Programme Area: Heavy Duty Vehicles

Project: HDV Gas WTM

Title: Zero Emission Heavy Duty Vehicle Study Report

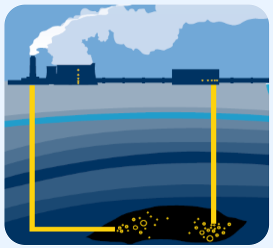
Abstract:

This document is a report on zero emission heavy duty vehicles. The report explores the potential feasibility of zero emission powertrain options, including fuel cell and battery electric powertrains, and provides associated cost projections. The report also includes a heavy goods vehicle physical packaging assessment and an analysis of the current state of development, and remaining barriers / technology gaps for zero emission powertrains in HDV's.

Context:

Natural gas is a potential long-term substitution for existing liquid fuel based technologies in heavy duty vehicles, but more research is required to assess the economic likelihood of this pathway. The software tool that Element Energy will develop will calculate the total greenhouse gas emissions (known in the industry as "well to motion") and the subsequent associated costs for different gas production pathways. It will also consider how the influence of product development over time could influence the cost, performance, technology choices and the market take-up of liquefied natural gas and compressed natural gas.

Element Energy, the strategic energy consultancy specialising in the analysis of and technical insights into low carbon energy markets are the prime contractor delivering this year long £300,000 contract. They are joined with sub-contract support from University College London, CNG Services Ltd, and Strateco AB.



Supporting assumptions for zero emissions HDV cost dataset – Final report

HDV Well to Motion Project

Deliverable 9.3

Version 1.2

17th January 2017

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Agenda

- **Introduction**
- ZE vehicle component costs and trends
- Specification of existing diesel HDVs
- Market review of existing zero emission HDVs
- Specification of zero emission HDVs
- Results from design exercise
- Conclusions and potential for innovation
- References

This report assesses the technical and economic feasibility of zero emission powertrains in the bus and truck sectors

- This report on zero emission heavy duty vehicles is submitted as Deliverable 9.3 of the ETI's Well to Motion Project.
- The extension to the original Well to Motion Contract was designed to explore the potential feasibility of zero emission powertrain options for heavy duty vehicles, and to provide updated cost projections to the ETI for use in its broader modelling work.
- This report has the following main objectives:
  - Review fuel cell and battery powertrain costs for light and heavy duty vehicles from 2015-2050.
  - Define indicative vehicle specifications and calculate costs, payload and packaging impacts relative to conventional diesel powertrains.
  - Assess the feasibility of fuel cell heavy vehicles, including physical packaging of zero emission powertrains.
  - Analyse the current state of development and remaining barriers and technology gaps.
  - Produce technical drawings to assess packaging constraints of zero emission powertrains on common vehicle chassis.
- This report is the final deliverable.

Context: Many countries are beginning to explore opportunities for zero emission heavy duty vehicles

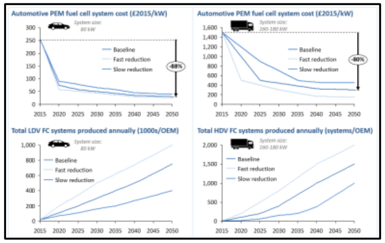
- In addition to the UK and recent agreement on the 5th Carbon Budget in June 2016, a number of countries are examining medium- to long-term carbon budgets and are beginning to find that big reductions in efficiency/fuel consumption will be increasingly difficult to achieve as fleet sizes and annual mileages increase.
- For example, in June 2016 the Office of Energy Efficiency and Renewable Energy (EERE) of the Department of Energy in the United States issued an Request for Information (RFI) on performance targets and specifications for medium and heavy duty fuel cell electric vehicles. EERE is likely to develop a new Funding Opportunity Announcement (FOA) but the structure and size will depend of feedback received in response to the RFI.
- In Scotland, Transport Scotland recently commissioned an assessment of total CO_2 emissions from all transport sectors. Results suggested that significant policy intervention will be needed to meet decarbonisation targets from surface transport sectors since only minimal reductions opportunities will be available from the marine and aviation sectors.
- Within several EU Member States, individual cities such as Amsterdam and Hamburg have already committed to zero emission procurement polices for new buses from 2020 or 2025, and others only permit zero emission trucks into town centres. This will place strong pressure on fleet operators to use zero emission models to continue operating in these areas.

