JRC TECHNICAL REPORT

Decarbonisation of Heavy Duty Vehicle Transport: Zero emission heavy goods vehicles

Workshop summary report (28 October 2020, JRC Petten, Netherlands)

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Contents

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Abstract

The European Union are committed to achieving carbon neutrality by 2050. Currently, 65-70% of inland freight is transported by diesel trucks, which are responsible for approximately 6% of all EU carbon emissions. As the amount of road freight is expected to increase by 55% by 2050, the decarbonisation of heavy-duty road transport is crucial to the EU. Heavy duty vehicles are known to be a particularly difficult sector to decarbonise because of the technical challenges accompanying their demanding mission profiles. To investigate these challenges, the JRC hosted an online workshop titled "Decarbonisation of Heavy Duty Transport: Zero Emission Heavy Goods Vehicles" on 28 October 2020. The workshop focussed on technologies that can lead to full decarbonisation of the sector, including being zero-emission at point of use. This included three technology options, hydrogen fuel cell trucks, battery electric trucks and catenary-powered electric trucks. None of these technologies have achieved the level of deployment that has been reached for smaller, short-range transport vehicles.

The workshop was structured into four sessions. Session 1 considered the Policy framework in which these technologies will need to operate. Session 2 reviewed the Technical Readiness of each of the options and their associated infrastructure. Session 3 contained Techno-economic Assessments and Life Cycle Analyses comparing the economic and environmental considerations respectively. Finally, Session 4 was a Panel Discussion involving a range of relevant stakeholders, aimed at reviewing the day's events, and at reaching conclusions and recommendations for the future approach towards implementation of these technologies.

This report summarises the presentations and discussions from the workshop, supplemented with relevant literature information. Ultimately, it aims to compare and contrast the technical, economic and environmental aspects of the aforementioned technologies and to provide recommendations for policy makers regarding the approach necessary for ensuring decarbonisation of this challenging sector within the necessary timelines.

Executive summary

With the 2030 Climate Plan, the EU has set a target for 2030 to achieve at least a 55% reduction in net greenhouse gas emissions (compared to 1990 levels) in order to be on a path to becoming climate neutral by 2050. To meet these targets the decarbonisation of road transport, including heavy-duty road transport, is key. While alternative drivetrains are already being deployed for light duty trucks, heavy duty trucks are harder to decarbonise because of the technological challenges that accompany their demanding mission profiles, in particular for long ranges.

JRC held a workshop covering technologies that aim at full decarbonisation of the sector, including being zero emission at the point of use. This report is the outcome of that workshop combining information from presentations given at the workshop with supplementary information provided by the authors.

For long distance heavy goods vehicle transport, there are three main competing technologies: hydrogen fuel cells, batteries and catenary-powered electric vehicles. The workshop was organised as a single day, online event. 145 attendees registered for the event, with a steady audience throughout the day of approximately 90-100 attendees. The workshop was structured into four sessions. Session 1 considered the Policy framework in which these technologies will need to operate. Session 2 reviewed the Technical Readiness of each of the options and their associated infrastructure. Session 3 contained Techno-economic Assessments and Life Cycle Analyses comparing the economic and environmental considerations, respectively. Finally, Session 4 was a Panel Discussion involving a range of relevant stakeholders, aimed at reviewing the day's events, and at reaching conclusions and recommendations for the future approach towards implementation of these technologies

The purpose of the workshop was to consider which of the options has the highest potential environmental benefit, identify challenges (and solutions) for these technologies and consider the infrastructure developments that will be needed in each case. The programme focussed on the Technical Readiness and the Life Cycle Assessment (LCA) of each of the technologies.

During the workshop it was discussed why Heavy Duty Trucks are particularly hard to decarbonise: key challenges for the vehicles are the weights, volumes and mission profiles that are involved, alongside the infrastructure requirements. Current regulations encourage the uptake of Zero Emission Vehicles whilst remaining technology neutral concerning the different options available. There are clear pros and cons for each technology based on the degrees of technology readiness (of both the trucks and infrastructure), economic considerations and environmental impacts. Significant challenges for Fuel Cell Electric Trucks (FCET) involve the space requirements around storage of hydrogen and the durability/lifetime of the fuel cells. A network of Hydrogen Refuelling Stations (HRS) is required and hydrogen compression is a major cost. Further work regarding refuelling protocols and hardware is needed. Battery Electric Trucks (BET) currently experience limitations based on the size and weight of the battery required, which induces a loss of payload. They require long charging times and have limited range. A network of high power charging points is necessary that may lead to grid capacity bottlenecks. The major challenge for Catenary Electric Trucks (CET) is the large-scale infrastructure requirements.

Estimated infrastructure costs for full EU coverage appear to be similar for both BET and FCET. Infrastructure costs are higher for CET. There were conflicting opinions represented regarding which technology is cheapest for Total Cost of Ownership (TCO).

From the environmental perspective, direct electricity use is favourable over conversion to hydrogen, due to the greater efficiency of direct use. When considering greenhouse gas emissions, the electricity mix and source of H_2 are crucial. In general though, LCA studies seem to suggest CET to have lower CO_2 emissions that BET, with FCET higher still. However, all were an improvement on diesel internal combustion engines (ICE). These improvements are enhanced by increased use of renewable energy sources (RES) for electricity production, coupled with electrolysis for hydrogen production. It should be noted that for certain environmental indicators (Human Toxicity Potential and Abiotic Resource Depletion) BET and FCET technologies are predicted by LCA to have a greater negative impact than diesel ICET until at least 2030.

Therefore, based on the information provided during the workshop and additional literature research performed by the authors, it seems likely that no one single ZE technology solution will be able to cover all mission profiles on the 2050 timeline. Direct electricity use (either through battery electric trucks or catenary/pantograph) is likely to be the best environmental option, however BET are limited by weight and range, whilst catenary is limited by infrastructure costs. Therefore, FCET will be needed to fill the gaps for the longest range and heaviest loads, in particular to remote locations. Furthermore, whilst it may be appropriate

to maintain the technology neutral approach for the trucks themselves, a coherent, coordinated approach to infrastructure will be necessary in order to maximise roll-out and achieve climate emission goals.

Policy context

The EU has set a target for 2030 to achieve at least a 55% reduction in net greenhouse gas emissions (compared to 1990 levels). To meet these targets, emissions from the transport sector will have to be reduced significantly. About a quarter of EU road transport emissions come from heavy duty vehicles, which, in turn, account for some 6% of total EU carbon emissions. Regulation (EU) 2019/1242, adopted in 2019, was the first EU-wide regulation setting CO_2 emissions standards for HDVs. The Regulation requires tailpipe emissions from the four hardest to decarbonise truck categories[1] to be cut by 15% by 2025 and by 30% by 2030 compared to 2019 levels. Complementary regulations and mobility packages include: the 2016 Clean Energy Package, the 2016 European Strategy for low-emission mobility, the Clean Vehicles Directive (2019), the Batteries Initiative, the Alternative Fuels Infrastructure Directive and the Eurovignette Directive.

Key conclusions

The workshop sought to provide some answers to the fundamental question of which ZEV technology will be most feasible, economically and practically, at decarbonising HDV road freight transport. Currently, the EC has adopted a technology neutral approach to allow the different technologies to develop and compete against each other. At some point, however, some technologies may begin to win over others and a choice may have to be made in order to provide investment certainty. It is highly unlikely that a single ZE technology solution will be likely to cover all mission profiles. Direct electricity use (either through battery electric trucks or catenary/pantograph) is the best environmental option, however BET are limited by weight and range, whilst catenary is restricted by infrastructure costs. FCET will be needed to fill the gaps for the longest range and heaviest loads, in particular to remote locations. During the workshop it was stated that public investment is needed in order to achieve the 2030 and 2050 emissions targets, in particular to support establishment of the minimum required refuelling and recharging infrastructure. Furthermore, whilst it may be appropriate to maintain the technology neutral approach for the trucks themselves, a coherent, coordinated approach to this infrastructure development will be required in order to optimise the roll-out and achieve climate emission goals. Participants also mentioned the need for a coherent policy framework, particularly regarding carbon pricing.

Main findings

The main parameters driving the choice of a powertrain are technology readiness, operational requirements, costs and life cycle environmental impacts. The current technical strengths and weaknesses of the three technologies considered are presented within this report. For FCET, the volume required for onboard hydrogen storage, and the durability of FC stacks are two significant issues specific to the technology. For BET, weight and range are potential limitations, whilst challenges exist concerning speed of charging and grid bottlenecks. For CET the major challenge is associated with infrastructure development and cost. The results of analyses related to cost and life cycle environmental impacts are highly sensitive to assumptions. Technologies change rapidly and many processes in the life cycle of zero-emission vehicles (e.g. lifetime) are still subject to a high level of uncertainty. Therefore, it is often difficult to compare different studies. Based on the information provided during the workshop, JRC recommends that future environmental assessments should include the impacts of the infrastructure required for different powertrain configurations.

Related and future JRC work

The JRC has a long-standing collaboration with EUCAR and CONCAWE aimed at providing the scientific input regarding the greenhouse gas emissions of powertrain technologies and fuels. In the latest update of the JEC Well-to-Wheels (WTW) report, HDVs have been included for the first time. The WTW greenhouse gas emissions of seven powertrain configurations for regional and long-haul HDVs are compared, including hydrogen and battery electric vehicles. JRC is also active in work on HDV CO_2 baseline estimates, which are determined through VECTO, a tool developed by the European Commission. JRC is also actively supporting the implementation of the HDV CO_2 certification regulation.

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[1] Vehicle Groups 4,5,9 and 10. Groups 4 and 9 are rigid trucks (trucks with a single rigid chassis), whereas Groups 5 and 9 are tractor-trailer trucks with an articulated chassis. These four groups accounted for almost 80% of all medium and heavy commercial vehicles-sales in 2018

Quick guide

As set out in the European Green Deal, the EU is committed to achieving carbon neutrality by 2050. To this end, the decarbonisation of road transport, including heavy-duty road transport, will be key. While alternative drivetrains are already being deployed for light duty trucks, heavy duty trucks are harder to decarbonise because of the technological challenges that accompany their demanding mission profiles, in particular for long ranges. JRC held a workshop covering technologies that can lead to full decarbonisation of the sector, including being zero emission at the point of use. For long distance heavy goods vehicle transport, there are three main competing technologies: hydrogen fuel cells, batteries and catenary-powered electric vehicles.

The purpose of the workshop was to consider which of the options has the highest potential of environmental benefit, identify challenges (and solutions) for these technologies and consider the infrastructure developments that will be needed in each case. The emphasis of the programme was to consider the Technical Readiness of each of the technologies and to consider Life Cycle Assessment aspects.

1 Introduction

1.1 Motivation for the Workshop

As set out in the European Green Deal, EU member states are committed to achieving carbon neutrality by 2050. To this end, the decarbonisation of road transport, including heavy-duty road transport, will be key.

Today, large lorries account for 65% to 70% of all CO_2 emissions from heavy-duty vehicles. Diesel lorries are a class of vehicles responsible for about 6% of all EU carbon emissions [1]. Indeed, in 2018, 85.4% of EU road freight transport (tonne-kilometres) was transported by vehicles with a maximum permissible laden weight of over 30 tonnes [2]. Moreover, road freight transport is expected to increase by 33% by 2030 and 55% by 2050 [3].

While alternative drivetrains are already being deployed for light duty trucks, heavy duty trucks are harder to decarbonise because of the technological challenges that accompany their demanding mission profile, in particular for long ranges. It has been shown that the distance class 500-1000 km is responsible for the greatest share of freight transport (tonne-kilometres) [4] and these are a key sticking point for the decarbonisation of road freight transport.

The future of freight transport will not only involve replacing diesel with cleaner alternatives, but may see a shift of freight to other modes of transport such as rail, shipping and perhaps even a reduction in demand for long-range road transport by moving production of goods closer to the point of demand. Notwithstanding these considerations, current forecasts show that road freight transport is here to stay and will even increase in volume. The EU envisions at least 80,000 zero-emission lorries in operation by 2030 and nearly all new HDVs to be zero-emission by 2050 [5].

Biofuels will be an option, as they can be renewable and can be used with existing combustion engines and refuelling infrastructure with minimal alterations. While biofuels can contribute to carbon neutrality as long as they are produced in a closed loop life cycle, we do not consider that they will be the main long-term solution for HDV as the supply of sustainable biofuels is limited and priority will likely be given to their use in even harder-to-decarbonise transport sectors such as shipping and aviation.

This workshop considered only technologies that can lead to full decarbonisation of the sector, including being zero emission at the point of use. For long distance heavy goods vehicle transport, there are three main competing technologies: hydrogen fuel cells, batteries and catenary-powered electric vehicles[2]. However, none of these have reached the deployment stage yet in the same way as smaller zero-emission short-distance transport has. All three technologies have high vehicle and infrastructure costs, so to date the EC has undertaken a technologically neutral approach to allow each technology to develop sufficiently before determining the most effective technology in terms of techno-economic considerations and potential for decarbonisation. It seems clear that a cohesive, pan-European strategy is needed, so the solution must be one that can be effectively deployed across Member States and even beyond.

The purpose of the workshop was, therefore, to consider which of the options has the highest potential of environmental benefit, identify challenges (and solutions) for these technologies and consider the infrastructure developments that will be needed in each case. The emphasis of the programme was to consider the Technical Readiness of each of the technologies and to consider Life Cycle Assessment (LCA) / Well-to-Wheel (WTW) studies of the options. Furthermore, the relative costs of each technology option and the associated infrastructure requirements were considered. The aim of this report is to summarise and supplement the output of the workshop in order to elucidate the techno-economic and environmental factors that will underpin the decisions made by policymakers and to indicate the strengths and weaknesses of each technology.

1.2 Format of the Workshop

The Decarbonisation of Heavy Duty Vehicle Transport workshop was organised by JRC Unit C.1 (Energy Storage) as a single day, online event. There were 145 attendees registered for the event, with a regular audience throughout the day of approximately 90-100 attendees. A detailed agenda is provided in Annex 1.

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[2] As hydrogen internal combustion engines and e-fuels are not zero-emission, they were not included in the scope of the workshop.

The workshop was divided into four sessions:

- Session 1: Introduction/Policy Context
- Session 2: Technology Readiness
- Session 3: LCA/WTW Studies and Techno-economic Assessment (TEA)
- Session 4: Panel Discussion and Conclusions

Session 1 began with an introduction from Paul Hodson, (Head of Unit, JRC.C1 Energy Storage, European Commission), who explained the motivation for the workshop. This was followed by presentations on the Policy Context of the workshop, providing a broad overview of the policy landscape, the background and motivation for decarbonisation of heavy duty road transport and an outline of the current CO_2 emissions standards for the transport sector with a focus on HDVs, with presentations from Claire Depré, Head of Unit at DG MOVE and by Carlos Serra, Policy Officer at DG CLIMA.

Session 2, Technical Readiness, covered the zero emission technology options for the decarbonisation of HDVs, focusing on Hydrogen Fuel Cell Electric Trucks (FCET), Battery Electric Trucks (BET) and Catenary Electric Trucks (CET) and the infrastructure required to operate them. Presentations were given by Jaime Sanchez Gallego from CNH Industrial on FCET, Erik Nellström from Scania on BET and Armin Sue from Volkswagen on the CET 'electric road' option.

Session 3 provided an overview of techno-economic assessments, life cycle assessment (LCA) and well-to-wheel (WTW) studies for each of the three technologies, comparing each technology to the incumbent State-of-the-Art and considering other liquid fuel options. Presentations were given by Nikolas Hill from Ricardo, Reinhold Wurster from LBST, Matteo Prussi from JRC.C2 (Energy Efficiency and Renewables), Steven Wilkins from TNO and finally, Andrew Kotz from NREL (USA).

Session 4 was a panel discussion reviewing the technology readiness of each of the three options: their feasibility, their practicality and their associated infrastructure costs. Furthermore, the results of the LCA studies were discussed, comparing the potential for reduction in greenhouse gases of each technology and other environmental impact factors.

The workshop ended with a concluding statement from Paul Hodson. After a short break, parallel networking sessions were then opened for attendees and presenters to interact if they so wished in a more relaxed environment.

Presentations from the workshop were uploaded to the Workshop website after the event[3].

1.3   Report of the Workshop

This report will summarise the events and discussions of the workshop event supplemented with additional information from external sources.

Conclusions will then be drawn regarding the status of the various technology options and recommendations for future steps to underpin decisions by policy makers.

Throughout the document, the authors have attempted to make it clear what is generally accepted as fact, and what is the opinion of the presenters at the workshop. In particular, where there has been disagreement between speakers, or where contradictory data has been presented this has been indicated. In the Technical Readiness chapter, where significant points were not addressed within the presentations, the authors have performed their own supporting research to provide supplementary information. These sections are provided in blue text boxes.

1.3.1   Contributors and their Affiliations

As mentioned above, the report is based on the presentations provided by a number of contributors who are experts in their field and supplemented by the authors' own opinions/knowledge and additional information

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[3] https://ec.europa.eu/jrc/en/event/workshop/heavy-goods-vehicles-workshop

obtained from the literature. The authors of this report have tried wherever possible to make a clear distinction between factual statement and the opinions of contributors. Furthermore, it was the intention that a fair balance would be found between proponents of the different technologies and between representatives of the public and private sectors. However, for the sake of transparency, this section provides an overview of the contributors and their affiliations.

Session 1: Policy

Introduction: Paul Hodson, JRC. Head of energy storage at the European Commission's Joint Research Centre.

Policy Context: Claire Depré, DG MOVE (European Commission). Head of Sustainable and Intelligent Transport Unit.

Policy Context: Carlos Serra, DG CLIMA (European Commission). Policy Officer, Road Transport Unit.

Session 2: Technical Readiness

FCET: Jaime Sanchez Gallego, CNH/Iveco. Head of Advanced Engineering

BET: Erik Nellström, SCANIA. Product Property Manager for Product Sustainability at R&D

CET: Armin Sue, Volkswagen. Project Manager, Catenary Trucks.

Session 3:

LCA: Nikolas Hill, RICARDO. Associate Director / Knowledge Leader in Transport Technology and Fuels

LCA: Matteo Prussi, JRC (European Commission). Researcher, Sustainable Transport Unit.

LCA: Andrew Kotz, U.S. Department of Energy National Renewable Energy Lab (NREL). Commercial Vehicle Research Engineer.

TEA: Reinhold Wurster, LBST. Senior Consultant (techno-economic and strategic evaluation of hydrogen and fuel cells in transportation applications)

TEA: Steven Wilkins, TNO. Senior Research Scientist (Electrified Powertrains).

Session 4:

Panellists:

Nikolaus Steininger, DG CLIMA, (European Commission). Senior Expert, Road Transport Unit.

Pietro Caloprisco, Fuel Cells and Hydrogen Joint Undertaking, Project Officer.

Rolf Döbereiner, AVL. Project Line Manager Commercial Vehicles.

Armin Sue, Volkswagen (see above)

Nikolas Hill, RICARDO (see above)

Thomas Fabian, European Automobile Manufacturer's Association (ACEA). Director Commercial Vehicles.

2   Policy Context

2.1   Introduction

This section will outline the directives, regulations and targets set for the decarbonisation of heavy duty vehicles by 2050. Presentations at the workshop were given by Claire Depré (Head of Unit for Intelligent Transport Systems, DG MOVE, European Commission), who gave a broad overview of the policy landscape, background and the motivation for decarbonisation of heavy duty road transport; and Carlos Serra (Policy Officer at DG CLIMA, European Commission) outlined the existing emissions legislation for HDVs and the regulatory steps to be taken in the future. This section is an amalgamation of both presentations, with most of the referenced data coming from Carlos Serra's presentation.

The EU has committed to achieving net-zero emissions by 2050, to meet the objective of the Paris Agreement of limiting the global temperature increase to well below 2°C and to aim to keep it to 1.5°C [6].

The target for 2030 to achieve at least a 40% reduction in net greenhouse gas (GHG) emissions (compared to 1990 levels) will be updated to 55%, as proposed by the European Commission (EC) in the European Green Deal (EGD). The EC is also set to include the 2030 Climate Target Plan into the European Climate Law, which aims to enshrine in EU law the commitments set out in the EGD.

Proposals to update sectoral legislation will be ready by June 2021. Among the many sectors, the Fuel Quality Directive, Trans-European Networks (TEN-T, TEN-E) and Alternative Fuels Infrastructure Directive (AFID, 2014/94/EU) are to be updated; heavy duty vehicle CO_2 standards are not expected to be under revision for 2021.

2.2   Current CO_2 emissions legislation for HDVs

EU transport emissions increased by 25% between 1990 and 2018 and continue to increase, with 21% of total EU carbon emissions in 2017 coming from road transport [1]. About a quarter of these road transport emissions come from heavy duty vehicles, which account for about 6% of all EU carbon emissions [1]. Despite recent improvements in fuel consumption efficiency, HDV CO_2 emissions continue to rise, mostly due to the increasing volume of road freight traffic [1].

Binding emissions targets for passenger cars and vans have existed since 2012 and 2014, whereas specific categories of HDVs covering a majority share of the HD-related emissions, have started to be regulated for their CO_2 emissions and fuel efficiency recently: The Regulation (EU) 2019/1242, adopted in 2019, was the first EU-wide regulation setting CO_2 emissions standards for HDVs. The regulation set targets to reduce the average emissions of new trucks from four of the hardest to decarbonise truck categories (outlined in the following section) that are responsible for 65-70% of all heavy duty road transport emissions. The Regulation would require average tailpipe emissions from these four categories to be cut by 15% by 2025 and by 30% by 2030 compared to 2019 reference levels. The regulation focuses on tailpipe emissions as calculated using the VECTO simulation tool [7] and the methodology laid out in Regulation 2017/2400 for simulating CO_2 emissions and fuel consumption of whole heavy-duty vehicles [8]. The regulation incentivises the uptake of zero- and low-emission vehicles in a technology neutral way, as manufacturers have the flexibility to balance emissions between different vehicle groups - even including non-regulated ZEV categories [9].

Complementary regulations and mobility packages include: the 2016 Clean Energy Package, the 2016 European Strategy for low-emission mobility, the Batteries Initiative, the Clean Vehicles Directive (2019) [10], the Alternative Fuels Infrastructure Directive [11], the Eurovignette Directive [12], the revision of the Energy Taxation Directive [13], the Renewable Energy Directive [14], the Fuel Quality Directive [15], and the EU Emissions Trading System [16].

