regulatory framework evolving with the widespread adoption of FCH applications in the transport and logistics industry needs to be synchronised with progress on the technological side.

As demonstrated in this study, FCH technologies and applications have immense potential to set up the heavy-duty transport and logistics industry for a carbon-neutral future. Implementing the suggested short-term R&I projects will help unlock the market potential of FCH heavy-duty trucks by increasing the production of FCH-powered trucks and the comprehensive build-up of the associated refuelling infrastructure networks. Moreover, it will generate and disperse FCH heavy-duty truck specific knowledge and support the development of common standards. A concerted push by a broad coalition of industry and public stakeholders is needed today to deliver on the current momentum. This can be further supported through synergies and spill-over effects of hydrogen applications from other industry segments. By transitioning to FCH heavy-duty trucks in the upcoming years, the transport and logistics industry will embark on a journey towards quiet, clean and innovative mobility solutions in line with the EU's ambitious climate protection efforts and emission reduction targets.

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