Source: US DOE (2016)

This document is divided into five main sections covering the literature reviews and analyses conducted

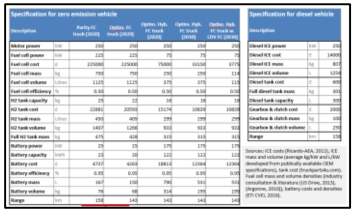
This document have four main sections:

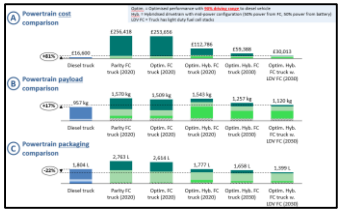
1. **ZE vehicle component costs and trends**
   - Latest fuel cell system cost targets and projects based on an extensive literature review and industry consultation.
2. **Specification of existing diesel HDVs**
   - Review technical specifications described in existing brochures for commercially available vehicles from leading OEMs.
   - Overview of archetypes developed for diesel heavy duty vehicles.
3. **Market review of existing zero emission HDVs**
   - Overview of existing zero emission heavy duty vehicles in development around the world.
4. **Specification of zero emission HDVs**
   - Model outputs for zero emission vehicle specifications.
   - Cost, payload and packaging impacts against the diesel incumbent.
5. **Results from design exercise**
   - Technical drawings for packaging battery and hydrogen storage
   - Assessment of packaging constraints

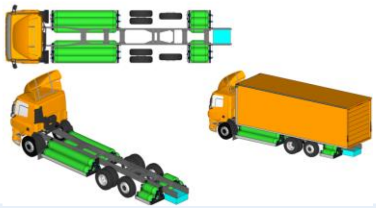


Specification	Units	Volvo	Scania	MAN	Archetype
Model (engine type)	-	*FH 4x2 (D13c420)*	*R 410 4x2 (DC13-115)*	*TGX 4x2 (D2676LF47)*	*4x2, rigid*
Gross combined weight	*tonnes*	Up to 60 (44 in UK)	Up to 70 (44 in UK)	Up to 44	44[1]
Diesel ICE power	*kW*	309	301	298	300
Diesel ICE torque	*Nm*	2100	2150	2100	2100
Diesel ICE displacement	*L*	12.8	n/a	n/a	12.8
Diesel tank capacity	*L*	150-900	300	400	300
Fuel consumption	*L/100km*	Data not available	Data not available	Data not available	45.0[2]
Engine efficiency (peak/average)	*%*	Data not available	Data not available	Data not available	44.5% / 42.7%[3]

Developer	Vision Corp	Vision Corp	TransPower	BAE Systems
Model	Tyrano	Zero-TT	ElecTruck	Kenworth T370
Configuration	Fuel cell hybrid electric	Battery with FC range extender	Battery with FC range extender	Fuel cell hybrid electric (battery dominant)
Duty cycle	Drayage	Terminal tractor	Drayage	Drayage
Gross weight	36 tonnes	60 tonnes	36 tonnes	36 tonnes
Fuel cell power	33 kW (Hydrogenics)	26.5 kW	2 x 30 kW (Hydrogenics)	80 kW (Ballard HD-7)
Battery capacity	*No data available*	*No data available*	120 kWh	100 kWh
Motor power	170 kW	170 kW	300 kW	360 kW
Range	*No data available*	*No data available*	160 km (H_2) 40 km (e)	*No data available*
H_2 storage capacity	20-40 kg @ 350 bar	15-20 kg @ 350 bar	20 kg @ 350 bar	30 kg @ 350 bar
Technology status	Vision Industries signed LoI in 2014 to supply 100 vehicles to TTSI but details of bankruptcy have slowed activity since late 2014.		Awarded R&D funding under ZECT II project (2015-2018)	







Abbreviations

APUB	Alternative Powertrains for Urban Buses study
BOP	Balance of plant
CCS	Carbon capture and storage
CNG	Compressed natural gas
CO2	Carbon dioxide
EERE	Office of Energy Efficiency and Renewable Energy
ETI	Energy Technologies Institute
FC	Fuel cell
FCEV	Fuel cell electric vehicle
FOA	Funding Opportunity Announcement
GDL	Gas diffusion layer
HDV	Heavy duty vehicle
HGV	Heavy goods vehicle
kW	kilo Watts
LDV	Light duty vehicle
LNG	Liquefied natural gas
MEA	Membrane electrode assembly
OEM	Original equipment manufacturer
PEM	Proton exchange membrane
Pt	Platinum
R&D	Research and development
RFI	Request For Information
UK	United Kingdom
US DOE	United States Department of Energy
ZE	Zero emission