2.3   How are HDV CO_2 emissions regulated?

Regulation (EU) 2019/1242 has made it mandatory since 2019 for OEMs to monitor and declare their CO_2 emissions for all newly EU-registered trucks produced under certain categories using the VECTO simulation tool and to be certified accordingly under type-approval certification legislation [8].

The regulated truck groups shown in Table 1 below are responsible for around two thirds of total HDV CO_2 emissions, hence they are the focus of current CO_2 emissions standards for HDVs (Regulation (EU) 2019/1242). Note: the full list of truck categories and classes are provided in Annex 2.

Table 1: HDV groups included in Regulation 2019/1242 and their axle and chassis configuration.

Vehicle group	Axle and chassis configuration	Without trailer
4	4x2 Rigid	
5	4x2 Tractor	
9	6x2 Rigid	
10	6x2 Tractor	

Source: CO₂ emission standards for heavy-duty vehicles, DG CLIMA (presentations) [17], [18]

Groups 4 and 9 are rigid trucks (trucks with a single rigid chassis), whereas Groups 5 and 9 are tractor-trailer trucks with an articulated chassis (a chassis with a pivot joint between the tractor and the trailer). There are also multiple types of axle configurations. The regulated truck groups have a technically permissible maximum laden mass (TPMLM) greater than 16 tonnes, or trucks with a 6 x 2 axle configuration for all TPMLMs. These four groups accounted for almost 80% of all medium and heavy commercial vehicles-sales in 2018 [19].

2.4 Incentive mechanisms

The Regulation imposes a target on each manufacturer. Manufacturers can meet their targets by increasing the efficiency of the trucks they sell, and/or by selling ZEVs and LEVs[4]. A ZEV counts as two vehicles and an LEV counts as up to two vehicles (depending on its specific emissions and other thresholds) towards achieving the manufacturer's specific CO_2 target, until 2024 [20]. The scope of the incentive is technology neutral. A 'low emission heavy duty vehicle' is defined as a vehicle with tailpipe CO_2 emissions at least 50% below the reference CO_2 emissions from its vehicle sub-group [21].

To avoid undermining the CO_2 emissions targets, the super-credits earned can be used to lower a manufacturer's average emissions by no more than 3%.

ZEV/LEV vehicles such as small trucks and other heavy duty truck categories that are not yet included in the regulation may contribute to the incentive, however ZEV buses and coaches are excluded.

From 2025 onwards, the super-credits system will be replaced with a bonus-only crediting system based on a 2% benchmark of the ZEV/LEV fleet. A manufacturer's specific CO_2 emissions target will be relaxed by one percentage point for each additional percent of ZEV/LEV exceeding the benchmark, subject to a cap.

The ZEV/LEV incentive mechanism is to be reviewed in 2022.

2.5 Governance Provisions

The 2019 CO_2 emissions reference baseline will be reviewed in 2022, to ensure that it is not inflated i.e. to ensure that the introduction of too many default components into VECTO do not lead higher than actual CO_2 certification values. To this end, criteria will be set for determining undue increases and how they should be corrected.

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[4] FCETs, BETs and CETs count as ZEVs.

In order for the CO_2 targets to be effective in bringing down real world emissions, the results from the type approval certification procedure (VECTO simulation tool) must be representative of real world emissions. To prevent an increase in the gap between real-world and certified emissions, the EC will assess by 2027 a mechanism to adjust the manufacturer's average CO_2 emissions for 2030 [22]. Type approval certification will be validated by monitoring of in-service vehicle CO_2 emissions. Financial penalties will be applied in case of non-compliance with the CO_2 emissions targets. The penalties are set at €4,250 €/gCO_2/tkm from 2025 to 2029 and €6,800 €/gCO_2/tkm from 2030. These penalties will incentivise the uptake of ZEVs, as they are above the marginal cost of meeting the targets [1].

2.6   Future Developments

In 2022, the EC will assess the effectiveness of the Regulation (Art 15 – Reg 2019/1242), reviewing five main topics: current CO_2 emissions targets, ZEV/LEV incentive mechanisms, bio and e-fuels, the VECTO simulation and certification tool and the extension of the scope of CO_2 emissions performance standards to other heavy-duty vehicle categories.

The CO_2 emissions targets for 2030 will be reviewed, with possible targets for 2035 and 2040 also being considered. The review may propose targets for other types of heavy-duty vehicles that are not yet regulated, such as smaller trucks, vocational vehicles, buses, coaches and trailers [8]. New CO_2 emissions reduction binding targets for 2025 and beyond will also be discussed (depending on HDV categories).

The VECTO certification tool will be reviewed and updated to include buses, coaches, smaller trucks and vehicles with electrified powertrains (pure and hybrid electric). Regarding VECTO certification of hybrid electric vehicles, CO_2 emissions pertaining to the amount of time spent in charge depletion mode (pure electric driving), or charge sustaining mode (pure conventional fuel driving), will be included, as well as electric consumption, electric driving range and the utility factor (ratio of distance driven in electric driving mode to the total distance driven) [23], [24].

The decarbonisation potential of renewable bio- and e-fuels, including hydrogen, will be assessed, taking into account life-cycle assessment (LCA) considerations and the possibility of CO_2 credits for manufacturers.

Apart from the Regulation (2019/1242), there will be a review of the 2014 Alternative Fuels Infrastructure Directive (AFID) in 2021. The review is expected to improve financial instruments to encourage the more rapid development of charging and refuelling infrastructure, amongst other strategies [25].

2.7   Main Issues at stake

Keeping in mind the goal of decarbonising road transport by 2050, the different options available need to be assessed for their potential impact and effectiveness.

An assessment of whether bio and e–fuels can contribute significantly to the decarbonisation of road transport is needed, considering the supply of raw materials and the demand from other sectors in a decarbonised global economy. Renewable synthetic fuels may only make sense if production costs can be reduced and sustainability issues resolved.

Regarding competing modes of transport, it remains to be seen how trucks perform versus rail and to what extent long-haul operation will be relevant for trucks. Cross-cutting studies are needed on how to align ZEV design, infrastructure and renewable hydrogen and electricity production.

Currently, the EC has adopted a technology neutral approach to allow the different technologies to develop and compete against each other [1]. At some point, however, some technologies will have to win over others and a choice may have to be made in order to provide investment certainty. Crucially, the chosen solution will have to be scalable across the European Member States and globally. The Hydrogen Valley projects within main EU corridors have shown potential for scaling up of a hydrogen economy, showing a way forward for the rest of Europe and possibly for the rest of the world [26], [27].

2.8 Conclusions

Considering the current technology state-of-art, clean hydrogen seems to be crucial for the decarbonisation of heavy-duty vehicles, though the adopted technology neutral approach remains. From a policy perspective, a toolbox of different instruments and a wide range of regulatory and non-regulatory measures are necessary to ensure the uptake of zero-emission technologies and to achieve a fully decarbonised road transport sector by 2050. Carlos Serra emphasised that "Zero and low carbon technologies need to be kick-started immediately" if we are to meet the targets.

The Review of the HDV CO_2 emissions standards Regulation by 2022 will only be the beginning as the regulatory elements will need continuous adjustments as technologies develop.

3 Key Performance Indicators

This section highlights a number of Key Performance Indicators (KPIs) and the corresponding state-of-the-art (SoA) values for each technology that will be relevant to the following sections, particularly to Section 4 on Technical Readiness. The majority of the values in the table have been taken from the FCH 2 JU Roland Berger study "Fuel Cells Hydrogen Trucks: Heavy-Duty's High Performance Green Solution" [31], unless otherwise indicated. The range of values given for each parameter reflects the wide ranging technical profiles of currently available commercial vehicles; many models are still in the prototype or pre-commercial phase and these will be discussed in later sections.

Table 2: KPI SoA values for FCETs, BETs and CETs

Parameter	Unit	FCET SoA	BET SoA	CET SoA
Truck type		rigid & tractor 6x4; rigid & tractor 4x2	rigid 6x4; tractor 6x4	6x4 tractor[1] 4x2 tractor[2]
System power	kW	208-745	355-536	350[1]; 130[2]
GCWR	Tonnes	34-64	26-47	40
Average range per charge/ refuel	Km	350-1,250	120-400	65-160[1]; 15[2]
H_2 consumption	Kg H_2/ 100 km	5-9		
Energy consumption	kWh/ 100 km	168 - 302[3]	100-140	88-147[1]; 120[2]
Battery Energy density (cell level)	Wh/kg		90-260[4]	
Battery capacity	kWh	56-120[5]	200-550	115-200[1]; 18.5[2]
Fuel cell power	kW	88-240		
System weight*	kg	800 – 3,647[6]	~1,250 – 4,216[7]	
Refuelling/ charging time	minutes	6-40	90-390	51[1]; 8[2]
H_2 storage pressure	bar	350; n/a		
System lifetime	years		5	5
Vehicle costs	EUR	n/a	140k-180k	158k-188k[1]

Source: Values taken from [31] unless otherwise noted.

Notes: (1) Non-hybrid (pure electric) (2) Diesel-hybrid with electric engine only (3) Calculated using 33.6 kWh/kg and H_2 consumption above. (4) Values from [32]. (5) Higher capacities up to 280 kWh are being considered for hybrid systems (6) Values calculated using assumptions from [32], see Annex 3 for calculations. (7) Values taken from [33]. *BET and FCET system weights not directly comparable as values correlate to the Average range per charge/ refuel given above)

4   Technical Readiness

The scope of the Technical Readiness session was to consider the technology / technical readiness and challenges and to give an overview of the maturity of the technology, the KPIs and the major technical bottlenecks of the three zero-emission technology options: Hydrogen Fuel Cell Electric Trucks (FCETs), Battery Electric Trucks (BETs) and Catenary Electric Trucks (CETs) and their relevant infrastructure.

Three presentations were given, each focusing on one of the technologies. Jaime Sanchez Gallego (CNH Industrial) focused on FCETs, covering the technical challenges of adapting the vehicle architecture to fit a FC system and hydrogen storage. Hydrogen storage and hydrogen refuelling technology options were compared including cost considerations. Erik Nellström (Scania) focused on BETs, considering their technical readiness, climate impact reduction potential, cost considerations and charging infrastructure challenges. Armin Sue (Volkswagen) discussed CETs and the relevant infrastructure, which is known as the Electric Road System (ERS). Sue analysed the potential of the ERS for reducing emissions on a few heavily-used freight transport routes in Germany; Sue described the ERS, compared it to the other ZEV options and discussed the advantages and costs of the necessary catenary infrastructure. The session concluded with a Q&A, chaired by Eveline Weidner (JRC).

This chapter is structured as follows: section 4.1 covers FCET technological considerations made by Sanchez Gallego (CNH Industrial); section 4.2 covers the BETs as presented by Nellström (Scania); section 4.3 covers the CET/ERS option presented by Sue (Volkswagen).

The sections are based on the presentations, with some supporting references. Where the authors thought it would benefit the discussion, some additional information has been added in text boxes.

4.1   Hydrogen Fuel Cell Electric Truck (FCET)

This section is based on the presentation delivered by Jaime Sanchez Gallego (CNH Industrial) on Hydrogen Fuel Cell Electric Trucks (FCETs). The main topics of discussion in the presentation were the evolution of the vehicle architecture for accommodating the hydrogen storage and fuel cell system, the hydrogen storage options, refuelling protocols available for HDVs and the hydrogen distribution chain. A section was included on polymer electrolyte fuel cell (PEMFC) stack challenges, which was not discussed in detail during the workshop, but was deemed an important aspect to include. Further important points were made in the Panel Discussion (Chapter 6) by Pietro Caloprisco (Project Officer at FCH 2 JU) about the challenges of compression technology at hydrogen refuelling stations and the lack of durability of fuel cell (FC) stacks. Finally, an overview of the current best-performing commercial FCETs is given as supplementary information to the reader, outside of the scope of the workshop. Additional information has been drawn from external sources throughout the section to supplement the content of the presentation.

4.1.1   Evolution of Vehicle Architecture

Evolving from a conventional articulated chassis of an ICE (internal combustion engine) vehicle to an electrified powertrain requires significant changes that are challenging and expensive. The vehicle architecture must be adapted to fit a fuel cell module, batteries and tanks for hydrogen storage. These modifications take up a significant share of the vehicle volume which present challenges for the turning radius and overall length of the truck, as well as compatibility with standard ISO trailers. Other challenges include the electrification of components and thermal management.

4.1.2   Hydrogen Production and Distribution

An ongoing study by CNH Industrial identified two main possible hydrogen delivery pathways. Hydrogen can either be produced via electrolysis from renewable and/or zero-emission primary energy sources (wind, solar, hydropower, biomass, nuclear), or via steam reforming of fossil-fuels[5].

After production, for the distribution path for CGH_2, hydrogen is transported as a compressed gas in tube trailer trucks and finally arrives at the HRS where it is stored. At the refuelling station, hydrogen is transferred

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[5] The authors would like to add that the distribution paths of CGH2 and LH2 are independent of the production method and that steam reforming is also possible with renewable (but non ZE) sources such as biomass.

from a low pressure compressed gas (CG) storage unit via a compressor to a high pressure CG storage unit from which the customer can refuel. These compressors have a high energy demand to bring the hydrogen to the required pressure level. A precooling system for the gas is needed for the CGH_2 pathway, adding complexity and increasing the energy consumption.

For liquid hydrogen (LH_2), the process involves liquefaction, transportation in liquid form to the refuelling station where it is stored as a liquid. LH_2 is then either dispensed in liquid form, or more commonly regasified, compressed and dispensed as CGH_2.

In terms of TCO, the cost of hydrogen is identified as the main challenge.

4.1.3 Hydrogen Storage Options

Hydrogen storage presents one of the main challenges to the development of FCETs due to the volume required to accommodate hydrogen storage tanks which could otherwise be occupied by the payload. In addition to this, storage options can be costly due to the materials (i.e. carbon fibre) required for compressed gas cylinders, or the complex technology required for insulating to maintain low temperatures for cryo-compressed and liquid hydrogen. Since freight transport companies operate under narrow margins and HDVs cannot exceed the legal dimensions permitted for their particular class, space and volume optimisation are key for making FCETs attractive to these businesses. Figure 1 shows the location and volume of the hydrogen storage system of a FCET design by CNH industrial.
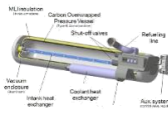
Figure 1: Hydrogen Storage system for FCET
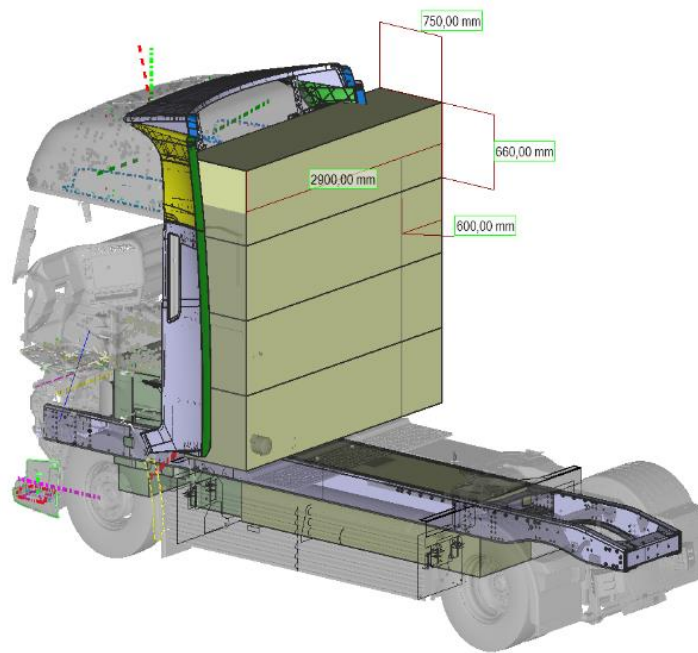
Source: presentation by CNH Industrial [34]

The main ways of storing hydrogen are as compressed hydrogen gas (CGH_2), cryo-compressed gas or liquid hydrogen (LH_2). Table 3 compares these four options.

Table 3: Hydrogen storage options for HDVs[6]

	Compressed H2 350 BAR	Compressed H2 700 BAR	Cryo Compressed H2	Liquid H2
Max storage pressure	350 bar	700 bar	300 bar	4 to 6
Volumetric Density (including BoPs)*	16 g H2/L of Tank	27 g H2/L of Tank	40 g H2/L of Tank	36 g H2/L of Tank
Maturity (status Aug 2020)*	Very Mature	Very Mature	Prototype	Mature for other applications (Aerospace)
Cost Estimation 2025	reference	+10% €/kg H2	-	-35% €/kg H2

Source: presentation by CNH Industrial [34]

Additional information – Hydrogen Storage

CGH2 tanks are made of carbon fibre reinforced plastic wrapping with an internal liner made of either metal (Type 3) or polymer (Type 4). Type 4 tanks are lighter, cheaper and more durable with repeated cycling than Type 3 tanks, but they have relatively low thermal conductivity which can pose difficulties with fast refuelling as gases release heat when compressed, potentially damaging the liner [35]. For this reason refuelling protocols have been designed to ensure that the tank does not overheat (see section on hydrogen refuelling below). To achieve a range of 800 km, on-board storage capacities >40 kg are needed for FCET. In the future, long-haul HDVs could opt for 700 bar compressed hydrogen storage systems (CHSS) in order to decrease tank volumes. However, the costs for hydrogen will increase due to the additional energy demand for compression.

For LH2 tanks, a key issue is boil-off. The tanks are not perfectly insulated and hydrogen evaporates easily, so to prevent pressure building up inside the tank some hydrogen gas is allowed to escape (this is known as "boil-off"); this can be greater than 5% per day [36]. Research is underway to decrease hydrogen losses due to boil-off [37].

For commercial automotive applications, compressed gas hydrogen (CGH_2) tanks are currently the most technologically mature and economically viable options. CNH Industrial has been working with cylinder manufacturers on composite material technology to protect the cylinder in the event of a crash and to improve its resistance to UV light that can damage the composite. Liquid hydrogen is still being developed for road transport applications, although it is mature for other sectors such as aerospace. Liquid hydrogen technology can store more than double the amount of hydrogen than a 350 bar tank and relative costs are projected to be cheaper by 2025 than 350 bar compressed hydrogen, as noted in Table 3. Cryo-compressed hydrogen is still in the prototype phase; it has, however, great potential as a hydrogen storage technology, given it has the highest volumetric density of all the options, but first technological complexities need to be solved.

A heavy-duty vehicle needs about 7 to 8 kg[7] of hydrogen per every 100 km driven, which will require several large volume storage tanks, depending on the pressure level (see also text box above). The main challenge for hydrogen storage in heavy-duty vehicles is the space-efficiency. Cylindrical tanks which are optimal for pressure management are, however, not ideal for vehicle volume (or Balance of Plant) exploitation, considering all the other components that need to be included such as hydrogen valves, pressure reducers and insulation.

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[6] According to SAE J2601, the volumetric density is given as CGH2 700 **24.6 g/L**; CHG2 350 bar **18.5 g/L**
[7] In literature other ranges are given, for example 5-9 kg/100km [31].

For heavy duty applications, 700 bar compressed hydrogen cylinders are a promising option, since the technology is mature and it has a sufficiently high volumetric density to make it acceptable for long-haul operation. In the long-term, liquid (or cryo-compressed) hydrogen may be the better option as it has an even higher volumetric density and costs less per kilogram of hydrogen; but liquid hydrogen technology is less mature for road transport applications, even though it is well-established in other sectors such as aerospace.

Additional information – PEM fuel cell stack challenges

According to the recent study by Roland Berger, fuel cells for this application have challenges to overcome in terms of lifetime and optimisation of the integration. In general, the powertrain should have low weight and dimensions, while reducing cost and increasing reliability. There are also issues with the thermodynamics of fuel cell system to be addressed. HGV have a power requirement of up to 300 kW, but FCH systems still need to be scaled up to this level [31].

For the hydrogen industry association Hydrogen Europe, key challenges are, at fuel cell stack level, improvements in terms of performance, durability and reliability. Durability is closely linked with the platinum loading on the electrocatalyst, which, however, greatly increases the cost; efforts are ongoing to optimise the linked parameters of lifetime, high power density and platinum loading. By 2030, stack lifetime should be 30.000h, stack costs drop to <50EUR/kW and PGM loading decreased to <0.3g/kW. Among the fuel cell system technology challenges improving HDV system manufacturability is also mentioned [38].

4.1.4   Hydrogen Refuelling

Liquid hydrogen has also been deemed promising for long-haul HDVs, as it enables longer range driving; however, the storage technology is still in the prototype phase and no refuelling protocols have been established. Cryo-compressed hydrogen is also still at the prototype stage and the appropriate refuelling protocols and infrastructure will still need to be developed. For both 350 and 700 bar compressed hydrogen, the hardware and protocols are available but more work is needed in order to adapt these to FCET applications (see Annex 4 for an overview of existing refuelling protocols).

The hardware and protocols for liquid hydrogen refilling stations for HDV applications are still under discussion. Liquid hydrogen requires slightly longer refilling times, but its high volumetric density means that it requires fewer refilling stops.

Additional information – Liquid hydrogen refuelling infrastructure

Liquid hydrogen refuelling infrastructure has the potential to be cheaper than CGH2 and so could be a viable option in the future, but a significant number of liquefaction plants would have to be built. The main drawback of LH_2 is the significant energy loss through the value chain due to the energy needed for liquefaction and the energy lost through hydrogen boil-off. However, liquid hydrogen is increasingly being considered a viable option for HDVs as demonstrated by the agreement signed by Linde and Daimler Truck AG to collaborate to develop LH_2 refuelling technology [39]. The energy demand for compression at the HRS is much lower than that for the CGH2 pathway, and the gas does not need further precooling. Therefore LH_2 refuelling stations require fewer components which lower the capital and operating costs relative to CGH_2 HRS.

4.1.5 Summary: Technology Challenges

The range of FCETs is affected by the volume of hydrogen that can be stored and by the efficiency of the fuel cell. The fuel cell efficiency is expected to improve with the technology as has occurred for other FCEV. Payload may be compromised by the volume taken up by hydrogen storage, so solutions to store sufficient amounts of hydrogen will need to be found. Another challenge is the refuelling time. The main TCO (total cost of ownership) driver is the cost of hydrogen, especially for long haul missions, but this should come down as hydrogen becomes more widespread.

During the Panel Discussion (Chapter 6), Pietro Caloprisco (FCH 2 JU) highlighted the importance of developing and standardising refuelling protocols and hardware for HDVs, as OEMs need certainty in order to scale up production. In the long term, it remains to be seen whether CGH2 or LH2 will prevail, as although CGH2 is currently more technologically mature and widespread, LH2 could significantly reduce hydrogen on-board storage costs. Compression technology is already a major technological challenge for CGH2 refuelling infrastructure and even more so for scenarios requiring high flow refuelling and thousands of tonnes being dispensed every day [31].