Agenda

- Introduction
- **ZE vehicle component costs and trends**
  - **Fuel cell technology and costs**
  - Battery technology and costs
- Specification of existing diesel HDVs
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Fuel cell costs differ significantly between light and heavy duty vehicles and both are considered in this cost study

Introduction to fuel cell costs

- This section reviews the latest evidence on the current and future cost trends for fuel cell systems.
- There is currently a fundamental division between light duty fuel cell systems used in cars and vans, and heavy duty systems used in buses and trucks. Light duty systems have lower costs (c.£500/kW versus £1,500/kW), but currently have significantly lower stack lifetimes and require stack replacements during the life of a vehicle.
- Fuel cell manufacturers are working to achieve a target stack lifetime of 25,000 hours for HDVs (compared with c. 15,000 hours for current systems), while light duty stacks currently have lifetimes of 5,000 hours, sufficient for operations in passenger cars
- However, discussions with LDV stack developers suggest that LDV stack lifetimes could be extended to c. 15,000 hours thereby requiring only one stack replacement if used for HDV applications. Hybrid applications (use of large traction batteries and fuel cells together) are a key enabler for longer lifetimes as they allow constant output operation of the fuel cell and reduce thermal cycling
- Costs of both light and heavy duty stacks are presented in this section, given there is **not yet a consensus on whether next generation heavy vehicles will use light or heavy duty stacks**, in part because this decision depends on the sales volumes of fuel cell cars which are currently difficult to predict.

Current light and heavy duty systems differ in their packaging, performance and design lifetimes

	Automotive (light duty) fuel cell	Heavy duty fuel cell
Design priorities	**Compact, high power to weight ratio**	**Long lifetime, high efficiency**
Pressure	1-5 bar requiring turbo compression (and associated energy use)	0.1-0.5 bar requiring blower centrifugal pump
Temperature	80^{o}C requiring after cooling	50-70^{o}C variable temperature to modulate power
Current density	High (>1 A/cm^2) to support compact design	Low (<1 A/cm^2) to maximise efficiency
Performance (e.g. power per unit mass)	**Optimised**: high current density requiring twice O_2 throughput to what is used	**Lower priority**: low current density to avoid compromising system efficiency
Efficiency	**Lower priority**: high air handling and heating energy requirements; high current density	**Optimised**: low temperature and pressure to minimise energy consumption; low current density
Packaging	**Optimised**: BoP and FC designed for space-constrained housing e.g. FC between driver and passenger	**Lower priority**: BoP and FC can be housed in multiple sites on the vehicles e.g. under bonnet or behind cab
MEA thickness	Thin to maximise power to weight ratio	Thick for resilience but with higher mass
Cell pitch	Thinner cell pitch to maximise power density	>3 mm otherwise graphite sheet becomes too brittle
Lifetime	5,000 hours (OEM average) – could rise to 15,000[1]	10,000-15,000 hours (DoE target: 25,000 hours)
Non-FC components	Uses DC-DC converter to match fuel cell and bus voltage	Higher voltage FC systems could eliminate DC-DC conversion

Source: Consultation with fuel cell suppliers

1 – higher lifetime estimate based on a heavily hybridised powertrain

Four public studies, involving fuel cell cost modelling, have been identified as most relevant to the literature review of this work

1

Description: Economic, technical and environmental assessment of alternative powertrain technologies for buses in Europe with extensive industry consultations.

Author: McKinsey & Co

Published: 2012

Use: Granular cost projections for HDV fuel cell systems.

2

Description: Component level cost modelling for LDV and heavy duty fuel cells including Monte Carlo sensitivity analysis. R&D management and tracking technological progress. Updated annually since 2006.

Author: Strategic Analysis

Published: 2014

Use: Granular cost projections.

3

Description: Detailed review of LDV fuel cell costs with bottom-up component level analysis and multiple scenarios for future projections.

Author: Roland Berger

Published: 2014

Use: Understanding of cost reduction opportunities for different components.

4

Description: US government LDV fuel cell cost targets annually updated to drive industry innovation.