Another challenge mentioned by Caloprisco was the adaptation of PEM fuel cell stacks for HDVs. Durability is a crucial limiting factor for automotive use of PEMFCs: 5000 hours of operation has been demonstrated for LDV use cases, but HDVs will require at least 30,000 h of operation [40] (see textbox above).

Additional information – Overview of current FCETs

IVECO and FPT Industrial, the commercial vehicle and powertrain brands of CNH Industrial, have teamed up with Nikola Motor Company to produce the Nikola TRE. Production of the BEV version is expected to commence in 2021, while the FCEV version will be tested under the EU-funded H2HAUL project for an expected market launch in 2023 [41].

The FCEV version of the Nikola Tre truck will come in 6x4 or 6x2 configurations with a maximum total power of up to 750 kW and a range of 500 -1200 km. The truck will have a 120 kW fuel cell and 800 V dc batteries. Production is expected to commence in 2023 [42].

Hyundai Motor Company is ahead of the curve having already delivered its first XCIENT Fuel Cell trucks to customers in Europe in October 2020 and intends to bring FCETs to the US and China too. From 2021, Hyundai plans to produce as many as 2,000 trucks a year. The XCIENT fuel cell truck features a GVW of 18 tonnes, and a 4 x 2 rigid body configuration [43].

4.2 Battery Electric Truck (BET)

This section is based on a presentation by Erik Nellström from Scania on battery electric trucks (BETs). During the workshop, Nellström described the climate impact reduction potential of BETs (based on an LCA study conducted by Scania), the potential energy and cost savings for the consumer and the charging infrastructure that is needed. Their study considers two types of BETs: one for urban distribution (rigid 6x2) and one for long haul operation (4x2 tractor with trailer). Their study only accounted for the vehicles not the impact from box or trailer production. The LCA findings and climate impact reduction potential are covered in Section 5.2 on Life Cycle Assessment and the cost considerations are included in the Techno-Economic Assessment in Section 5.1. Some additional information was provided in the presentation by Steven Wilkins from TNO, as indicated where appropriate.

4.2.1 Evolution of Truck Architecture

Batteries replace the space that would have been occupied by a combustion engine and extra batteries are mounted on the chassis frame. At present, truck manufacturers are likely to modify existing models and convert them for an electric propulsion system. Further optimisations are likely to be made once the production volumes increase [44]. Steven Wilkins from TNO presented the following potential evolution: For the 1st generation of electrified trucks these would be largely based on conversion of existing platforms to include electric powertrain. The placement of components and systems would be based around on practical integration design decisions. For the 2nd generation of electrified trucks, higher levels of integration of the electric powertrain within the truck would take place. More significant charging capabilities should be present. These design would see the inclusion of integrated e-axle technologies and higher degrees of optimisation. Optimisation frameworks to balance between topology, sizing, and control are to become important methodologies [45]. For the 3rd generation electrified trucks, there will be clean sheet design for the truck, with optimised placement of battery pack and innovations in terms of transmission, improved topology and sizing of components.

4.2.2 Battery Design and Performance

In order to perform the LCA study, Scania makes assumptions concerning the battery capacity and the performance of the electric powertrain. The capacity is assumed to be 700kWh for long haulage BET. The currently offered BET model with 9 Li-ion batteries has a capacity of 300kWh[8] [46]. For the LCA the BET energy consumption is set at 130kWh/100km.

Additional information – Battery Design and Performance

Most BETs have battery capacities that range from 200-550 kWh, with average range per charge varying from 120-400 km [31]. As shown in the KPI table in Section 3, battery weights range between 2 and 7 tonnes, taking up a significant share of the truck's GVW [47] Nonetheless, this issue is somewhat compensated by the additional ZEV weight allowance (2 t) granted under the EU Weights and Dimensions Directive [48] and overall savings due to replacing a conventional with an electric drivetrain, which could be up to 2.4 t [33]. Furthermore, advancements in battery energy density are expected to reduce the weight of the battery; a 2020 study by Ricardo forecasts battery energy density to increase to 0.318 kWh/kg by 2030 compared to 0.183 kWh/kg today [49].

4.2.3 Charging Infrastructure

In order to ramp up the necessary infrastructure there should be a focus on fast charging using interoperable solutions between trucks and buses. The use of existing standards (OCPP 1.6 and IEC-61851 / 15118) should be encouraged. For higher power levels the following options exist:

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[8] Scania see these as two quite realistic LCA examples but are currently working at refining the LCA. Thirdparty verified LCA will be made publicly available during the first half of 2021 for Urban Distribution and subsequently for all new BEV introductions.

- Depot charging (50kW)

- Continuous/Dynamic charging (50-100kW)

- Opportunity charging (150-200kW)

- Fast Opportunity Charging (300kW+)

A big challenge facing BETs is that they will not be able to cover all the monthly daytrips that an ICE truck will, due to a combination of reduced range and payload due to the size of the battery as well as longer charging times. An indicative study by Scania has identified the number of days of missing mileage over the course of a total of 20 daytrips when replacing an ICE diesel (4x2) truck with a BEV truck with a range greater than 400 km. Unsurprisingly, almost all (data is not available to the public) BETs of all ranges will accrue missing mileage over the month; this could pose a challenge for customers, who operate within tight margins. Scania proposes the development of a smart located mega-charger network, so that trucks can charge during legally required breaks.

Additional information – Charging Infrastructure

Deploying millions of BETs by 2030 and 2050 (as set out in EU targets) comes with major challenges for charging infrastructure. According to one study, a single truck charge of 1 MWh, at a charging power of 1 MW (fast charging), draws as much power as 2500 houses [47]. Such high power demand would require increasing the electric grid capacity significantly. The challenge is further illustrated when considering that today in the EU there are 4.5 million trucks; if all were to be battery-powered, the total electricity demands would equate to 324 TWh, or just over 10% of the total EU electricity generation in 2015 [47]. In order to avoid overloading the electricity grid infrastructure, smart management of charging infrastructure will be needed. Overnight charging will likely provide most of the charging for the BET and will likely be the cheapest option, but may not be feasible for large capacity batteries which may require more than 10 hours to recharge when connected to an AC charger [50]. Crucially, fast-charging stations will require the scaling up of transformers and connection to the medium voltage grid which will incur high capital costs, especially as the medium-voltage grid is expensive to scale up and is typically only used by industry. Moreover, the cost of connection scales with distance from the infrastructure [51].

Additional information – Overnight versus Opportunity Charging

According to EU rules, truck drivers are legally required to take 30 minute breaks every 4.5 hours. Assuming an average speed of 80 km/h, a driver can expect to cover 360 km between mandatory breaks. A high power mega-charger (1.2 MW) is capable of charging a range of 400 km for the long-haul BET within 30 minutes. Similarly, a high-power rapid charger (600 kW) can provide a range of 200 km for regional delivery BETs in 30 minutes. Overnight chargers with a power rating of 150 kW and 75 kW can fully charge the long-haul and regional BETs, respectively, in 8 hours [33]. Currently, trucks are restricted to charging overnight and during lunch breaks at the depot, due to challenges with establishing a network of fast chargers.

4.2.4 Summary: Technology Challenges

According to Wilkins (TNO), research and development is needed regarding the battery size and weight. In order to increase the power density, different battery chemistries should be explored. Battery lifetimes need to be increased in order to reduce costs. In general the range and performance of BET should be improved, and the adaptation of vehicle architecture brought forward.

Building up a network of recharging (fast charger) stations will be crucial to accelerate the deployment of BETs. Incentives will be needed to encourage the uptake of BEV technology, including financial support to cover the cost of supporting an overcapacity of charging infrastructure, until a sufficient number of BEVs are deployed. The reverse situation is seen as untenable, as BETs will not be able to operate without the necessary infrastructure.

Another recommendation is to solve the grid capacity bottlenecks before BETs become widespread. Providing the power needed to these charging stations may be challenging in some locations. While the deployment of BETs may only increase the annual electricity consumption by 1–3%, the necessary charging infrastructure would most likely overwhelm local grids near logistics centres and rest stations along major roads unless grid capacity were sufficiently scaled up [52]. Grid capacity bottlenecks could pose a significant challenge especially given the high power demand for BET.

According to Scania, the current technology is ready to be deployed and the climate impact of the technology is on the decrease. There are still certain technical challenges but no showstoppers, even for long haulage applications. The main takeaway provided by Nellström was that it is more an infrastructure and correct CO_2 pricing challenge than a vehicle technology challenge. Incentives are needed to make BEVs more cost-competitive for customers and policies to encourage the development of the charging infrastructure. However, Scania would prefer longer term incentives, for example a CO_2 price via the ETS or a broad fossil fuel carbon tax for the sectors outside of the ETS, than short term incentives. This is because they state that long term market mechanisms are needed for the transport sector to decarbonise in a cost effective way for both customers, OEMs and society.

Additional information – Overview of current BETs

Currently, no commercial BETs exceed 500 km range on a full charge. Most commercial BET models have a range of 400 km per charge and have gross vehicle weights ranging from 7.5 tonnes to 30 tonnes making them most appropriate for regional and urban delivery. A handful of models (such as the Freightliner eCascadia, Tesla Semi, Xos ET-One and Peterbilt 579EV[1]) have GVWs between 35-40 tonnes, with ranges on a single charge between 300-500 km; however, these are all still under development.

Scania launched its first range of electric trucks in 2020 with an installed capacity ranging from 165 kWh (5 battery packs) with 130 km range, to 300 kWh (9 packs) with a maximum driving range of 250 km [53]. The biggest truck has a maximum GTW of 29 t.

BYD offers a wide range of all-electric trucks, including the heavy-duty BYD 8TT. The truck has a GTW of 48 t, a battery capacity of 435 kWh, and a driving range of 200 km at full-load and 270 km when half-loaded.

The battery electric Nikola TRE is a 4x2 tractor for regional missions, with a range of up to 400 km [54] . It features a modular battery system with a total capacity of 720 kWh which can be modified to suit customers' needs. The powertrain will deliver 480 kW power output with 1800 Nm peak torque. 2- and 3-axle rigid versions with GVW ranging from 18 to 26 tonnes will also be available.

Tesla unveiled its BET (Tesla Semi) in 2017, and the first deliveries are expected for 2021. The payload capacity of the truck is 36 t and two driving range options will be available: 480 km and 800 km, with an advertised energy consumption lower than 125 kWh per 100 km.

Other BETs that are expected to hit the road in the near future are the eCascadia from Freightliner (37 t GTW, 400 km range, and usable capacity up to 475 kWh), T680E from Kenworth (37 t GTW, 240 km range).

4.3   Catenary Electric Truck (CET) & eHighway System

This section is based on a presentation by Armin Sue from Volkswagen, who described the catenary electric vehicle option, also known as the eHighway or Electric Road System (ERS). Demonstration projects were carried out in Germany, hence the focus on its role in decarbonising German road transport.

The German Environmental Ministry (BMU) awarded funding to Volkswagen AG Group Innovation and Siemens Mobility GmbH for the development of "e-highways" on three major German roads in partnership with Scania and Erneuerbar Mobil.

4.3.1   Motivation

One fifth of all German carbon emissions come from traffic and one third of these are from road transport. Despite their small number of vehicles, heavy-duty transport have a significant impact on road transport emissions. As can be seen in Figure 2, the class of trucks weighing 40 tonnes are small in number and yet are responsible for the greatest share of German road freight transport CO_2 emissions.

Figure 2: Graph comparing the mileage, CO_2 emissions and number of vehicles for different classes of truck by weight.
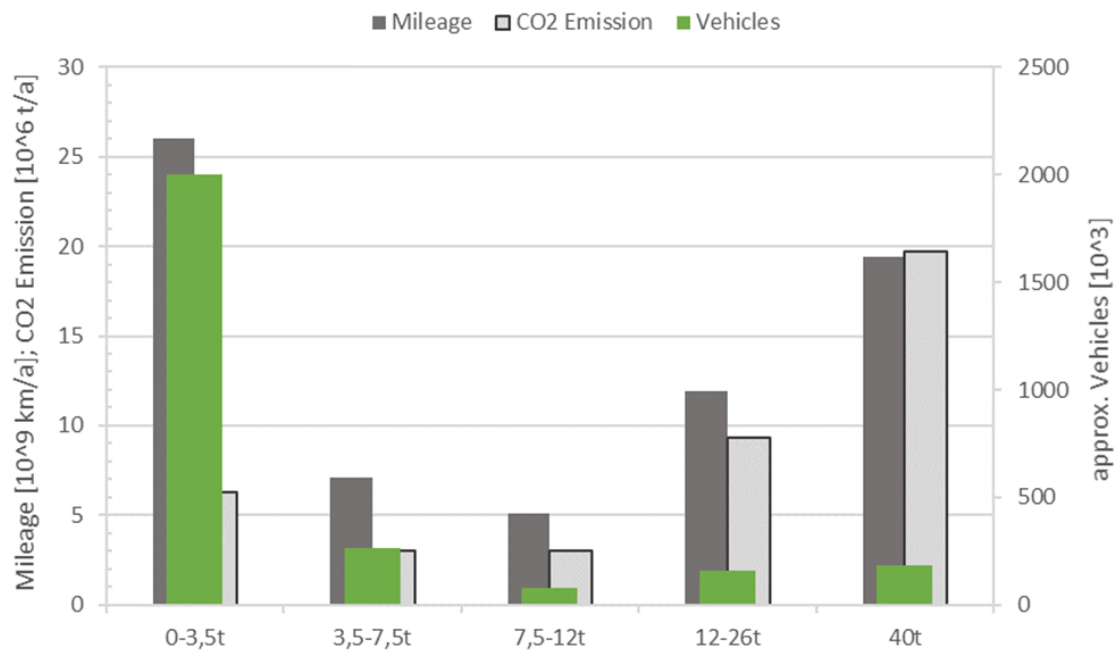
The catenary or eHighway option presents an alternative, technologically mature option for HDVs: using the electrical power from the overhead catenary lines removes the need to store a lot of energy on-board the truck itself. This means the truck has a smaller battery that weighs and costs less and is only required for instances where there are gaps in the infrastructure, for example, driving from the depot to the eHighway or in an urban environment. The main challenge for CEV technology is the infrastructure, which would entail the necessary catenary lines to be built and maintained.

4.3.2 About the Technology

The core principle of the catenary electric truck (CET) design is a pantograph (see Figure 3) combined with a hybrid electric drivetrain. Trucks equipped with the system draw electricity from the overhead catenary lines along the eHighway to power their traction motors and charge their batteries [56]. CETs are equipped with a small battery along with a hybrid engine to enable autonomous driving when not connected to the eHighway. The system can be configured in a number of ways to suit operational requirements: serial or parallel hybrid systems with a combustion engine or fuel cells can be used, as well as purely electric drives with a range of battery capacities. Note: only fuel cell hybrids or pure electric satisfy the scope of this workshop/study, however hybrid systems with a combustion engine are likely to be a transition technology in the short term.

The eHighway boasts an efficiency of 80 to 85 percent from substation infeed to wheel [57]. Regenerative breaking can either recharge the battery or be transmitted back to the catenary, further improving the energy efficiency of the system.

Two types of Scania trucks with different strong electrified powertrains are being tested in the demonstration project. Real drive tests will be carried out on all three German test roads and a sustainability analysis and strategical outlook will be carried out.

Figure 3: Current Prototype Vehicle

Source: Presentation by Volkswagen. Original figure from Scania. [34]

4.3.3 eHighway System

Crucially, catenary-pantograph technology is a well-established technology that has been used in the railway industry for a long time.

The whole system consists of the vehicle, the power supply, the driveway and the operation. Each of these subsystems are comprised of other subsystems:

- **Vehicle:** pantograph, drive system, energy storage (small battery), control system
- **Power supply:** substation, contact line
- **Drive way:** infrastructure (roads), Traffic management.
- **Operation:** Maintenance, Traffic Management (SCADA[9])

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[9] SCADA is an acronym for 'supervisory control and data acquisition', a computer system for gathering and analysing real time data. SCADA systems can be used as a traffic management system for eHighway operation.

4.3.4 Hybrid Powertrain for eHighway Trucks

The powertrain requires only a very small battery – the Scania trucks used in the project had an 18 kWh battery. A dc/dc converter is needed to convert the power from the catenary lines from about 670 V to the voltage level of the truck and an ICE is included to fuel the engine in cases where the truck is not connected to the overhead line. Figure 4 illustrates the powertrain layout.

Sue stated that the hybrid drivetrain enables the optimization of carbon emissions reduction, costs and weight. This flexibility reduces the negative impact on the customers' logistics and allows trucks to drive in electric mode in urban areas. In the future, with more catenary infrastructure, a pure battery truck can be the base vehicle for this technology.

Figure 4: Schematic Powertrain Layout
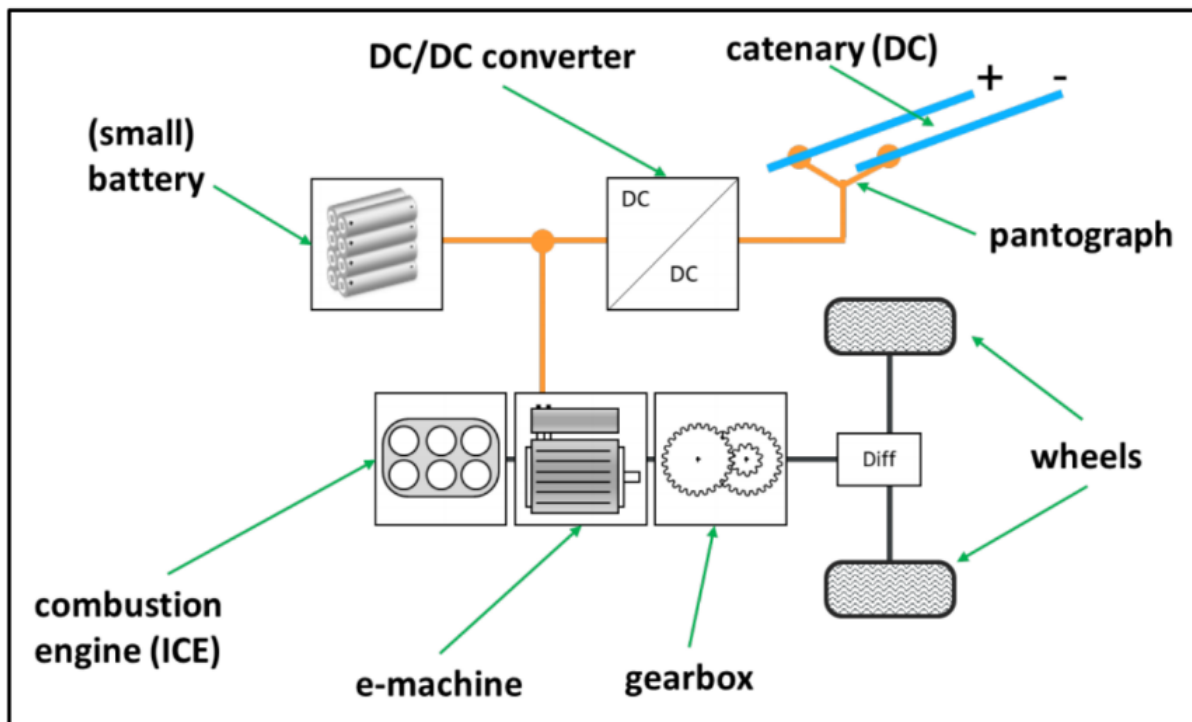
Source: Presentation by Volkswagen. Original figure from Scania [34]

4.3.5 Infrastructure Considerations

An analysis of the road network by the Institute for Energy and Environmental Research in Heidelberg identified that 60% of HDV emissions stem from 2% of the German road network (about 12,000 km) and that the most intensely used routes, covering about 4,000 km, handle 60% of all tonne-kilometres travelled in Germany. Figure 5 illustrates the routes with the highest emissions (routes with the highest average number of journeys per road segment are shown in darker red). Hence, a significant reduction in CO_2 emissions is possible by focusing on the most intense traffic routes.

Figure 5: Analysis of Road Network
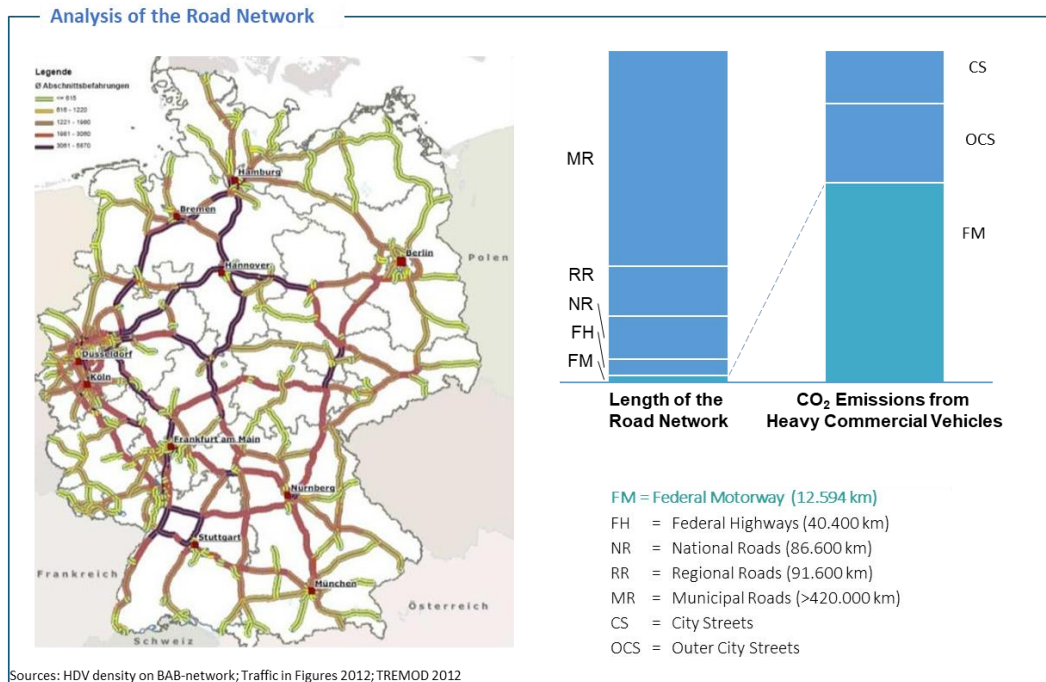
Sources: Presentation by Volkswagen, based on "HDV density on BAB-network ; Traffic in Figures 2012; TREMOD 2012"

According to a study by Strategy& (PWC), if all HDVs on European highways were replaced with CETs, catenary infrastructure would have to be built along 21,500 km of roads. In comparison, if all European trucks were replaced with BETs, the necessary Point-of-Supply infrastructure would entail 1,400 high power charging stations. A similar scenario for FCETs would require 920 HRSs [58].

The optimal eHighway coverage for a 35 t long haul type II truck (260 kW EM, 74 kWh gross capacity) would be between 40 and 60% of the route, as visualised in Figure 6.

Figure 6: eHighway overhead wire (OW) coverage for long haul scenario
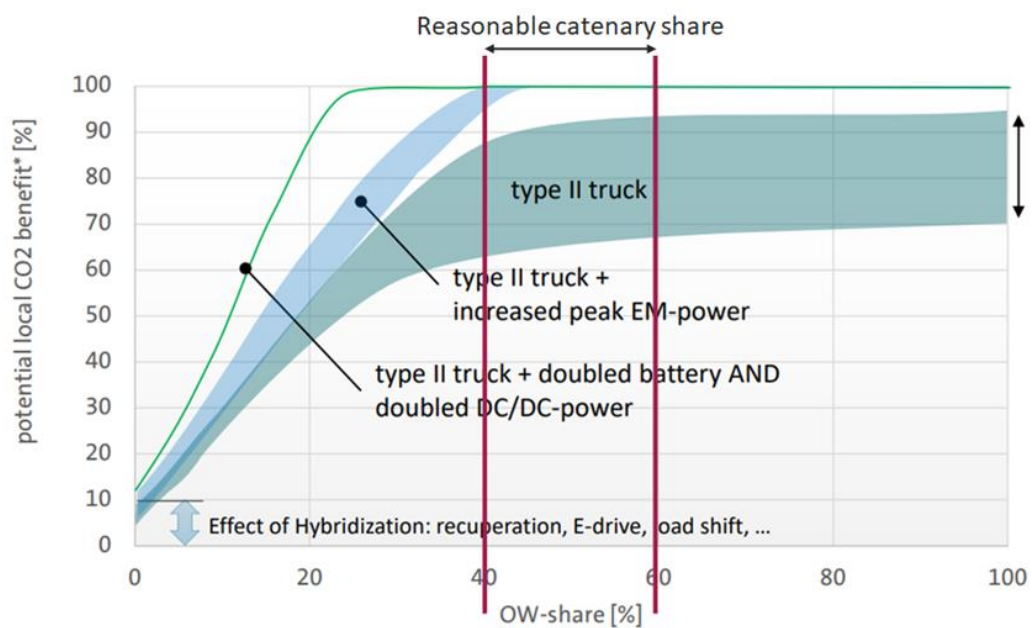
Source: Presentation by Volkswagen [34]

4.3.6 Future Considerations

As for the other technologies, the eHighway infrastructure is a key aspect of the technical and economic feasibility of the technology. Studies have yet to be carried out regarding how to optimise the infrastructure in terms of length and position to achieve decarbonisation without incurring too much cost and how it would be rolled out across Europe. European standardisation of components will be needed if the technology is to be scaled up. More LCA studies are needed as the concept is still relatively new and the possible infrastructure impact on the grid is not yet clear. Other concerns include voltage safety and finding the optimal nominal voltage.

5   Techno-economic Assessment (TEA) and Life Cycle Assessment (LCA)

The third session was devoted to the environmental, technical and economic assessments of the different zero-emission HDV technologies and their infrastructure. The session was envisioned to provide support in the decision-making process regarding the HDV technology/technologies to adopt in the transition towards a zero emission future.

Five presentations were given: two focusing on techno-economic aspects, and the rest on the environmental impacts. For the techno-economic analyses: Reinhold Wurster (LBST) talked about the potential ramp-up of FCETs; and Steven Wilkins (TNO) presented more generally the challenges and opportunities for highly electrified HDVs. For the environmental analyses: Matteo Prussi (JRC) gave an overview on the latest update of the JEC[10] Well-to-Wheels report (v5); Nikolas Hill (Ricardo) presented an LCA comparison of powertrain technologies and fuels; and Andrew Kotz (NREL) focused on the life cycle implications of zero-emission HDVs. Each presentation concluded with a Q&A, chaired by Jonathan Davies (JRC).

This section of the report is structured as follows: in 5.1 the main techno-economic considerations highlighted by Wurster (LBST) and Wilkins (TNO) are reported; in 5.2 the environmental assessment results presented by Prussi (JRC), Hill (Ricardo) and Kotz (NREL) are reported; finally, a discussion regarding the outcomes of this session is provided in section 5.3. The consistency with the economic and environmental considerations presented in the technical readiness session (e.g., LCA study performed by Scania) is also discussed.

5.1   Techno-Economic Assessment

As Wilkins (TNO) introduced in his presentation, electric trucks need to be mature to sell at volume in the market by 2030 if we want to reach the ambitious GHG goals set by the EU. Considering that the typical development cycle for vehicles is 5-7 years and that the adoption curve can be even more gradual, research and development must be accelerated over the next few years to have the technology ready by 2025-2030.

The question then becomes, which zero emission technology should we prioritize in the route to upscaling?

Wilkins (TNO) and Wurster (LBST) seem to agree that not a single technology, but diversification should be the way forward. Wurster (LBST) envisions a future where BETs are used for short-range logistics in moderate climate, dedicated fleets of CETs serve high frequency point to point relations, and FCETs that could in principle serve all applications, given their versatility. In the array of technologies, Wilkins (TNO) includes the plug-in hybrid electric trucks (PHETs) with a hydrogen internal combustion engine as a bridging solution that will be gradually replaced with FCETs and BETs as fuel cell and battery technologies improve further. Wurster (LBST) predicts that FCETs will be more cost-effective than PHETs by 2030. The advantage of PHETs in the short term is the flexibility in terms of refuelling/recharging (with the disadvantage of requiring two infrastructures at the depots), and the more moderate technological step from ICEVs.

Wurster (LBST) sees the ramp-up of FCETs as inevitable. LBST's analyses identify the following advantages compared to other zero emission technologies: lower total cost of ownership (TCO), longer operating range, comparable payload to diesel, faster refuelling, better flexibility in logistics, cheaper infrastructure requirements, and better integration into the energy transition landscape through the decoupling storage function of H_2.

As for the costs, according to the study from Neuhausen et al. [58] cited by LBST, FCETs guarantee the lower cumulative infrastructure investments needed for the ramp-up stage. The results of their analysis are summarized in Table 4. The installation of the 920 hydrogen refuelling stations needed to provide a complete coverage of Europe with sufficient capacity would cost 29.4 billion euros. The refuelling station considered can refuel 100 trucks/day with 80/100 kg H_2 per refuelling. The cost of installing 1,400 high power charging stations to cover the same area would be slightly higher (29.5 billion euros). However, the investments into stationary electricity storage for system integration are not included in this instance. The infrastructure investment needs for a complete coverage of Europe for catenary trucks would be much higher: the installation of 21,500 km of catenary network would cost approximately 50% more (44.1 billion euros). In their study, Neuhausen et al. [58] also assessed the investment needs to enable pan-European trips (area-

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coverage network): in this case, a FCET network would require significantly lower investment (0.6 billion euros compared to the 2.5 billion euros for BETs and 36.2 billion euros for CETs).

Table 4. Cumulative infrastructure investments per ramp-up stage of the different electric truck powertrains

Cumulative Infrastructure Investments per ramp-up stage		BEV Truck	FCEV Truck	CEV Truck
Pilot Network	Pilot projects with focus on areas with high traffic (> 100.000 HDT annually)	0.7 B€ (35 HPCs)	0.6 B€ (20 HRSs)	2.7 B€ (600 km)
Area Coverage Network	Complete coverage of Europe as a consistent network	2.5 B€ (120 HPCs)	2.2 B€ (70 HRSs)	36.2 B€ (21,500 km)
High-demand Network	Complete coverage of Europe with sufficient capacity	29.5 B€ (1,400 HOCs)	29.4 B€ (920 HRSs)	44.1 B€ (21,500km) With more converter stations (increasing capacity)

Source: Presentation by LBST [34] based on Neuhausen et al. [58]

In line with these numbers, Neuhausen et al. [58] estimated a TCO for FCETs in 2030 of 0.65 €/km, slightly lower than the 0.68 €/km for BETs, and significantly lower than the 0.79 €/km for CETs and the 0.95 €/km for trucks running on synthesised Power-to-Methane ($PtCH_4$) or Power-to-Liquid (PtL) fuels. In the assessment, TCO included fuel/electricity cost (including infrastructure), maintenance cost, and the depreciation of vehicles. The fuel costs were assumed to be 6.8 €/kg H_2, 0.29 €/kWh$_e$, and 2.3 €/L PtL, respectively. The renewable electricity demand from well to wheel considered for the different powertrain options (rigid 12t truck) are reported in Table 5, where it can be seen that FCETs and $PtCH_4$/PtL would require 2-3 times and 5 times, respectively, the renewable energy capacity of BETs. The annual mileage was assumed to be 100,000 km, and the holding time 4 years. The TCO per km for FCETs and BETs is expected to remain higher than diesel trucks (0.57 €/km), but a carbon tax higher than 50 €/t CO_2 could make the alternatives competitive.

Table 5. Renewable electricity demand per 100 km for 12 t trucks

BETs	FCETs	Power-to-Methane	Power-to-Liquid
84 kWh	192 kWh	407 kWh	380 kWh

Source: Presentation by LBST [34]

In the technical readiness section Sue (Volkswagen) presented a different conclusion based on TCO calculations. According to [59], electrifying highways would be the most cost-effective option to decarbonise the HDV sector. The quoted study suggested that overhead catenary was the only option to have an average TCO in terms of euros per kilometre travelled below that of conventional diesel in the period 2020-2030. The higher infrastructure costs of the overhead line network would be compensated by the savings in operational costs with respect to the other HDV technologies. However, as highlighted in [59], the cost estimates are subject to uncertainties as they are strongly dependent on assumptions regarding the use of the infrastructure and the subsequent infrastructure design.

LBST also compared the investment needed for infrastructure if only one powertrain technology was adopted (BETs) or a combination of different solutions (BETs and FCETs). The analysis assumed that all the energy fuelling the vehicles comes from renewable sources. The results, reproduced in Figure 7, show that the total infrastructure investment needs for a fleet of 46 million BEVs in Germany by 2050 would be 75 billion. If, on the other hand, 50% of these vehicles were FCEVs, the investment needs for the overall infrastructure would be 23% lower (58 billion euros). The higher costs for Case A (100% BEVs) were justified by the high demand for stationary electricity storage in case all the energy was produced from intermittent renewable sources (which would be the case for Germany at the latest by 2050). In that scenario, LBST found that it would be more efficient in terms of total investment needs to use hydrogen as storage medium.

Figure 7. Comparison of the investment needs for electric vehicles infrastructure where all vehicles were BEVs (Case A) and where they were 50% BEVs and 50% FCEVs (Case B).
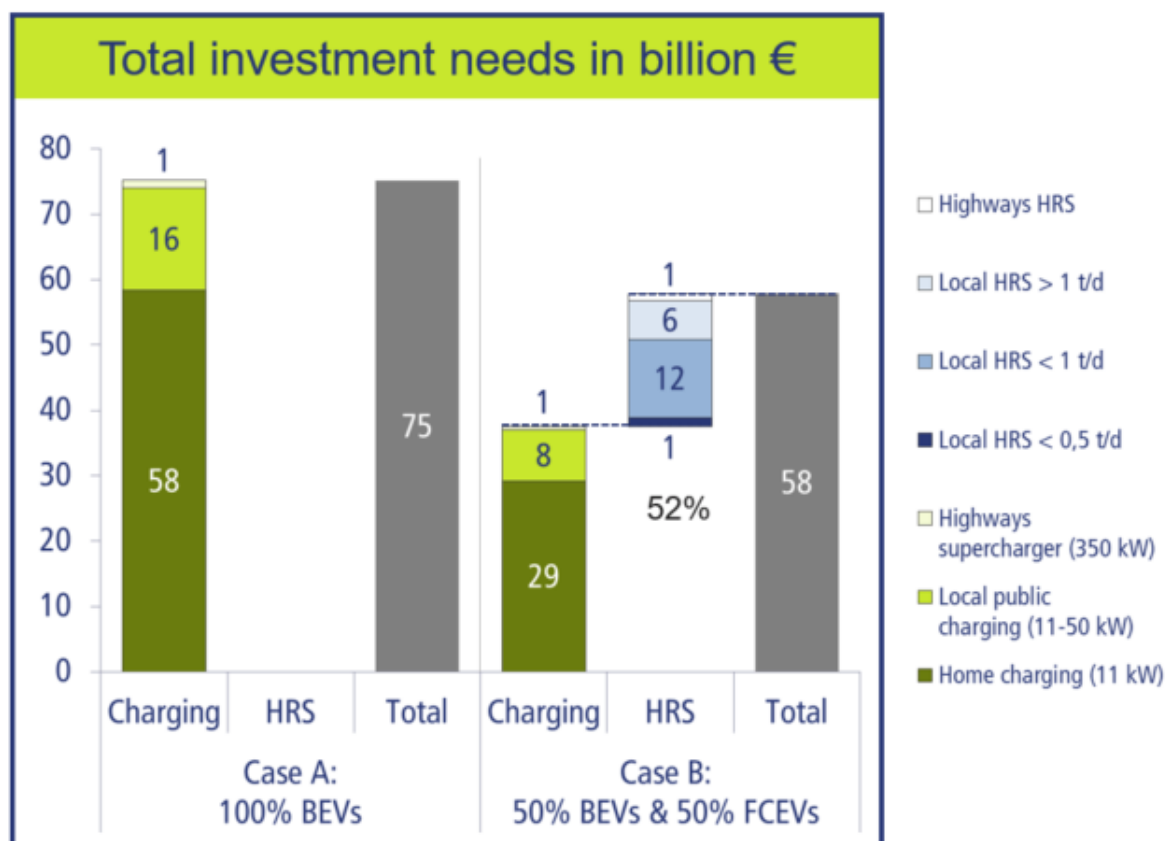
Source: Presentation by LBST [34]

The main parameters driving the choice of a powertrain are technology readiness, operational requirements, costs and life cycle environmental impacts. However, as also highlighted in the following LCA section (5.2), the results of analyses related to the last two parameters are highly sensitive to assumptions. Technologies change rapidly and many processes in the life cycle of an electric vehicle (e.g. lifetime, end-of-life) are still subject to a high level of uncertainty. Therefore, it is often difficult to compare different studies. Nevertheless, it can be agreed that there is still considerable room for improvement for electric trucks. As Wilkins (TNO) points out, as the vehicles are rolled out, drivers and manufacturers learn how to optimize their operation. Moreover, the costs will reduce as well. According to LBST, this is particularly true for fuel cells: whereas batteries have been mass manufactured for decades, the cost reduction potential of fuel cells through mass manufacturing has not yet been tapped. The cost picture of fuel cells versus batteries is expected to change dramatically after 2025, when mass manufacturing of metallic bipolar stacks will have started.

Uniform policies across cities and nations are crucial for optimizing the operational stage of electric trucks. Moreover, with the help of government incentives, the TCO should decrease according to Scania. In Norway, for example, the government has introduced some of the most generous incentives for BEVs in Europe, covering between 40% and 50% (depending on the size of the company) of the cost (CAPEX) difference between BEVs and ICE vehicles, as well as complete exemption from road tax and city tolls in big cities. The result was that in 2020 BEV sales rose to a record 54.3% of all new cars sold in Norway [60]. Similarly, the full exemption of road tolls for electric trucks in Switzerland has substantially facilitated the commercial viability of FCETs and their introduction into the market since 2020.

5.2 Life Cycle Assessment

Life cycle assessment (LCA) is an instrument to assess the potential environmental impact of a product or activity throughout their lifecycle. The procedure to perform the assessment is normalised according to international standards ISO 14040 and ISO 14044.

In the workshop, the results of four environmental analyses related to the decarbonisation of HDVs based on the LCA methodology were presented. In this section, the main methodological features and outcomes of the studies are presented.

5.2.1 Goal and Scope

The LCAs presented had different goals and scopes.

The well-to-wheels (WTW) report presented by Prussi (JRC) is the result of a long-standing collaboration between the European Commission's Joint Research Centre, EUCAR and CONCAWE aimed at providing the European Union and international organizations (e.g., Intergovernmental Panel on Climate Change) with scientific input regarding the greenhouse gas (GHG) emissions of powertrain technologies and fuels. The difference between a WTW analysis and a LCA is that the former does not include the impacts related to plant and vehicle productions, nor their end of life. Hence, for instance, wind and solar power are considered to be emission free. In the latest update of the JEC report (v5), a focus on HDVs has been included. The WTW GHG emissions of seven powertrain configurations for regional ("group 4" 18 t rigid) and long-haul ("group 5" 40 t tractor semi-trailer) HDVs are compared: internal combustion engine (ICE), hybrid electric (HE), battery electric (BE), fuel cell electric (FCE), and catenary electric (CE). For configurations requiring internal combustion (ICE and HE), both compressed and positive ignition engines were investigated. The powertrain technologies considered in the different LCAs relevant for this report are reported in Table 6. A broad spectrum of fuels were considered for ICE vehicles: diesel (B0 and B7), dimethyl ether (DME), ethanol mixtures (ED95), biodiesel, paraffinic diesel, compressed natural gas, liquefied natural gas, and oxymethylene dimethyl ether (OME). The goal of the assessment is "to assist the reader and guide stakeholders in answering questions about possible alternative pathways to produce a certain fuel and which of these offer the best performance in terms of energy/GHG emissions".

Data gathered for the JEC study have been also partially used as input for the LCA performed by Ricardo, ifeu and E4tech for the European Commission. This assessment, presented by Hill at the workshop, is the result of a 2-year project for DG CLIMA led by Ricardo aimed at comparing the life cycle environmental impacts of an extensive range of vehicle types, powertrains and energy chains. Similar to the JEC study, two types of HDVs were considered: a 12 t rigid lorry for urban delivery and a 40 t articulate lorry for long-haul transport. In contrast to the JEC WTW study, the LCA performed by Ricardo is not limited to GHG emissions, and it also includes the emissions resulting from the production and the end-of-life of vehicles and plants for energy production.

The LCA performed by Kotz et al. from NREL aimed at comparing a variety of FCETs (pickup, straight, vocational, refuse, construction, tractor-trailer and drayage) and conventional diesel counterparts in terms of WTW energy use and emissions to air. Special attention was given to the actual energy consumption of the different vehicles thanks to the use of high-fidelity vehicle dynamic simulation models and real-world vehicle test data. The research was supported by the Fuel Cell Technologies Office (FCTO) of the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE).

Finally, SCANIA performed an in-house LCA to compare the environmental impacts of BETs with the traditional ICE counterparts. Unlike the previous studies, the LCA is not publicly available yet (the third party verified LCA is expected to be publicly available during the first half of 2021). Therefore, only the assumptions and conclusions reported in the presentation given at the workshop will be discussed.

Table 6. Zero-emission powertrain technologies investigated in the environmental analyses presented at the workshop

	JEC	Ricardo	NREL	SCANIA
BE	X	X		X
CE	X	X		
FC	X	X	X	

Source: JRC HDV Workshop, 2020.

5.2.1.1   System Boundaries

The main stages related to the life cycle of a vehicle are shown in Figure 8 (Ricardo). The life cycle starts with the extraction of raw materials to manufacture the vehicle and finishes with the demolition of the vehicle where components can be either reused, recycled, or disposed of (generally to landfill or incineration with energy recovery). In between, environmental impacts are generated from driving and maintaining the vehicle. In addition to on-road direct emissions, impacts are also generated in the production and distribution of energy vectors (from "well to tank"). This is particularly relevant for energy vectors such as electricity and hydrogen, which are used in zero-emission vehicles. To avoid underestimating the environmental impact or shifting the burden to a different stage of the vehicle lifecycle, a complete environmental life cycle assessment should include all the stages reported in Figure 8. Nevertheless, depending on the goal of the study and on data availability, the system boundaries can be narrowed.

The assessments from Ricardo and Scania cover more stages of the vehicle lifecycle than the other studies presented here, including vehicle production and end-of-life impacts. The Ricardo study excluded activities that were considered either irrelevant for the goal of the assessment (e.g., impacts from road infrastructure, which are the same for all the technologies compared), with an expected low significance (e.g., impacts from the production of the vehicle production plant), or they were excluded due to missing information (e.g., charging and refuelling infrastructure). The processes excluded from the Ricardo analysis are reported outside of the system boundary in Figure 8. As for the scope of the JEC and NREL studies, the assessments are limited to the processes from "well to wheels" (WTW), which include the operation of the vehicle and the production of fuel and electricity (green units in Figure 8).