Author: US DoE

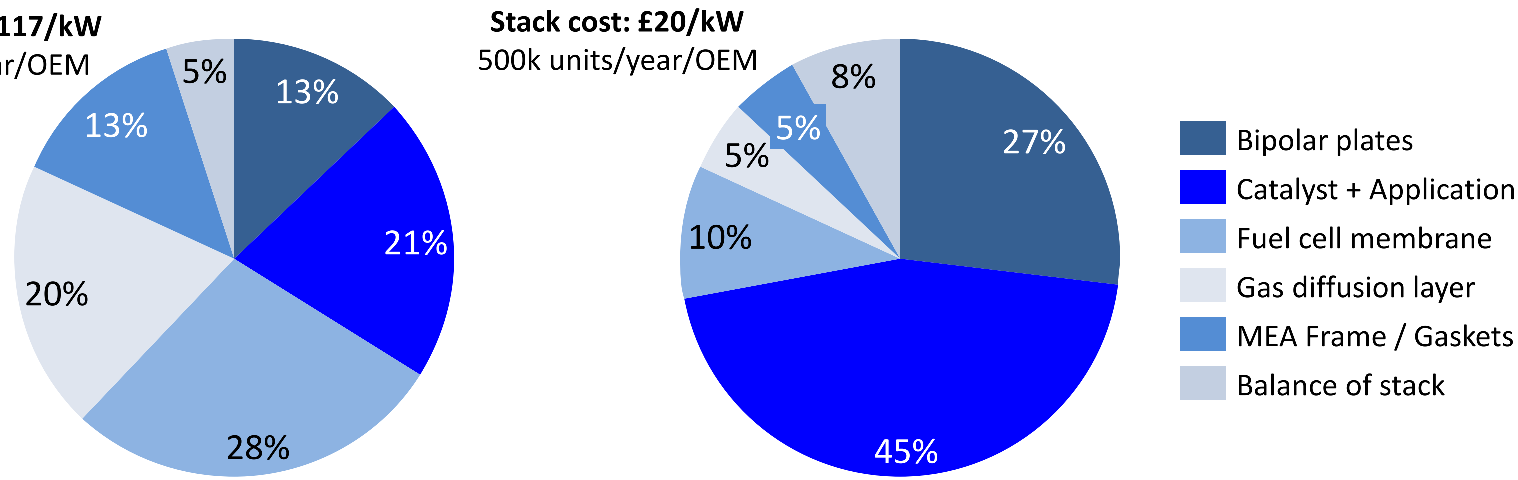
Published: 2015

Use: Ensure consistency between targets and projections.

Additional fuel cell cost projections have been obtained from presentations published by TIAX (2009) and Austin Power (2015)

Specialist stack component costs are likely to be sensitive to increased production volume but mature parts are unlikely to be significantly affected

Breakdown of target LDV fuel cell stack costs



- Catalyst and bipolar plate costs are governed by platinum and steel commodity prices respectively which are not expected to vary significantly with production levels below 1 million systems (annual production of 500,000 80 kW fuel cell systems containing 0.125 g_{Pt}/kW would represent c. 2% of global platinum demand). Reducing catalyst loading per cm^2 or per kW power output is one of the main drivers of fuel cell cost reduction
- Consequently, as fuel cell production volumes increase (from 1,000 to 500,000 systems/year/OEM) metal and application costs represent almost half the total stack cost and bipolar plates form over a quarter.
- Fuel cell membranes and GDLs are specialist items therefore their costs will benefit from economies of scale. This is illustrated by a decrease representing c. 50% to 15% of the total stack cost as volumes increase.
- MEA frames and balance of stack units are relatively mature technologies making cost savings difficult to achieve without redesign.

Sources: US DOE (2015)

There are many opportunities for improving current fuel cell technology costs which are being addressed in labs around the world

- Often strategies to improve fuel cell stack cost have detrimental effects to durability (and vice-versa), thus necessitating a design trade-off, e.g. stack cost and durability are both linked to the quantity (loading) of Pt catalyst.
- The table below describes a number of opportunities for improving stack cost where durability must not be detrimentally affected.