Figure 8. Main life cycle stages of a vehicle. The blue line indicates the system boundary of the study performed by Ricardo.
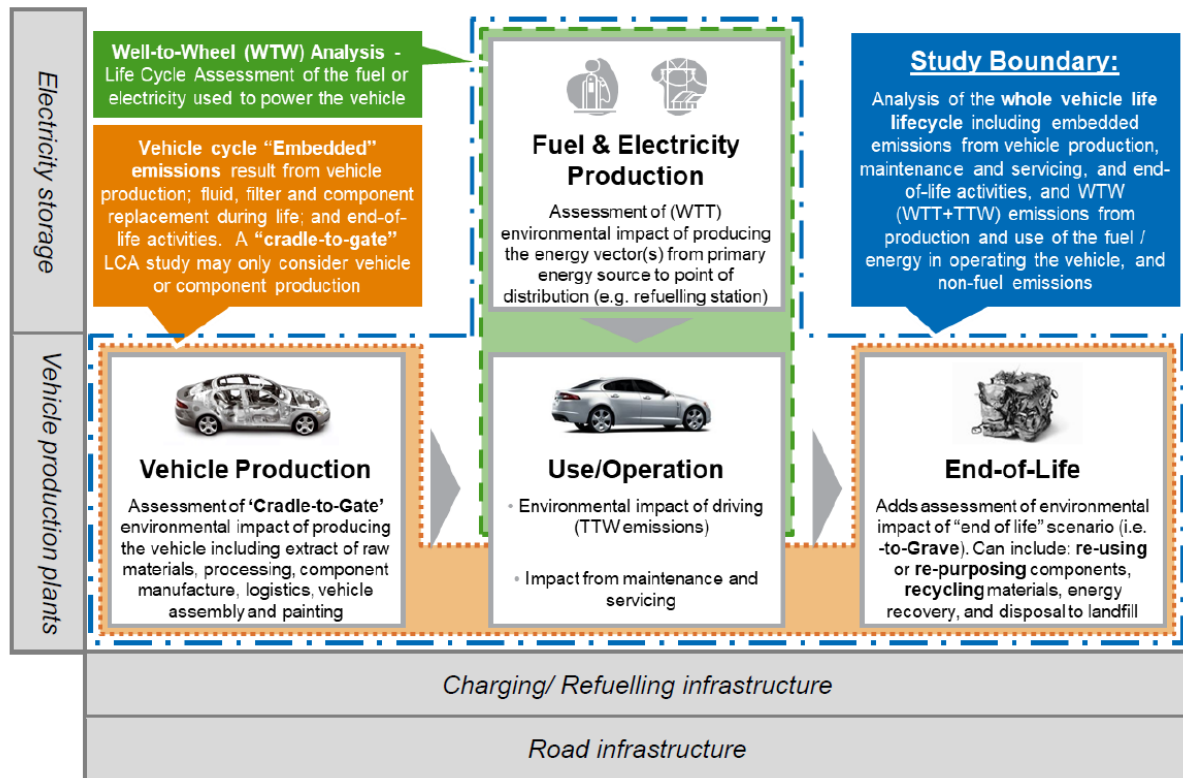
Source: Presentation by Ricardo [34]

5.2.1.2 Functional Unit

The unit used for the comparison of the results by Ricardo and JEC is tonne-km (tkm), indicating the environmental impacts generated to transport one tonne per one kilometre (taking into account the available payload capacity for the different powertrain types). Since the same payload condition for diesel and FC vehicles were considered by NREL, their results were presented just as a function of the distance covered (mile or km). As for Scania, the total distance travelled by the different truck types during their service life was used as functional unit (i.e., 1,350,000 km for long-haul trucks and 400,000 for urban distribution).

5.2.1.3 Impact Categories

Different categories of environmental concern have been investigated in the analyses. All the studies assessed the global warming potential (GWP) impact referred to a time horizon of 100 years of the different technologies in terms of mass of CO_2 equivalents (CO_2-eq.). As for the characterization factors used for the different greenhouse gases, in the Ricardo case they are taken from the 5th assessment report of the IPCC [61], including climate-carbon feedbacks[11] and adjusted for methane conversion into CO_2 (fossil CH_4: 36.75 kg CO_2-eq./kg CH_4; N_2O: 298 kg CO_2-eq./kg N_2O [62]. In the JEC case, the characterization factors are taken from the 4th assessment report of the IPCC (2007) including carbon feedbacks: fossil CH_4: 25 kg CO_2-eq./kg CH_4; N_2O: 298 kg CO_2-eq./kg N_2O [63]. For the NREL study, the characterization factors used by GREET are from the 5th assessment report and do not include carbon feedbacks (fossil CH_4: 30 kg CO_2-eq./kg CH_4; N_2O: 265 kg CO_2-eq./kg N_2O). Scania used the characterization factors from the ReCiPe 2016 v1.1 hierarchist methodology [64] (CH_4: 36 kg CO_2-eq./kg CH_4; N_2O: 298 kg CO_2-eq./kg N_2O).

In addition, Ricardo investigated the cumulative energy demand (MJ) and the potential life cycle impact on acidification (SO_2-eq), eutrophication (PO_4^{3-}-eq.), photochemical ozone formation (NMVOC-eq.), ozone depletion (R11-eq.), ionising radiation (U235-eq.), particulate matter (PM2.5-eq.), human toxicity (CTUh[25]), eco-toxicity (CTUe[26]), resource depletion (Sb-eq.), land use (m²*a), and water scarcity (m³). As for the GWP impact,

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[11] Climate-carbon feedbacks refer to the indirect climate variations due to perturbations in the carbon cycles caused by the emission of the specific greenhouse gas. As the effect is indirect, the estimate is subject to an additional layer of uncertainty.

the product environmental footprint (PEF) supporting information have been used as a guideline for the impact assessment [62]. Although the impact on specific environmental categories has not been assessed in the NREL study, the life cycle emissions of criteria air pollutants (VOC, CO, NO$_x$, PM10, PM2.5, SO$_x$) have been estimated.

5.2.1.4 Geographical and Temporal Context

The JEC, Ricardo, and Scania LCAs refer to Europe, while the NREL study is based on the US context. As for the time horizon, all studies consider both the current status and future scenarios (up to 2050 for Ricardo). The main variations in the input parameters for the future scenarios are electricity mixes, vehicle energy demand, fuel supply, vehicle manufacturing, and material production.

5.2.1.5 System Model and Background LCI Data

In the JEC assessment a "consequential" approach was followed. Consequential modelling aims at identifying the consequences that a decision in the foreground system[12] has on the economy. Different from the "attributional" approach, which is based on specific supply chains or average ones, the supply-chain in a consequential system is modelled on the basis of market mechanisms, political interactions, and consumer behaviour changes. Instead of attributing a portion of the global burden to a product system, the consequential approach tries to assess the potential environmental impact induced by a marginal change in product supply [65]. An ideal consequential LCA requires that all the activities in the product system are modelled predicting every consequence of these activities. This is practically impossible to achieve, and it inevitably increases the uncertainty of the results. Therefore, consequential LCAs typically rely on an attributional framework with consequential components layered in when feasible [66]. For instance, various data sources have been used for the JEC assessment, including ones that rely on an attributional framework, [67]. Moreover, possible scale-driven consequences or market-mediated effects on other sectors of the economy are excluded from the analysis [68]. As for the data sources, in addition to LCA databases, scientific literature, internal JRC studies, and industrial reports were used. A detailed description of the data sources is provided in the annexes of the JEC Well-to-Tank report v5 [68].

A mainly attributional approach was used for the LCA performed by Ricardo, with average electricity mixes and fuel blends based on EC energy-system modelling (i.e. cost-optimised techno-economic and environmental modelling accounting for energy demand and available supply of resources). Moreover, consequential components were added as sensitivity analyses. In addition to data collected specifically for the project (primary data), ecoinvent v3.5 ("cut-off" system model) was used as background source [69] with gaps filled mainly from GREET[13]. A detailed description of the data sources is provided in the final report of the project [49].

As for the NREL WTW analysis, an attributional framework was used with GREET and the United States Environmental Protection Agency (EPA) model MOVES[14] being the background data sources. The Autonomie model[15] was employed for vehicle dynamic simulation to evaluate the fuel efficiency of the vehicles. Vehicle components were sized based on truck market information and in-use truck activity data.

Finally, Scania adopted an attributional approach using primary data and GaBi databases [70] for its assessment. No environmental credit is considered for the recycling of the materials at the end-of-life (cut-off).

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[12] Foreground system is defined as those processes of the system that are specific to it, or those processes that are directly affected by decisions analysed in the study [78].

[13] The GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) model is a tool by Argonne National Laboratory sponsored by the US Department of Energy that simulates the energy use and emissions output of various vehicle and fuel combinations (www.greet.es.anl.gov/)

[14] EPA's MOtor Vehicle Emission Simulator (MOVES) is a state-of-the-science emission modeling system that estimates emissions for mobile sources for criteria air pollutants, greenhouse gases, and air toxics (www.epa.gov/moves/latest-version-motor-vehicle-emission-simulator-moves)

[15] Autonomie is a system simulation tool for vehicle energy consumption and performance analysis (www.autonomie.net/expertise/Autonomie.html).

5.2.1.6 Co-products

In cases of multi-functional activities (i.e., activities generating valuable co-products), different approaches can be used to assess their impact. JEC, in line with its consequential approach, used substitution to address multi-functionality. This means that all energy and emissions generated by the process are allocated to the main or desired product, while co-products generate energy and emission credits equal to the energy and emissions saved by not producing what the co-product is most likely to displace. This approach better represents real life, as in the economic choices made by stakeholders. On the other hand, it increases uncertainty given that the outcome of the assessment depends on the fate chosen for the co-products.

The approach in the JEC study is different, for instance, from the one used in the European renewable energy directive (RED), which allocates the emissions among co-products based on their energy content. The latter approach was also used in the Ricardo study for the different fuels, in line with the ifeu refinery model used as source for the assessment. As for the background data, given that the cut-off system model from ecoinvent was adopted, an allocation based on the market value of the co-products is used. For most of the fuels, a sensitivity analysis using substitution instead of allocation was also performed. As for the end-of-life, the circular footprint formula proposed for the Product Environmental Footprint is adopted in the Ricardo study. Differently from the cut-off background methodology, the formula includes the environmental benefits resulting from recycling the materials, including the EV batteries.

As for the NREL and Scania studies, GREET and GaBi offer different allocation approaches to deal with multi-functionality, but the presentations do not mention what approach is used.

5.2.2 Inventory

In this section, the key indicators for the trucks (Table 7) and energy chains (Table 8) considered in the assessment are presented.

5.2.2.1 Trucks

Average parameters for the trucks are based on a combination of internal studies, market information, simulation models (e.g., VECTO[16]), and expert consultation. The parameters are reported to enable the comparison of the results among different studies. It can be observed that even for the same truck category there is a large variability in the parameters adopted, for instance in the curb weight and payload. This inevitably affects the overall performance of the vehicle when the emissions are reported as a function of the tonnes transported. Battery electric trucks were found to have the most significant limitation compared to a conventional powertrain regarding maximum permissible payload capacity and operating range. The range considered for long-haul BET by Ricardo is significantly higher than the one considered by JEC. In the former case, the range was based on market analyses and future expectations based on mass deployment and battery technology improvements and cost reduction, assuming that BET would need to meet current performance of diesel vehicles. On the other hand, the same target of rigid trucks regarding the operating range was assumed for articulated trucks in the JEC study because a larger range would result in an unreasonable restriction in payload capacity. As for the battery capacity for catenary vehicles, in the JEC study it is considered to be lower than the one for BETs: 100 kWh and 150 kWh[17] for rigid and articulated trucks, respectively. The capacity required to reach the same target range is expected to reduce to 65 and 105 kWh by 2025, respectively. Somewhat higher battery capacity were assumed for catenary vehicles in Ricardo's study. As for the battery used in FCETs, capacities of 10 kWh and 20 kWh were assumed in the JEC study for rigid and articulated trucks, respectively.

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[16] VECTO (vehicle energy consumption calculation tool) is the simulation tool developed by the European Commission used for determining CO_2 emissions and fuel consumption from HDVs with a gross vehicle weight above 3.5 tonnes [7].
[17] The battery capacity for CETs in the JEC study is significantly higher than the one operated in the trials presented by Volkswagen (18 kWh).

Table 7. Key truck parameters

		Rigid				Articulated			
		JEC	Ricardo	NREL	Scania	JEC	Ricardo	NREL	Scania
Curb weight (t)	ICE	2.1	6.15 [4.67]*	4.41		7.5	14.5 [10.5]*	10.7	
	FC		6.42 [4.49]*	4.46			15.9 [10.5]*	10.2	
	BE		7.07 [4.56]*				20.9 [11.2]*		
Maximum payload (t)	ICE	10.1	5.85 [7.33]*	2.40		25.0	25.5 [29.5]*	20.5	
	FC	10.4	5.58 [7.51]*	2.40		25.6	24.1 [29.5]*	20.5	
	BE	6.30	4.93 [7.44]*			19.7	19.1 [28.8]*		
Average payload (%)		50[18]	40			70	40		
Nominal power (kW)		220	175			325	325		
Lifetime	years		12		10		10		10
	1,000 km		570				800		
FC operating range (km)	2020	608	500			614	1000		
	2030	700	500			746	1000		
BET battery (kWh)	2020	570	140		300	840	1,370		700
	2030	420	202			616	958		
	2050		253				1,147		
BET battery (range)	2020	367	200			371	500		
	2030	370	300			382	820		
	2050		350				1,000		

Source: JRC based on studies presented by Prussi (JRC) [63], Hill (Ricardo) [43], Kotz (NREL) [66], and Nellström (Scania). Figures presented for Scania indicate the preliminary conservative assumptions presented during the workshop. *Ricardo's study includes the unladen mass of both the tractor and the semi-trailer for articulated trucks. Unladen mass figures are for 2020, in future periods the unladen mass of both conventional and alternative powertrain vehicles is decreased significantly through general structural lightweighting measures, as well as powertrain and energy storage density improvements. Values for 2050 are provided in brackets. Assumptions on electric range were updated for the workshop versus those used in the study for DG CLIMA.

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[18] To consider the limitation of BEVs in terms of payload capacity compared to other vehicle configurations, a 63% load factor was considered for BEVs in the analysis instead of 50%.

5.2.2.2 Energy Chains

A fundamental parameter in the LCA of electric vehicles is electricity production. In Table 8 the emission factors for electricity production considered in the different studies are reported. Given the consequential approach of the JEC study, the GWP of EVs are determined by the pathway of the marginal electricity production and/or by the electricity displacement from the industry sector to the transportation one. The values reported in the table are referred to the baseline scenario, and they include the distribution and the transformation to low voltage electricity (different pathways have been analysed for sensitivity purposes). The European electricity mix for 2030 is based on the IEA predictions, but the new targets of the Green Deal could further accelerate the decarbonisation of the European grid. Ricardo's electricity mix for 2030 and 2050 is based on a scenario consistent with the EU contribution to meeting the Paris Agreement objective of keeping global temperature increase to a maximum of 1.5°C. Emission factors include distribution. The future electricity mix incorporates the demands from electric vehicles (as well as other sectors) in the additional capacity added as a consequence of changes in demand. In Ricardo's study, accounting is also made in the calculations for the change in the fuel/electricity mix over the lifetime of the vehicle (e.g. between 2020 and 2029 for an articulated truck sold/manufactured in 2020, with a 10 year operational lifetime). The GHG intensity of the EU electricity grid used in the Scania study is significantly lower than the ones considered by JEC and Ricardo (19% and 27% lower, respectively). In the Scania case, the GHG intensity was assessed with GaBi from the 2019 IEA world energy outlook; two scenarios were considered: one assuming a static carbon intensity and the other based on the stated policies. Finally, the GHG intensity of the US electricity grid considered by NREL is higher than the one used for the European grid in the other studies.

In Table 8 the energy chain considered for FCETs is also reported. In the JEC and NREL studies, hydrogen is assumed to be produced via steam methane reforming (SMR), both for the current scenario and the one post-2025. As for Ricardo, while the production of hydrogen is assumed to come entirely from SMR in the 2020 scenario (since at this point production from grid average electricity mix would result in higher GHG emissions). However, the percentage of hydrogen produced from electrolysis is assumed to be 20% in 2030 and 50% in 2050. While in 2030 all the electricity used for the electrolysis is assumed to come from the grid, in 2050, 50% is assumed to come from electrolysis of which 20% is from dedicated intermittent renewable capacity. At the same time, the CO_2 emitted from the remaining SMR quota (50%) is assumed to be captured via CCS technologies.

Table 8. Key energy parameters

		JEC (EU)	Ricardo (EU)	NREL (US)	Scania (EU)
Emission factor electricity (g CO_2-eq./kWh)	2020	396	438	448	320
	2030	268	248		320 / 192[19]
	2050		12		
Hydrogen production	2020	SMR	SMR	SMR	
	2030	SMR	80% SMR 20% electrolysis (grid)	SMR	
	2050		50% SMR + CCS 30% electrolysis (grid) 20% electrolysis (ren)		

Source: JRC based on studies presented by Prussi (JRC) [63], Hill (Ricardo) [43], Kotz (NREL) [66], and Nellström (Scania).

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[19] The different values were used for the two scenarios considered by Scania: static carbon intensity (320 g CO_2-eq./kWh) and stated policies (192 g CO_2-eq./kWh).

5.2.3 Results

In this section selected results of the three assessments are summarised.

Prussi (JRC) presented first the TTW results, highlighting how all electric vehicles (BE, CE, and FC) produce zero GHG emissions from tank to wheels. Electric HDVs also showed higher energy efficiency compared to traditional ICE trucks. Energy efficiency for articulated electric HDVs ranged from a maximum of 0.58 MJ/tkm for the current fleet of FCETs (predicted to decrease to 0.48 MJ/tkm by 2030) to a minimum of 0.34 MJ/tkm for CETs. On the other hand, ICE HDVs show energy efficiencies worse than 0.6 MJ/tkm even after 2030. When the well-to-tank stages are also taken into account, the GHG benefits of xEVs technologies compared to traditional ICE trucks are less obvious. Even so, all xEV technologies showed lower GHG emissions than fossil fuelled ICE trucks. Among the EV technologies, CE shows the best performance, followed by BE. Fuel cell trucks perform significantly worse than catenary and battery electric trucks mainly due to the higher energy requirements per tonne-km. Moreover, while the decarbonisation of the grid post-2025 trigger a relevant GHG reduction (up to 40%) for BETs and CETs, the reduction in GHG emissions post-2025 for FCETs is limited to the improvement of the technology, given that hydrogen is still assumed to be produced via SMR. As a result, FCETs emit more than double the GHG per tonne-km compared to BETs and CETs in the scenario post-2025. The comparison of the WTW GHG emissions for the different powertrains is reported in Figure 9. Among all combinations of fuel/energy carriers and powertrains explored in this WTW report, the use of vegetable oil from waste and compressed biomethane represent the least GHG intensive routes.

Figure 9. Comparison of the well-to-wheels greenhouse gas emissions for the different HDVs powertrain systems assessed in the JEC study for the current situation (2016) and a future scenario (2025+).
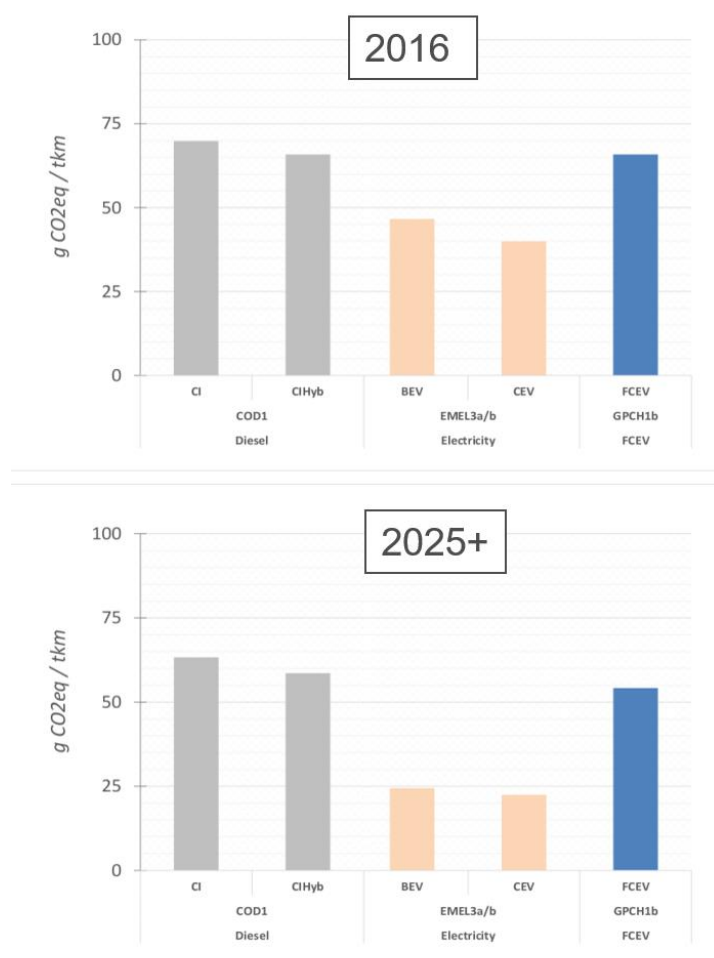
Source: Presentation by JRC JEC WTW [34].

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Similar results were obtained when the comparison included the production and end-of-life of vehicles and of the energy production plants: the Ricardo study shows a lower GWP for electric HDVs compared to diesel HDVs in 2020, but a significant increase in the GHG benefits is expected from 2030 (i.e., when a ramp up of these technologies in the European fleet is expected). The GHG emissions per tonne-km of electric trucks will probably reduce even more by 2050, thanks to a further decarbonisation of the electricity grid and improvement in manufacturing and technology. Similar to the JEC study, BE showed a better GHG performance than FC, due to the more efficient end-to-end energy chain. Also in this study, CE is the best performing of the three zero emission technologies. It is important to consider that the catenary infrastructure, as for the JEC study, was not included in the assessment. The performance of BETs depend on the electricity mix: if the regional mix was used instead of the average European mix, the GHG per tkm for articulated BETs in Estonia would be almost 7 times the values for Sweden. Apart from Estonia and Poland, all other EU countries already achieve significant savings for BETs compared to ICETs, in 2020. The comparison for the different EU countries is presented in Figure 10. In 2030, Estonia and Poland are also expected to achieve significantly lower GHG than ICETs. A similar conclusion was drawn for the US in the NREL study: in Wyoming, long haul BETs currently perform worse in terms of GHG than diesel trucks. However, if the average US electricity mix is considered, BETs already perform better than diesel trucks in the US. The Ricardo study also investigated whether renewable electricity is more efficiently employed for producing e-fuels or for BE/FC vehicles. The results show that the production of e-fuels would require from 5 to 7 times the energy demand of running EVs.

Figure 10. Regional variation of the global warming potential impacts of articulated BETs assessed by Ricardo.
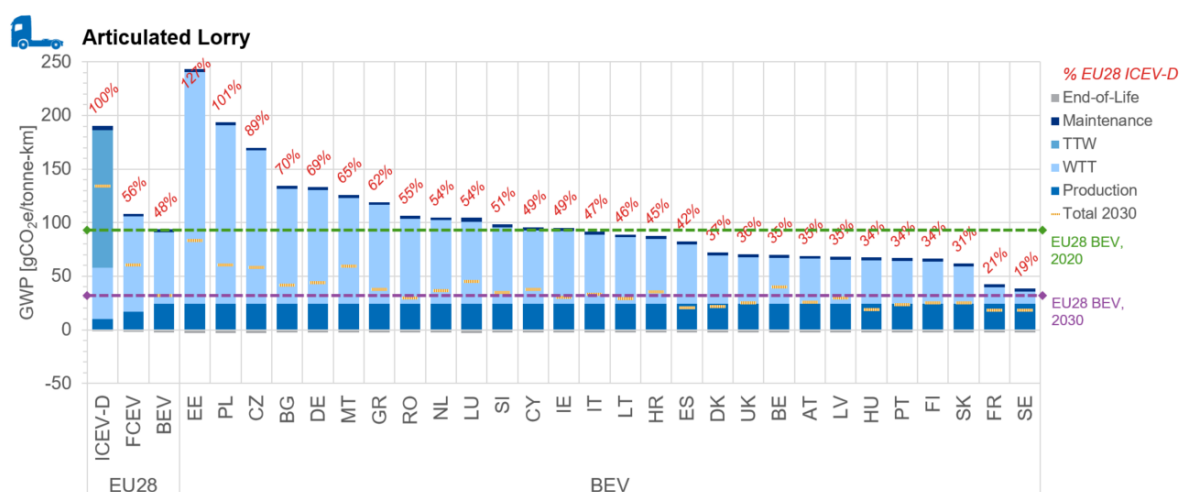

Source: Presentation by Ricardo [34]. Impacts include accounting for the projected change in electricity mix over the vehicle lifetime. The results presented in the bars are for 2020 manufactured vehicles. The reduction in 2030 manufactured vehicle totals are indicated using the orange marker lines, and the EU averages for 2020 and 2030 are indicated with the green and purple dotted lines to facilitate comparisons. Impacts of diesel and fuel cell trucks are reported for reference.

The key finding of the NREL study is that FCETs provide substantial benefit over conventional diesel trucks. The benefits are two-fold: reduction of GHG emissions and reduction of critical pollutants. The use of gaseous hydrogen from methane steam reforming allows for a reduction in GHG emissions of 19-45% for the different types of vehicles considered compared to diesel trucks. The largest savings are shown for trucks often driven at low speed, thanks to the use of regenerative breaking and the higher consumption of ICE trucks at idle. The lowest savings are seen for long-haul trucks, due to the optimization of the ICE for these driving cycles. For this truck category, the use of liquefied hydrogen would actually increase the WTW GHG emissions compared to diesel trucks. The difference in the GHG emissions resulting from the use of gaseous and liquefied hydrogen in the different truck configurations considered by NREL are shown in Figure 11. The higher emissions for liquefied hydrogen are due to the extra energy required for liquefaction. Nonetheless, both forms of hydrogen will reduce the WTW emissions of pollutants generating smog: VOC, CO, NO_x and PM. Among these pollutants, the lowest reduction was noticed for PM. The reason could be ascribed to the non-negligible PM emissions of FCETs during their use phase, from the wearing of brakes and tires, to the production of hydrogen via SMR. Moreover, the adoption of particulate filters on diesel trucks significantly

reduced their overall PM emissions. An opposite trend was seen for SO$_x$, with higher emissions for FCETs compared to diesel trucks due to the introduction of low sulphur diesel and the higher use of electricity, still partially relying on sulphur-rich coal. Therefore, although a cleaner electricity grid would have a limited effect on the WTW emissions of diesel trucks, it has a large potential for reducing the emissions of electric vehicles.

Figure 11. Comparison of the well-to-wheels greenhouse gas emissions assessed by NREL for diesel trucks (D) and fuel cell trucks fuelled by gaseous (G.H2) or liquid (L.H2) hydrogen.
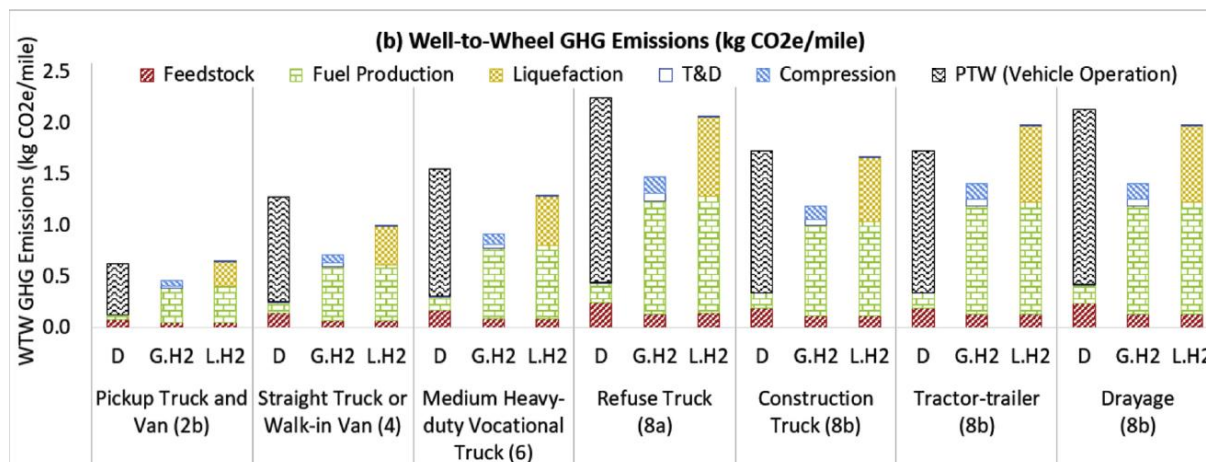
Finally, the LCA performed by Scania confirmed the lower life cycle GHG emissions of BETs compared to ICE trucks. Although the BET production phase is shown to be more GHG-intense than diesel trucks (mainly due to the emissions created when producing the battery), after one year of utilization BETs already show lower cumulative GHG emissions. The greenhouse gas emissions "return on investment" for urban BETs compared to ICETs is highlighted in Figure 12. After 10 years of operation (i.e., assumed end of life), BETs allow for a 45% GHG emission reduction compared to diesel trucks. For urban BETs, approximately two thirds of the life cycle GHG are related to the production of electricity during the use phase. The GHG emission reduction compared to a diesel truck could go down to 86% if electricity from wind (assumed to have a GHG intensity of 4 g CO$_2$-eq./kWh) was used instead of the average EU mix. Even larger GHG savings (94%) would be achieved for long-haulage BETs recharged with electricity from wind.

The energy consumption and greenhouse gas emissions per tonne-km assessed in the different studies are summarized in Table 9 and Table 10, respectively. To provide data in equivalent units, the NREL results have been divided by the payload factor of the trucks (an average 50% load was assumed). At this stage not enough information was provided for the unpublished Scania LCA study to include their results. A large variation in the results per tonne-km can be observed, most likely due to the different scopes covered (e.g. geographical context), truck features (e.g. payload capacity), methodological procedures (e.g. attributional vs. consequential LCA, impact assessment method), data sources, and assumptions (e.g. excluded activities, future fuel/electricity production) of the studies presented.

Figure 12. Comparison of the cumulative global warming potential of BETs and ICETs during their lifetime.
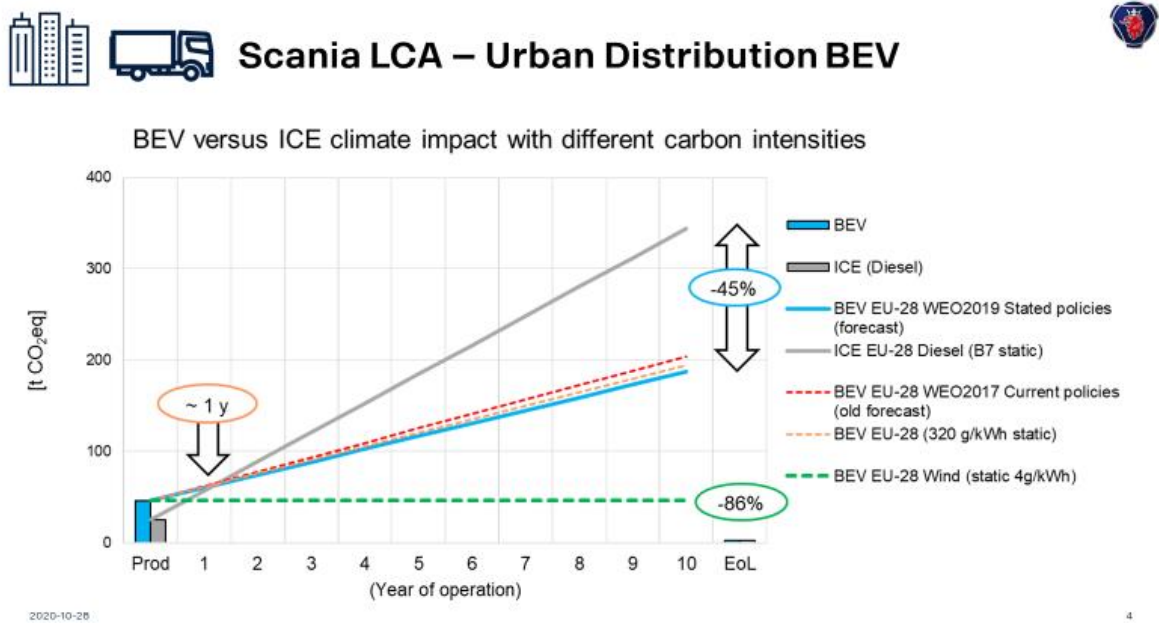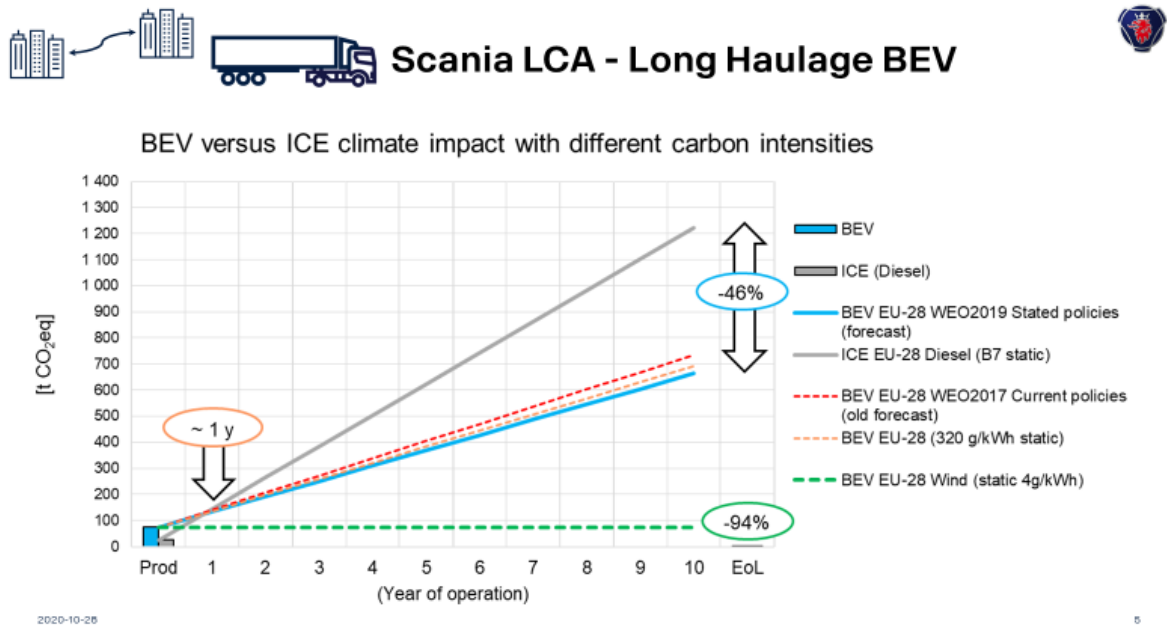
Source: Presentation by Scania [34]

Table 9. Energy consumption for the different rigid and articulated trucks assessed in the studies (MJ/tkm).

		Rigid						Articulated					
		FC		BE		CE		FC		BE		CE	
		WTW	LCA	WTW	LCA	WTW	LCA	WTW	LCA	WTW	LCA	WTW	LCA
JEC	2020	4.07		4.23		3.71		1.18		1.25		1.08	
	2030	3.54		2.87		2.64		0.97		0.76		0.70	
Ricardo[20]	2020		3.82 [4.33]		3.45 [2.23]				2.23 [2.15]		2.12 [1.28]		1.60 [0.92]
	2030		2.57 [3.00]		2.42 [1.75]				1.53 [1.72]		1.06 [0.76]		0.93 [0.65]
	2050		2.20 [2.71]		2.01 [1.65]				1.21 [1.26]		0.79 [0.64]		0.72 [0.59]
NREL	2020	5.6						1.3					

Source: JRC based on studies presented by Prussi (JRC) [68], Hill (Ricardo) [49], and Kotz (NREL) [71].

**Table 10**. Greenhouse gas emissions for the different rigid and articulated trucks assessed in the studies (g CO_2-eq./tkm).

		Rigid						Articulated					
		FC		BE		CE		FC		BE		CE	
		WTW	LCA	WTW	LCA	WTW	LCA	WTW	LCA	WTW	LCA	WTW	LCA
JEC	2020	228		158		137		65.7		46.7		39.8	
	2030	198		90.9		84.3		54.1		24.4		22.3	
Ricardo[20]	2020	246 [27.5]	292 [73]	130 [7.2]	189 [63]			111 [16.6]	129 [34.3]	69 [4.8]	95 [29.0]	58 [3.9]	74 [16.6]
	2030	181 [19.0]	216 [46]	70 [6.5]	105 [40]			93 [11.8]	109 [26.2]	25 [2.8]	41 [17.4]	21 [2.6]	32 [13.9]
	2050	28 [13.5]	60 [41]	3.5 [5.2]	35 [36]			11 [6.8]	24 [18.1]	1 [2.1]	13 [13.0]	1 [2.0]	11 [11.5]
NREL	2020	368						43					

Source: JRC based on studies presented by Prussi (JRC) [68], Hill (Ricardo) [49], and Kotz (NREL) [71].

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[20] Ricardo values indicate the cumulative energy demand when the average fuel/grid electricity mix is considered. Values presented in the workshop referring to a scenario where fuels are produced from 100% renewable electricity are reported in brackets. The CE option was deemed not applicable for 12 tonnes rigid trucks.

The impact assessment of the Ricardo study was not limited to the global warming potential. In Figure 13, the results for the main impact categories considered by Ricardo for long-haul trucks are presented. In the figure, 100% indicates the impact for a specific impact category obtained for the reference powertrain technology: diesel ICE truck in 2020. Electric trucks perform better than diesel trucks in most of the environmental impact categories by 2030. The exceptions are the consumption of minerals and metals (ARD_MM) and the human toxicity potential (HTP). One of the reasons for the higher consumption of metals, in addition to their use for batteries and fuel cells, is the higher aluminium consumption to reduce the mass of the vehicles. Nevertheless, given the long lifetime of HDVs, the production phase of the electric trucks is less relevant to the life cycle emissions compared to, for instance, electric cars. By 2050, the potential impacts of electric trucks are expected to be significantly lower than the 2020 diesel counterpart for all the environmental impact categories considered.

Figure 13. Comparison of the life cycle environmental impacts of different powertrains for long haul HDVs [Ricardo]. GWP: global warming potential, CED: cumulative energy demand, POCP: photochemical ozone creation potential, PMF: particulate matter formation, HTP: human toxicity potential, ARD_MM: abiotic resource depletion (minerals and metals), WaterS: Water scarcity; D: diesel, ERS: electric road system, REEV: range extended electric vehicle.

Source: Presentation by Ricardo [34].

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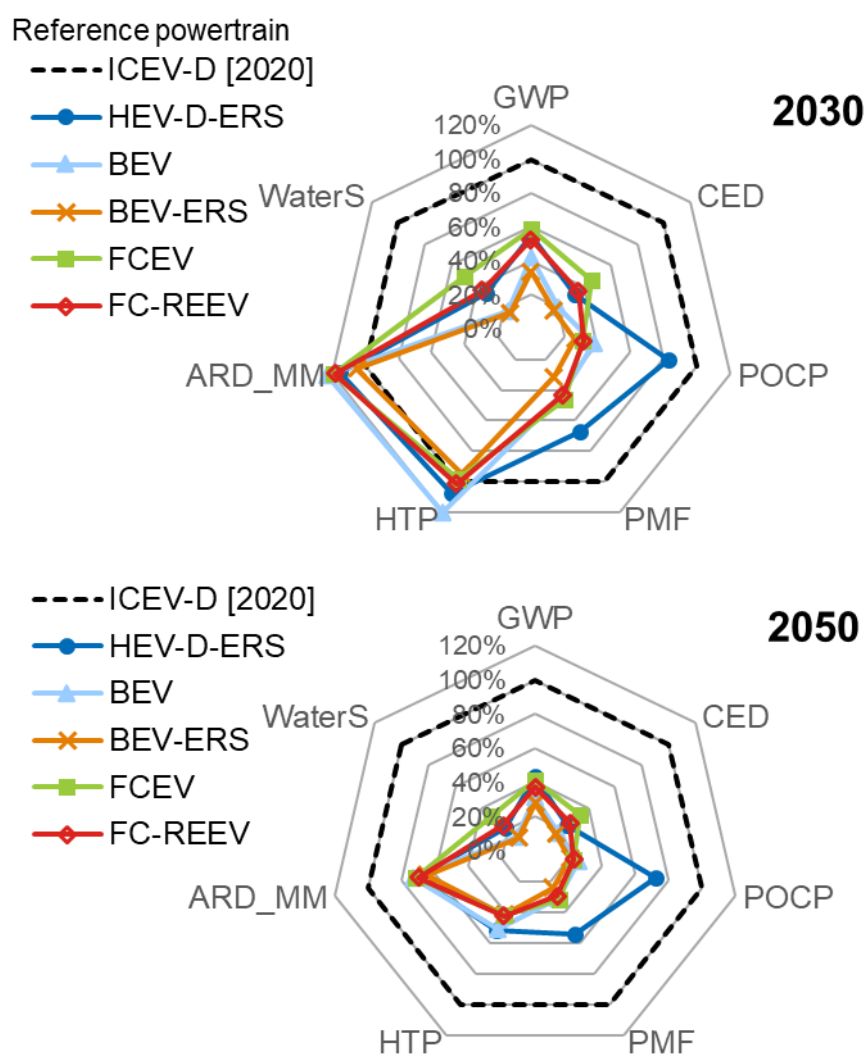
5.3 Discussion

As reported in the literature review performed by Ricardo, less than 5% of LCAs of vehicles include HDVs in their assessments. The studies presented in this session of the workshop add, therefore, a significant contribution to the scarce literature on the potential environmental impacts of alternative powertrains for HDVs.

Even though the studies presented differ greatly in terms of scope and assumptions, similar general conclusions were drawn. Electric trucks provide life cycle GHG benefits compared to traditional diesel trucks, and their environmental performance will improve even more in the future with the decarbonisation of the electricity system. Given that the GHG emissions from the use phase of electric trucks depend to a large extent on the electricity mix used to recharge the battery or produce the hydrogen, the new energy-related targets of the European Green Deal could accelerate the benefits of using electric vehicles.

The life cycle GHG emission ranking for the different powertrains is similar for rigid and articulate trucks. However, rigid trucks give rise to significantly higher GHG emissions per tonne transported, due to the lower payload capacity. Nevertheless, the NREL study highlighted the higher emission reduction potential for electric urban vehicles due to the very high energy consumption of diesel trucks in urban environments (e.g. at idle). Moreover, electric vehicles in an urban context would significantly improve the air quality due to the zero tail-pipe emissions of pollutants responsible for smog formation.

Among the different zero-emission technologies, catenary and battery electric trucks seem to provide lower life cycle GHG emissions compared to FC trucks. The difference is mainly due to the less efficient end-to-end energy chain for hydrogen fuel cell trucks. As pointed out several times during the workshop, using hydrogen via electrolysis requires about two to three times more electricity than using electricity in BET and CET (and about 5 times as much for PtCH4 and PtL). Range extended FC trucks seem to reduce the overall environmental impact of FCETs, according to the Ricardo study. On the other hand, although liquid hydrogen might reduce the complexity of the refuelling infrastructure, the additional energy demand to liquefy the hydrogen makes it significantly more GHG-intense than gaseous hydrogen from well to wheel according to the NREL study. It is important to point out that the recharging/refuelling infrastructure and the energy storage to manage the electricity network were excluded from all the life cycle assessments considered here. According to the LBST presentation, the inclusion of the infrastructure for energy storage in the assessment could greatly favour the ramp-up of FC powertrains due to the lower storage costs of hydrogen compared to electricity. Only 4% of the LCA studies reviewed by Ricardo included infrastructure in their assessment. There is therefore a need for more LCA studies of future scenarios that include the overall infrastructure in the assessment.

Unlike the WTW analyses, the LCA performed by Ricardo included the environmental impacts of the production and end-of-life stage of vehicles. Moreover, it provided more nuances such as the evolution of the energy mix with time (impacting both operational energy consumption and the impacts from production of raw materials, manufacturing and end-of-life treatment of vehicles), rather than snapshots in different years. Given the long lifespan of HDVs, production and end-of-life phases are currently less GHG-intense than the operational stage. However, as seen in Table 10, this will change in the future, mainly thanks to the decarbonisation of electricity. It is therefore important to avoid shifting the burden from the use phase of the vehicle to its production and end-of-life. Batteries and fuel cells are currently the main cause of the higher impacts of electric trucks in the production phase. In Scania's study, the traction battery lithium ion accounts for 12.4% of the global warming potential for urban trucks and 8.7% for the long-haul ones. Although Scania predicts that from 2030 batteries will cease to be a climate issue, Hill (Ricardo) points out that there are still large uncertainties regarding their end-of-life treatment. Moreover, current LCA impact categories do not always effectively capture the issues related to certain resources, like lithium, cobalt and nickel. To capture the actual implications of resource uses, additional modelling complimentary to LCA is required. For the other environmental impact categories investigated by Ricardo, electric trucks show significant benefits compared to the traditional diesel counterpart, already by 2030.

As for the complexity of LCA, more standardization in the methodology and transparency is required to be able to compare studies. As shown in Table 10, results can vary significantly among different studies. In addition to the different scope (e.g. US-based study for NREL compared to EU-based studies for JEC and Ricardo) and the different characteristics of the trucks considered (e.g. payload), there could be several methodological reasons for the discrepancies in the results: system modelling adopted (consequential vs. attributional), data sources, characterization factors for impact assessment, co-production allocation.

Finally, more primary data are necessary (e.g., real life performances) to improve the accuracy of the LCA of alternative powertrains for HDVs.

Based on the presentations given at the workshop, the following points are recommended for future environmental assessments:

- To investigate the impacts of the infrastructure required for different powertrain configurations;

- To investigate the potential impacts of different energy system scenarios, based on the penetration rate of the different powertrain technologies (particularly on critical resources);

- A greater standardisation for vehicle LCAs, with common methodologies and assumptions. The greater the transparency regarding the methodology, assumptions and data used for assessments, the greater the benefit for the wider research community.

6 Panel Discussion

Session 4 of the online workshop consisted of a one hour panel discussion, chaired by Paul Hodson, Head of Unit C1: Energy Storage, of the JRC. This panel session aimed to tie together the themes that had been presented throughout the day. This included considering the technical readiness of the zero emission solutions, their feasibility, practicality and the cost of implementing the required infrastructure. Furthermore, the LCA/sustainability studies of the different options and their potential for reduction in greenhouse gas emissions and other environmental impact factors was considered.

The panel was selected in order to provide a balanced discussion regarding the different solutions and stakeholders. The following panel members took part in the discussions:

- Pietro Caloprisco, Fuel Cells and Hydrogen Joint Undertaking.

- Rolf Döbereiner, AVL.

- Armin Sue, Volkswagen.

- Thomas Fabian, ACEA.

- Nikolas Hill, Ricardo.

- Nikolaus Steininger, DG CLIMA of the European Commission.

The panel discussion is summarised below. Whilst the discussion took place as a series of Questions and Answers, it is summarised below according to the technology being discussed and the general conclusions reached.

6.1 FCETs

Pietro Caloprisco from the FCH 2 JU outlined the main challenges facing FCETs and their relevant infrastructure. Along with its industrial partners, the FCH 2 JU will be seeking to overcome a number of technological and economic barriers. Caloprisco highlighted that although a stack durability of 5000 hours has been achieved in light duty commercial vehicles, this is still a long way off from the 30,000 hours needed for HDVs [38]. Improvements will need to be made to the PEMFC stack in order to achieve greater durability, eventually aiming for vehicle lifetimes of 10-12 years or longer. Reducing the platinum loading on the PEM fuel cell stack is also key to bringing costs down.

In order to bring products rapidly to market, manufacturing methods will need improvement and OEMs need to reach a consensus on the standardisation of products such as hydrogen tanks. Developments are also being made in the standardisation of hydrogen refuelling protocols for heavy duty transport, as shown in the FCH2 JU – funded project PRHYDE (Protocol for Heavy Duty Refuelling) [72] that is developing refuelling protocols for medium and heavy duty hydrogen vehicles.

Regarding the development of HRS technology, compression remains one of the key cost factors, accounting for about a quarter of dispensed hydrogen cost. Technological improvements are still ongoing and could be the deciding factor in the TCO comparison between BETs and FCETs in certain use cases. Detailed analysis can be found in a study published by the FCH 2 JU in December 2020 comparing the TCO factors for FCEVs and hydrogen, BEVs and CEVs [31].

Caloprisco emphasised the need to reach commercialisation of FCETs quickly, as OEMs are clear that if they do not see a rapid increase in the number of sales, they will not be able to reach the 2025 targets, let alone the 2030 targets.

6.2 BETs

Rolf Doebereiner (AVL) questioned whether the infrastructure for long haul BEVs would be feasible in the future, given the large power requirements for charging an HDV: An HDV can achieve a typical full charge of 700 kWh within 45 minutes at 1 MWh charging power – equivalent to the power drawn by about 2000 average houses. Considering that at each charging station there would be about 10 or 20 lorries, this poses a major challenge for infrastructure. *To appreciate the magnitude of the challenge, if the entire fleet of HDVs in Europe (about 4.5 million trucks) were to be replaced with BETs the total electricity required to charge them would equate to 324 TWh, or just over 10% of the EU electricity generation in 2015* [47]. It's therefore important to assess other emission free energy carriers as well.

6.3 CETs

With freight transport projected to increase for the foreseeable future, road freight transport will remain an important part of global logistics. While rail transport has the benefit of being able to transport large volumes of freight, existing rail infrastructure is congested and the prioritisation of passenger trains leads to lower punctualities of freight trains. Compared to rail, *the electric road system offers the advantages of flexibility of operation, lower cost of operation and speed*. As Armin Sue (Volkswagen) stressed, the infrastructure development of an ERS is far cheaper than building new rail networks.

In comparison with BETs and FCETs, the ERS option faces fewer technological complications for the development of the truck architecture: the truck requires only a small battery for travelling the short distance between the depot and the eHighway – the rest of the power is provided by overhead lines, a technology which is already well known.

Clearly, *the biggest challenge for CETs is the development of the ERS infrastructure*. Nikolas Hill from Ricardo argued that while their study did not take into account infrastructure costs, other studies have shown that the cost of infrastructure of the ERS has a low impact on the TCO[21] (as well as a low environmental impact), especially considering the long lifetime of such an infrastructure. Hill suggested that the infrastructure costs of ERS may bring it level with BETs in terms of overall costs.

A practical aspect that is under consideration is how to pay for the electricity drawn from the pantograph. Armin Sue (Volkswagen) suggested that trucks would have on-board monitoring of the energy usage that would determine the amount to be paid at tolls.

6.4 General Discussion

Thomas Fabian (ACEA) highlighted key areas in which public funds would need to be invested, in order to achieve the 2025 and 2030 emissions targets. Firstly, investment in *public refuelling and recharging infrastructure* is important, as private investment in ZE trucks will effectively not be made if the infrastructure does not exist. Secondly, Fabian highlighted the need for a *coherent policy framework*, particularly regarding *carbon pricing*. Finally, Fabian underlined the clear commitment of the truck industry to prioritising the development and production of ZEVs as the main solution to achieving carbon neutrality.

The fundamental question is this: which ZEV technology will be most feasible, economically and practically, at decarbonising HDV road freight transport. Nikolas Hill suggested that the best options overall (from an environmental perspective) were BETs and CETs for a number of reasons: the direct use of electricity in both technologies optimises the use of renewable energy sources, hence enhancing their decarbonisation potential; both technologies are mature and improvements, especially in batteries, are occurring. Practical considerations are favourable as operating costs are lower than for FCETs and diesel trucks. Moreover, new models of usage may compensate for range limitations of BETs. Nonetheless, hydrogen has a role to play in the long-term storage of energy produced from intermittent and unreliable renewable sources *and may be most relevant in the transport of the heaviest goods for the longest missions.*

Nikolaus Steininger (from DG CLIMA) pointed out the need for a combination of solutions, suggesting that the ERS may be best suited to the most congested freight routes, whereas hydrogen trucks would be a better solution for remote areas and regions *where the electricity grid is inadequate to support power-hungry*

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[21] This somewhat contradicts the data presented by LBST in Table 4.

catenary infrastructure. Steininger also made the point that solutions will depend on the future European energy mix, including the likelihood that some energy will need to be imported from abroad.

In terms of achieving the 2025 and 2030 emissions targets, Thomas Fabian (ACEA) expressed concern that *existing policy measures would not be sufficient to meet the targets,* citing a severe lack of investment in infrastructure for the hundreds of thousands of electrified HDVs that would need to be deployed in the coming years. Fabian also expressed the opinion that hydrogen seems likely to play an important role in achieving carbon neutrality, again stressing the importance of investing in the relevant infrastructure. In addition, Fabian underlined that the volume of HDVs on the truck market are small compared to the passenger car market, so profit margins for OEMs are low, hence the need for manufacturers and policy makers to focus their efforts in order to generate the respective margins and enabling the transition to carbon-neutrality. Finally, Fabian indicated the need *for a harmonised approach that could be rolled out across the entire European single market.*

Infrastructure was highlighted as one of the most pressing areas that needs large scale investment. Caloprisco claimed that the cost of HRS infrastructure could drop by 30 to 40% by shifting from a mechanical compressor, which suffer from poor efficiency, reliability and incur substantial capital and maintenance costs, to innovative compression technologies such as hybrid metal-hydride compressors, which significantly reduce capital and operating costs due to the absence of moving parts and lower energy requirement. Only 120 HRS currently exist across Europe, but Caloprisco maintained that costs could drop considerably, if HRS infrastructure were to be scaled up.

Questions were raised about the cost of the electricity grid infrastructure: Whereas Pietro Caloprisco maintained that the development of an electricity grid capable of sustaining an ERS or a megawatt-scale electric charging infrastructure in certain European regions would hardly be feasible and extremely costly, Nikolas Hill counter-argued that studies have shown that cost of infrastructure are similar for all three options.[22] Regarding megawatt chargers, Hill remarked that a megacharger was equivalent to 3 x 350 LDV combo chargers and that the number of charging points should not be a challenge, but acknowledged that the charging power required was an issue. Hill also argued that while CEV infrastructure may be more expensive than HRS, the savings in fuel cost dwarf the difference in infrastructure costs, making the electric options by far the most economically attractive option.

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[22] This somewhat contradicts the LBST data presented in Table 4.

7 Conclusions and Recommendations

It is clear that Heavy Duty Trucks, especially those serving on long-haul duties, are a particularly hard to decarbonise sector because of the weights, volumes and mission profiles that are required from the trucks, and the infrastructure requirements. In general, to date the EU-level regulations in place are there to encourage the uptake of Zero Emission Vehicles whilst remaining technology neutral concerning the different vehicle and infrastructure options available.

There are clear challenges facing each technology based on the degree of technology readiness (of both the trucks and infrastructure), economic considerations and environmental impacts.[23]

Significant challenges for Fuel Cell Electric Trucks involve the space efficiency around storage of hydrogen and the durability/lifetime of the fuel cells. A network of HRS is required and compression is a major contributor to the cost of the hydrogen. Consistency between refuelling protocols and hardware is needed. Their lifecycle environmental impacts (particularly GWP and cumulative energy demand) are calculated significantly higher than BE or CE truck alternatives due to lower well-to-wheel energy efficiency (see Section 5.2).

Battery Electric Trucks currently experience limitations based on the size and weight of the battery required, which induces loss of payload. They require long charging times and currently have a limited range. A network of high power charging points is necessary that may lead to grid capacity bottlenecks. In addition, there are some concerns over the availability of key/critical materials for batteries that require further investigation at a system/fleet level.

The major challenge for Catenary Electric Trucks are the large-scale infrastructure requirements.

Infrastructure costs for full EU coverage are predicted to be similar for both BET and FCET. Infrastructure costs are higher for CET. Workshop contributors expressed conflicting opinions regarding which technology is cheapest for TCO.

From the environmental perspective, direct electricity use is favourable over conversion to hydrogen due to the higher efficiency of direct use. When considering CO_2 emissions, the electricity mix and source of H_2 are crucial. In general though, LCA studies suggest CET to have lower CO_2 emissions that BET, with FCET higher still. However, all were an improvement on diesel ICE. These improvements are enhanced by increased use of RES for electricity production, coupled with electrolysis for hydrogen generation. It should be noted that by some measures (Human Toxicity Potential and Mining of Materials) BET and FCET technologies have higher impact than diesel ICE. However, from an overall resource consumption perspective (i.e. including the thousands of tonnes fuel consumed by diesel ICE over their lifetime) BET and FCET are vastly better.

Taking into account these aspects of the different ZEV technologies, the following Conclusions and Recommendations have been identified:

- A cohesive pan-European strategy and policy framework is needed to provide clarity for investors. Industry representatives expressed concerns as to whether the current EU policy measures in place are sufficient to achieve 2030 goals.

- Acceleration in vehicle and infrastructure commercialisation is needed. This will require major efforts regarding public fueling and electricity infrastructure as private investment in trucks is risky without infrastructure assurances.

- A clear commitment from the truck industry to prioritising the development and production of ZEVs is needed. Trucks are produced in low volumes (compared to personal vehicles) and profit margins are low. Therefore, the number of options needs to be reduced for a given mission profile.

- However, there are advantages of diversification between the ZEV options for different mission profiles: BETs are currently disadvantaged for longer, higher payload missions due to their weight, but are well suited to short-range missions, extending also to medium-range missions in the future as battery technology improves. CET is most applicable to dedicated high-frequency

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[23] Note: Additional challenges such as Safety and Public/Industry Acceptance were outside the scope of this workshop.

routes. FCET are the best suited for longer-range missions and the heaviest goods, enabling connectivity to more remote areas.

- However, remaining technology neutral may not solve imminent concerns regarding the coherent and timely roll-out of infrastructure. Targeted, structured diversification is needed supporting the options but preventing unnecessary duplication of infrastructure.

- Therefore, a successful policy framework that either allows a coherent mix of technologies to develop at a European level simultaneously or uses policy measures that favour certain technologies over others is needed, in order to provide investment certainty. Based on the estimated costs of infrastructure, decisions need to be made whether it is beneficial to roll out multiple types of infrastructure or to focus support on a single technology, so as to make best use of public money.

- In the latter case, there is a need for all stakeholders to identify and prioritise the most important factors in deciding upon the favoured technology: e.g. private TCO cost, public cost, environmental impact, electricity consumption, energy efficiency.

- In case of multiple options, additional modelling of the options would be required, including to determine how best to optimise the competing technologies geographically in the case of deploying multiple infrastructures. The implications of ZEV hybrids need to also be considered (e.g. BET or CET with FCET range extenders). The potential improvements in the technologies need to be taken into account.

- Furthermore, there is scarce LCA literature regarding heavy-duty vehicles. More primary data is needed and the GHG emissions and energy impacts of infrastructure, end-of-life etc. need to be included. Care will need to be taken regarding the potential environmental impact, during the widespread adoption of the proposed ZE technologies, for example regarding the mining of materials.

- One further interesting and important aspect that was not discussed in the workshop is how any future autonomous commercial vehicles transport system will affect the total driven distance and average payload, and subsequently how it will affect climate impact, especially if such a development is purely market driven.

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List of abbreviations and definitions

AC	Alternating Current
ACEA	European Automobile Manufacturer's Association
AFID	Alternative Fuels Infrastructure Directive
ARD_MM	Abiotic Resource Depletion (Minerals and Metals)
AVL	Anstalt für Verbrennungskraftmaschinen List, Austrian-based automotive consulting firm and independent research institute.
BE	Battery Electric
BET	Battery Electric Truck
BEV	Battery Electric Vehicle
BMU	Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (Germany)
CAPEX	Capital Expenditure
CE	Catenary Electric
CED	Cumulative Energy Demand
CET	Catenary Electric Truck
CEV	Catenary Electric Vehicle
CFF	Circular Footprint Formula
CGH2	Compressed Gaseous Hydrogen
CHSS	Compressed Hydrogen Storage Systems
CTU	Comparative Toxic Units
D	Diesel
DC	Direct Current
DG CLIMA	Directorate-General for Climate Action (of the European Commission)
DG MOVE	Directorate-General for Mobility and Transport (of the European Commission)
DG SCIC	Directorate-General for Interpretation (of the European Commission)
DME	Dimethyl Ether
DOE	(US) Department of Energy
EERE	Office of Energy Efficiency and Renewable Energy (US)
EGD	European Green Deal
EC	European Commission
EPA	Environmental Protection Agency (of the US)
ERS	Electric Road System
EU	European Union
EUCAR	European Council for Automotive Research and Development
EV	Electric Vehicle
FC	Fuel Cell
FCET	Fuel Cell Electric Truck
FCEV	Fuel Cell Electric Vehicle

FCH	Fuel Cells and Hydrogen
FCH (2) JU	Fuel Cell and Hydrogen Joint Undertaking (2)
FCTO	Fuel Cells Technology Office (of the US)
GaBi	Ganzheitliche Bilanz (LCA software brand name)
GHG	Greenhouse Gas
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
GVW	Gross Vehicle Weight
GWP	Global Warming Potential
HDV	Heavy Duty Vehicle
HE	Hybrid Electric
HEV	Hybrid Electric Vehicle
HGV	Heavy Goods Vehicle
HRS	Hydrogen Refueling Station
HTP	Human Toxicity Potential
ICE	Internal Combustion Engine
ICET	Internal Combustion Engine Truck
IEC	International Electrotechnical Commission
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organisation for Standardisation
IT	Information Technology
JEC	JRC-EUCAR-Concawe consortium
JRC	Joint Research Centre (of the European Commission)
KPI	Key Performance Indicator
LBST	Ludwig-Bölkow-Systemtechnik GmbH
LCA	Life Cycle Analysis
LEV	Low Emission Vehicle
LH2	Liquid Hydrogen
MOVES	Motor Vehicle Emissions Simulator
NMVOC	Non-methane volatile organic compounds
NREL	National Renewable Energy Laboratory (of the US)
NWP	Nominal Working Pressure
OCPP	Open Charge Point Protocol
OEM	Original Equipment Manufacturer
OME	Oxymethylene dimethyl ether
OW	Overhead Wire
PEF	Product Environmental Footprint
PEMFC	Proton Exchange Membrane Fuel Cell
PGM	Platinum Group Metal
PHET	Plug-in Hybrid Electric Truck

PM	Particulate Matter
PMF	Particulate Matter Formation
POCP	Photochemical Ozone Creation Potential
PtL	Power to Liquid
Q&A	Question and Answer
REDII	Renewable Energy Directive II
REEV	Range Extended Electric Vehicle
SCADA	Supervisory Control and Data Acquisition
SMR	Steam Methane Reforming
SoA	State of (the) Art
SoC	State of Charge
TCO	Total Cost of Ownership
TEA	Techno-economic Assessment
TEN-E	Trans-European Networks for Energy
TEN-T	Trans-European Transport Network
TNO	Toegepast Natuurwetenschappelijk Onderzoek (Netherlands Organisation for Applied Scientific Research)
TPMLM	Technically Permissible Maximum Laden Mass
TTW	Tank to Wheel
USA	United States of America
VECTO	Vehicle Energy Consumption calculation TOol
VOC	Volatile Organic Compounds
WTT	Well to Tank
WTW	Well to Wheel
xEV	Electric Vehicles
ZEV	Zero Emission Vehicle

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Annexes

Annex 1. HGV Workshop Full Agenda

Table 11: Agenda for the Workshop

Start	End	Activity	Speaker/Chair (Organisation)
10:00	**11:15**	**Session 1: Introduction and Policy Context**	**Paul Hodson (JRC)**
10:00	10:10	Welcome	Jon Davies (JRC)
10:10	10:25	Introduction: Decarbonisation of Heavy Duty Vehicle Transport	Paul Hodson (JRC)
10:25	10:45	The Climate Ambition: An Opportunity for the Transport Sector	Claire Depré (DG MOVE)
10:45	11:05	Heavy-duty vehicles CO_2 emissions: EU policy context	Carlos Serra (DG CLIMA)
11:05	11:15	Questions and Answers: Session 1	Paul Hodson (JRC)
11:15	11:30	Break	
11:30	**12:45**	**Session 2: Technology Readiness**	**Eveline Weidner (JRC)**
11:30	11:35	Introduction	Eveline Weidner (JRC)
11:35	11:55	Decarbonisation of Heavy Duty Vehicles: Fuel Cell Truck Architecture and Hydrogen Storage	Jaime Sanchez Gallego (CNH)
11:55	12:15	Decarbonisation of Heavy Duty Vehicles: Battery Electric Vehicle readiness	Erik Nellström (Scania)
12:15	12:35	Decarbonisation of Heavy Goods Vehicles with a Catenary System: The „eHighway"	Armin Sue (Volkswagen)
12:35	12:45	Questions and Answers Session 2	Eveline Weidner (JRC)
12:45	13:30	Lunch Break	
13:30	**15:30**	**Session 3: LCA/WTW and Techno-economic Assessments**	**Jon Davies (JRC)**
13:30	13:35	Introduction	Jon Davies (JRC)
13:35	13:55	A comparative life-cycle analysis of low GHG HGV powertrain technologies and fuels	Nikolas Hill (Ricardo)
13:55	14:15	Renewable Hydrogen in Fuel Cell Heavy Duty Trucking – Ramp-up towards 2030	Reinhold Wurster (LBST)
14:15	14:35	JEC WTW v5: Well-to-Wheels analysis of future automotive	Matteo Prussi (JRC)

Start	End	Activity	Speaker/Chair (Organisation)
		fuels and powertrains in the European context	
14:35	14:55	Challenges and Opportunities for Highly Electrified Heavy Duty Vehicles	Steven Wilkins (TNO)
14:55	15:10	Break	
15:10	15:30	Life Cycle Implications of Zero Emission Heavy Duty Vehicles	Andrew Kotz (NREL)
15:30	16:30	Session 4: Panel Discussion and Conclusions	Paul Hodson (JRC)
15:30	16:20	Panel Discussion: Rolf Döbereiner (AVL); Pietro Caloprisco (FCH 2 JU); Nikolaus Steininger (DG CLIMA); Thomas Fabian (ACEA); Armin Sue (Volkswagen)	Paul Hodson (JRC)
16:20	16:30	Concluding statements	Paul Hodson; Jon Davies (JRC)
16:30	16:45	Break	
16:45	17:30	Networking Sessions	

Source: JRC 2020.

Annex 2. EU Classification of Vehicles & Regulated Truck Categories

European vehicle categories are labelled as follows:

- Category L: Mopeds, Motorcycles, Motor Tricycles and Quadricycles

- Category M: Motor vehicles having at least four wheels and for the carriage of passengers

- Category N: Power-driven vehicles having at least four wheels and for the carriage of goods

- Category O: Trailers (including semitrailers)

HDVs fall into vehicle categories N and O and are further classified in the following subcategories:

- N1: Vehicles for the carriage of goods and having a maximum mass not exceeding 3.5 tonnes

- N2: Vehicles for the carriage of goods and having a maximum mass exceeding 3.5 tonnes but not exceeding 12 tonnes

- N3: Vehicles for the carriage of goods and having a maximum mass exceeding 12 tonnes

- O1: Trailers with a maximum mass not exceeding 0.75 tonnes

- O2: Trailers with a maximum mass exceeding 0.75 tonnes, but not exceeding 3.5 tonnes

- O3: Trailers with a maximum mass exceeding 3.5 tonnes, but not exceeding 10 tonnes

- O4: Trailers with a maximum mass exceeding 10 tonnes

The amended Regulation 2017/2400 on type-approval of vehicles based on emissions from heavy duty vehicles (Euro VI) differentiates between 18 different sub-categories of N-type heavy duty vehicles [74]. The Regulation 2019/1242 setting CO_2 emissions standards for HDVs covers vehicle groups 4, 5, 9 and 10 which have a technically permissible maximum laden mass (TPMLM) greater than 16 tonnes. These categories are described in Table 12 below.

Table 12: Classification of Category N vehicles by vehicle configuration and mission profile

Elements relevant to the classification in vehicle groups			Vehicle group	Allocation of mission profile and vehicle configuration							Standard body allocation
Axle configuration	Chassis Configuration	Technically permissible max. laden mass (tons)		long haul	long haul (EMS*)	Regional delivery	Regional delivery (EMS*)	Urban delivery	Municipal utility	Construction	
4x2	Rigid	>3.5 – <7.5	(0)	not covered yet							
	Rigid (or tractor**	7/5/10	1			R		R			B1
	Rigid (or tractor)**	>10 -12	2	R+T1		R		R			B2
	Rigid (or tractor**	>12 – 16	3			R		R			B3
	Rigid	**>16**	**4**	**R+T2**		**R**			**R**		**B4**
	Tractor	**>16**	**5**	**T+ST**	**T+ST+T2**	**T+ST**	**T+ST+T2**				
4x4	Rigid	7/5/16	(6)	not covered yet							
	Rigid	>16	(7)	not covered yet							
	Tractor	>16	(8)	not covered yet							
6x2	**Rigid**	**all weights**	**9**	**R+T2**	**R+D+ST**	**R**	**R+D+ST**		**R**		**B5**
	Tractor	**all weights**	**10**	**T+ST**	**T+ST+T2**	**T+ST**	**T+ST+T2**				

Elements relevant to the classification in vehicle groups			Vehicle group	Allocation of mission profile and vehicle configuration							Standard body allocation
Axle configuration	Chassis Configuration	Technically permissible max. laden mass (tons)		long haul	long haul (EMS*)	Regional delivery	Regional delivery (EMS*)	Urban delivery	Municipal utility	Construction	
6x4	Rigid	all weights	11	R+T2	R+D+ST	R	R+D+ST		R	R	B5
	Tractor	all weights	12	T+ST	T+ST+T2	T+ST	T+ST+T2			R	
6x6	Rigid	all weights	(13)	not covered yet							
	Tractor	all weights	(14)	not covered yet							
8x2	Rigid	all weights	(15)	not covered yet							
8x4	Rigid	all weights	16							R	(generic weight+ CdxA)
8x6 8x8	Rigid	all weights	(17)	not covered yet							

Notes: T = tractor; R = Rigid and standard body; T1, T2 = Standard trailers; ST = Standard semi-trailer; D = Standard dolly.

Source: DG CLIMA Presentation [75], Stakeholder Meeting, T. Frongia and N. Steininger, 2018

Annex 3. KPI table – System weight calculations

This Annex refers to the entry 'System Weights' in Table 2, Chapter 3.

The FCET system weight was calculated as follows:

1. FC stack weight: stack power multiplied by specific stack power (0.86 kW/kg [73])
2. Hydrogen tank weight (Table 13): multiply range per charge by hydrogen consumption by gravimetric capacity:

Table 13: Values used in tank weight calculations

Truck type	range per charge (km)	H$_2$ consumption (kg/km)	Gravimetric capacity (kg/kg H$_2$)	tank weight (kg)
4x2 rigid, 350 bar	350	0.07	15	392
4x2 tractor, 700 bar	1250	0.07	20	1838

Source: All values used in the calculations were taken from [31]

3. Battery weight: divide battery capacity by energy density.
4. System weight (Table 14) is total of 1, 2 and 3.

Table 14: Values used in system weight calculations

truck type	stack power (kW)	FC stack weight (kg)	tank weight (kg)	battery capacity (kWh)	energy density (kWh/kg)	battery weight (kg)	TOTAL (kg)
4x2 tractor	240	279	1838	280	0.183	1077	**3647**
4x2 rigid	88	140	392	56	0.183	622	**800**

Source: All values used in the above calculations were taken from [31] and included in **Table 2**, with the exception of fuel cell specific stack power (0.86 kW/kg [73]) and battery energy density (0.183 kWh/kg [33]).

Annex 4. Hydrogen Refuelling Protocols

Today in Europe, there are about 180 hydrogen refuelling stations in operation, with intentions to build more than 750 by 2025 and 3700 by 2030, of which approximately 1,500 will be tailored for HDVs. These targets are expected to be included in the 2021 AFID review.

A parameter for refuelling is achieving a high final State-of-Charge (SoC), however the maximum refuelling pressure must not exceed 125% of the normal working pressure (NWP) of the tank. The SoC is affected by the initial temperature and pressure of the vehicle hydrogen tank as well as the flow rate (i.e. refuelling time). The maximum temperature in the tank during refuelling must not exceed 85^{0}C in the tank to ensure safety, hence precooling is required for high flow refuelling. The transfer of information between the vehicle and the refuelling station also needs to be defined. All these issues are covered by refuelling protocols.

The existing refuelling protocol SAE J2601-2 – 'Fueling Protocol for Gaseous Hydrogen Powered Heavy Duty Vehicles' establishes "the boundary conditions for safe heavy duty hydrogen surface vehicle fuelling, such as safety limits and performance requirements for gaseous hydrogen fuel dispensers used to fuel hydrogen transit buses", and covers fuelling at flow rates up to 120 g/s [76]. It has a focus on vehicles with an NWP of 350 bar. However, this protocol only provides limited guidance on how to actually refuel vehicles, and even higher flow rates may be required for refuelling HDV. Therefore further development is undertaken by the FCH 2 JU project "Protocol for Heavy Duty Hydrogen Refuelling" (PRHYDE), which focuses on refuelling at high transfer rates of hydrogen with a maximum flow rate of 300 g/s, meeting the cost targets for hydrogen as well as interoperability between all heavy duty vehicle types on the roads. This project defines a refuelling target of 80 kg of hydrogen in 10 minutes for the largest HDV category, i.e. N3 tractor trailer vehicles for long haul use, in order to be competitive with diesel trucks. For smaller N3 vehicles with lower range requirements, it is estimated that 10-40 kg of hydrogen could be refilled in 5-8 minutes to be competitive [77]. Hydrogen refuelling protocols and hardware are summarised in Table 15.

Table 15: Hydrogen Refuelling Protocols and Hardware

	Compressed H₂ 350 bar	Compressed H₂ 700 bar	Cryo-compressed H₂	Liquid H₂
Hardware[24]	H35 – Available HF35F – Available	H70 – Available HF70H – under development	-	Under discussion for HDV application
Protocol[25]	H35 – Available HF35F – Available	H70 – Available HF70H – under development (Vehicle /Station two way communication)	-	Under discussion for HDV application
Refilling time	3.6 kg/min 7.2 kg/min	3.6 kg/min 10 kg/min	-	5 kg/min est.

Source: presentation by CNH Industrial [34]

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[24] Further information: [79]
[25] Further information: [80]

Annex 5. Attendee Feedback on the Workshop

Introduction

The planning of the workshop began in 2019, with the initial intention of holding a "real-world" event in June 2020. Due to the necessary measures put in place due to COVID-19, the workshop was first postponed and then arranged as an Online Workshop on Wednesday 28th October 2020, organised by JRC.C1 (Energy Storage Unit).

For Directorate C, this was the first external event to be arranged completely as a virtual event. Therefore, it was necessary to receive input and support from colleagues in JRC Corporate Events Planning and DG SCIC and considerable assistance from the JRC Petten IT and Communications teams. Webex was selected as the tool of choice for the event as it was the only suitable tool fully supported by our IT colleagues.

The initial plan for the real-world event was to have 100 participants. For the online event, 145 people registered and throughout the day a constant audience of approximately 90-100 people attended, though it was apparent that not exactly the same attendees were present in each session.

A feedback survey was prepared by our colleagues from SCIC and sent out after the event via email to all registered participants. In total, 15 responses were received to this survey, upon which the following section is based. In a real-world workshop such surveys are handed out at the time of the workshop and therefore a higher degree of response is received. An improvement for future online workshops would be to incorporate the feedback as part of the actual event proceedings (as a series of polls, for example) at the end of the event, in order to maximise participation.

Poll Responses

There were three types of questions included in the survey:

- Those that required a ranking from 1 (poor) to 5 (excellent)
- Those that required a YES/NO response
- Those that provided an empty field for a free text response

Overall Feedback on the Workshop

The first two questions concerned the overall impression of the workshop. Figure 14 shows the responses regarding the overall organisation and content. An average score of 4.53 (out of 5) was achieved regarding the overall organisation of the event, and of 4.26 for the overall content of the event. This, in general, is very pleasing, although it is clear that several respondents did not rate the content as highly as the organisation.

Figure 14: Responses to the questions regarding the level of satisfaction of the attendees concerning (a) the organisation of the event; (b) the content of the event
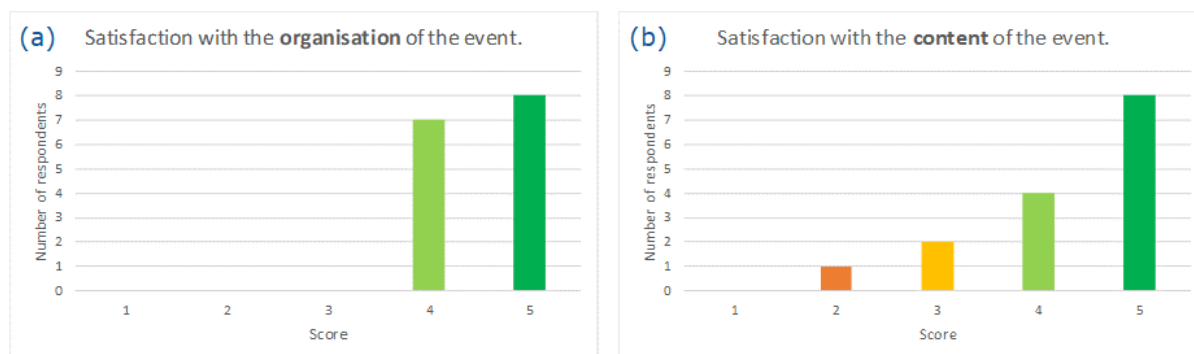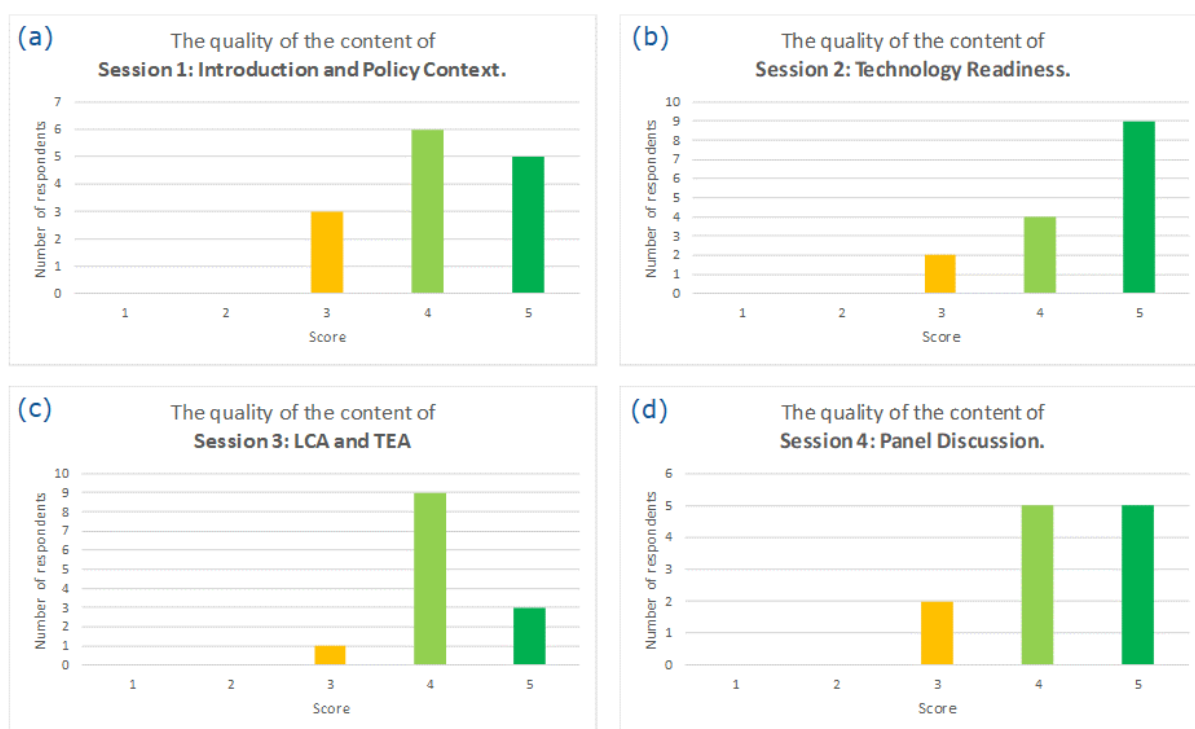

Source: JRC, based on information provided to a feedback survey prepared by DG SCIC, 2020.

Feedback per Session of the Workshop.

The next four questions concerned the opinion on the quality of the content in the individual sessions of the workshop (Figure 15). Average scores were received of:

- Session 1: 4.14

- Session 2: 4.47

- Session 3: 4.15

- Session 4: 4.27

Figure 15: Responses to the questions regarding the level of satisfaction of the attendees concerning (a) Session 1 – Introduction and Policy Context; (b) Session 2 – Technology Readiness; (c) Session 3 – LCA and TEA; (d) Session 4 – Panel Discussion.

Source: JRC, based on information provided to a feedback survey prepared by DG SCIC, 2020.

In general, quite similar scores were achieved across the four Sessions with the highest score being achieved by Session 2, regarding technical readiness. Pleasingly, no scores lower than a 3 were obtained for the content in any individual session.

Respondents were given the opportunity to provide suggestions as to where the individual sessions of the workshop could have been improved.

For Session 1, two suggestions were received. The first suggested that an overview of current policies supporting H_2 within the EU could have been given in order to put in context how much effort the EU is using to pursue this issue. The second point suggested that clear descriptions of the role and mandate of the presenting DGs in the topics discussed could have been presented.

No comments were received for Session 2.

For Session 3, two comments were also received. The first suggested that a better state of the art comparison between FCEV, BEV and CEV would have been expected. The second suggested that a perspective from energy system modellers would have been nice to not only have techno-economic assessment from the user perspective but also the total system.

For session 4 a single comment was received that good and straightforward questions were answered by the panellists, and that it was a great achievement.

Virtual Platform

The next two questions involve the use of the virtual platform, in this case Webex Meetings. In Figure 16 (a) the results can be seen regarding how easy it was to navigate the virtual event platform. This received an average score of 4.40. Secondly, participants were asked whether they were more likely to attend this type of virtual event than attend an in-person conference. In Figure 16 (b) it can be seen that 13 out of the 15 respondents stated that they would be more likely to attend the virtual conference.

Figure 16: Responses to questions regarding virtual events
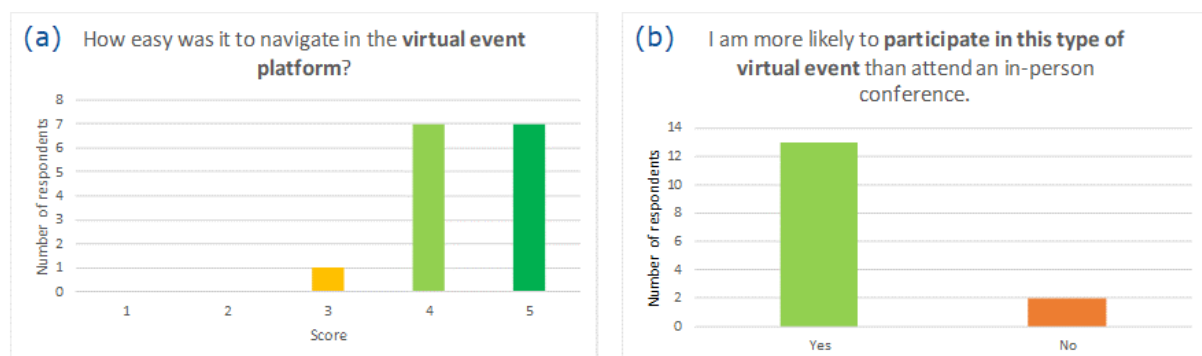
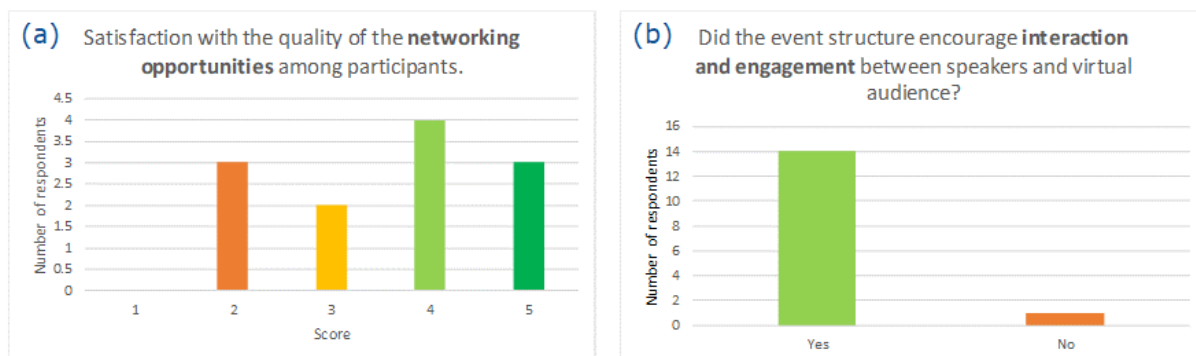Source: JRC, based on information provided to a feedback survey prepared by DG SCIC, 2020.

Engagement and Networking

The next two questions were regarding the degree of networking and engagement that was possible at the virtual event.

Figure 17 (a) shows the level of satisfaction with the quality of the networking opportunities among the participants. This is a much more mixed result than seen for the previous categories with an average score of 3.58. There are a number of possible reasons for this, which should be considered when planning any future events. Firstly, it proved more difficult to provide networking opportunities at an online event than in a real-world event. In order to have an orderly event, it is necessary to exercise a degree of control over microphones to prevent too much background noise, and to keep to the time schedule. Question and Answer sessions were carefully moderated for similar reasons. The event did foresee three parallel networking sessions at the end of the day (one for each of the three sessions: Policy, Technical Readiness, LCA/WTW). However, due to technical issues only two of these took place (Policy, LCA/WTW). However, this was also at the end of a long day of presentations and was not highly attended (approx. 20 people in total). It should be noted that the technical issue that arose was that in Webex Meetings the same person can only host two Webex sessions in parallel, which led to the third session "dropping out". This could be rectified in future by having multiple hosts.

Figure 17 (b) shows the response to the question as to whether the event structure encouraged interaction and engagement between speakers and the virtual audience. In this instance 14 out of 15 respondents replied "Yes". Attendees were able to enter questions for the presenters in the Webex chat. At the end of the presentations (or in the Q&A sessions) the moderators then put these questions to the speakers. Whilst there was not always time to ask all the questions, speakers were encouraged to respond to additional questions in the Webex chat, and this led to several interesting debates.

Figure 17: Responses to questions regarding networking opportunities

(a) Satisfaction with the quality of the **networking opportunities** among participants.

(b) Did the event structure encourage **interaction and engagement** between speakers and virtual audience?
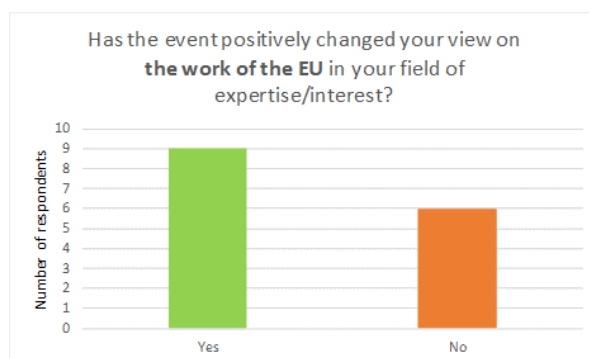
Source: JRC, based on information provided to a feedback survey prepared by DG SCIC, 2020.

View of the EU

The final question related to whether the event positively changed the attendee's view on the work of the EU in this field. In response, 9 out of 15 attendees replied that their view on the work of the EU in this field had been improved.

Figure 18: Reponses to the question regarding participants view of the EU.

Has the event positively changed your view on **the work of the EU** in your field of expertise/interest?

Source: JRC, based on information provided to a feedback survey prepared by DG SCIC, 2020.

Lessons learnt regarding Virtual Event Management

The following lessons were learnt from the point of view of managing an online event of this size. This list was compiled by Carine Nieuweling (of the Communications team).

- Preparations for this sort of event need to be started at least 3 months and preferably 6 months in advance

- The event should be registered in the necessary databases (in this case, Connected and SCIC)

- Ensure that you have a core team that is committed and given sufficient resources (in the case of an online workshop, this means time). We organised weekly coordination meetings and worked through an extensive action list.

- More time will need to be invested in rehearsals than for a physical event. It is important to make test calls with all presenters and panels members, even those that are familiar with the (Webex) system.

- Have an individual event webpage as a portal to all information regarding the event. In this case an event page on the Science hub was used [34].

- Use social media to announce the event. The number of registrations was doubled after the announcement tweet was published.

- Ensure that you engage with your local IT team from the start of the process. Their assistance will be invaluable.

- A registration system provided by DG SCIC was used for the event. This was user-friendly and made the process of approving registrations and communicating with the participants simple for the event organisers. DG SCIC also facilitated the satisfaction survey after the event.

- In general, we would propose that a virtual event should be limited in time to half a day. In our case, this was not possible (as we were converting a planned real-world event to an online event). We were fortunate to have a very engaged audience, mostly present from 10-18h, with the necessary breaks in between. However, retaining everyone's focus for an online event is more difficult for an online event than a real-world one, and splitting the event over two half-days may have been a better option in retrospect.

- To engage the audience we worked with the chatroom for Q&A. Prepare a script to give guidelines on how to use the chatroom, e.g. start your question with the name of the presenter to whom the question is directed. This worked very well. However, be conscious that the chair/presenter will not have the time to check Q&A – we had a specific Q&A team who would filter and relay suitable questions to the moderator of each session.

- We did not only have to check the Q&A, but also the functional mailbox: during the day we received several e-mails from participants with a variety of (urgent) requests. This is something we took care of, but we had underestimated how much it would be used within the course of the actual event.

- Webex Meetings doesn't offer a straightforward way for having break-out rooms. We set up parallel sessions to simulate the break-out rooms we know from Zoom. It is not ideal. Be aware that you can host maximum 2 sessions at the same time, so you need to appoint other hosts and let them create the meetings in order to run them smoothly.

- It is crucial to keep very tight control over timings. This is particularly important for online events as people are more likely to join for part of the event or specific speakers.

- For this workshop, the main host and communications team representative were at the same location. This was extremely useful for quick communication and reminders via a gesture or whispered word, and we would recommend this for future events. We had also planned for the main IT support to be in the same location for the same reasons, however, due to practical considerations this was simply not possible at the time.

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