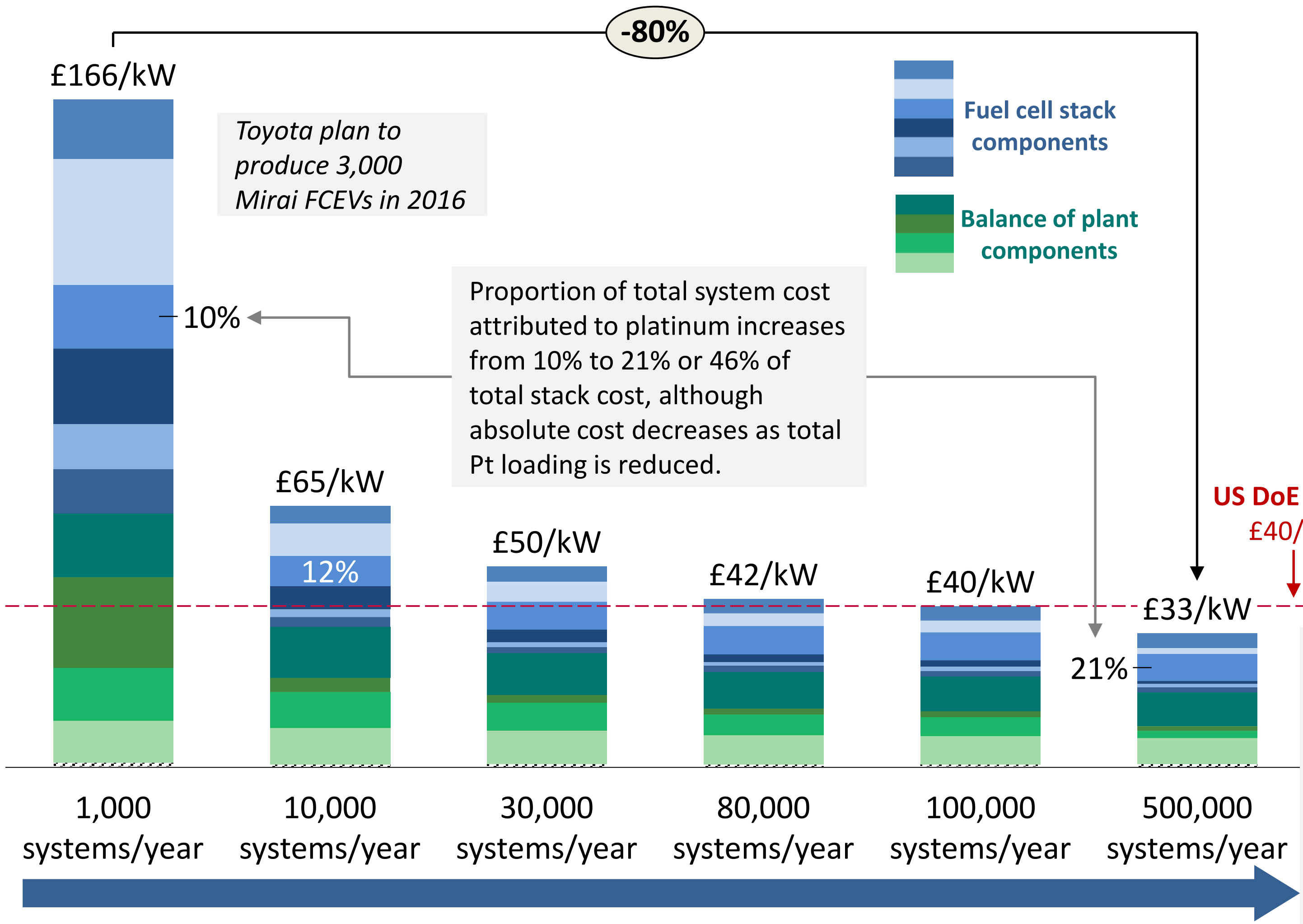
Component	Improvement
Materials	Use more a active catalyst to reduce Pt requirement (e.g. d-PtNi, PtCoMn, d-Pt_3Ni_7)
	Increase catalyst surface area (e.g. dispersion techniques, nano-frame or core shell structure)
	Develop non-Pt catalysts (e.g. nitrogen complexes of transition metals such as Zirconium)
	Explore alternative materials for bipolar plates (e.g. carbon-polymer composites)
Design	Standardise membranes that operate without humidification (e.g. via water retention and recirculation)
	Increasing operating temperature to enable greater impurity tolerance and reduce radiator size
	Developing system with high operating voltage (e.g. 600-700 V) to remove need for DC-DC conversion
	Increase stack current density thus reducing cell active area and Pt requirement
	Improve component sizing (e.g. membrane humidifier, air compressor, H_2 recirculation system)
	Improve understanding of degradation mechanisms to develop better mitigation strategies
	Improve stack performance thereby reducing BOP component requirements
	Develop system for efficient exhaust heat management
Manufac -turing process	Improve methods for applying Pt catalysts (e.g. slot die coating and vacuum deposition)
	Develop cheaper methods for coating and machining steel bipolar plates
	Develop cheaper methods for fabricating membrane sheets and the GDL
	Move from batch to continuous production (short-term opportunity)

Sources: industry consultation, Element Energy research, US Drive (2013)

Fuel cell cost projection vs volume production (1/2)

Bipolar Plates
Membranes
Catalyst Ink & Application
GDLs
MEA Gaskets
Other stack components
Air Loop
Humidifier & Water Recovery Loop
Sensors
Other BOP components
System assembly and testing

LDV PEM fuel cell system cost (£/kW [2015])

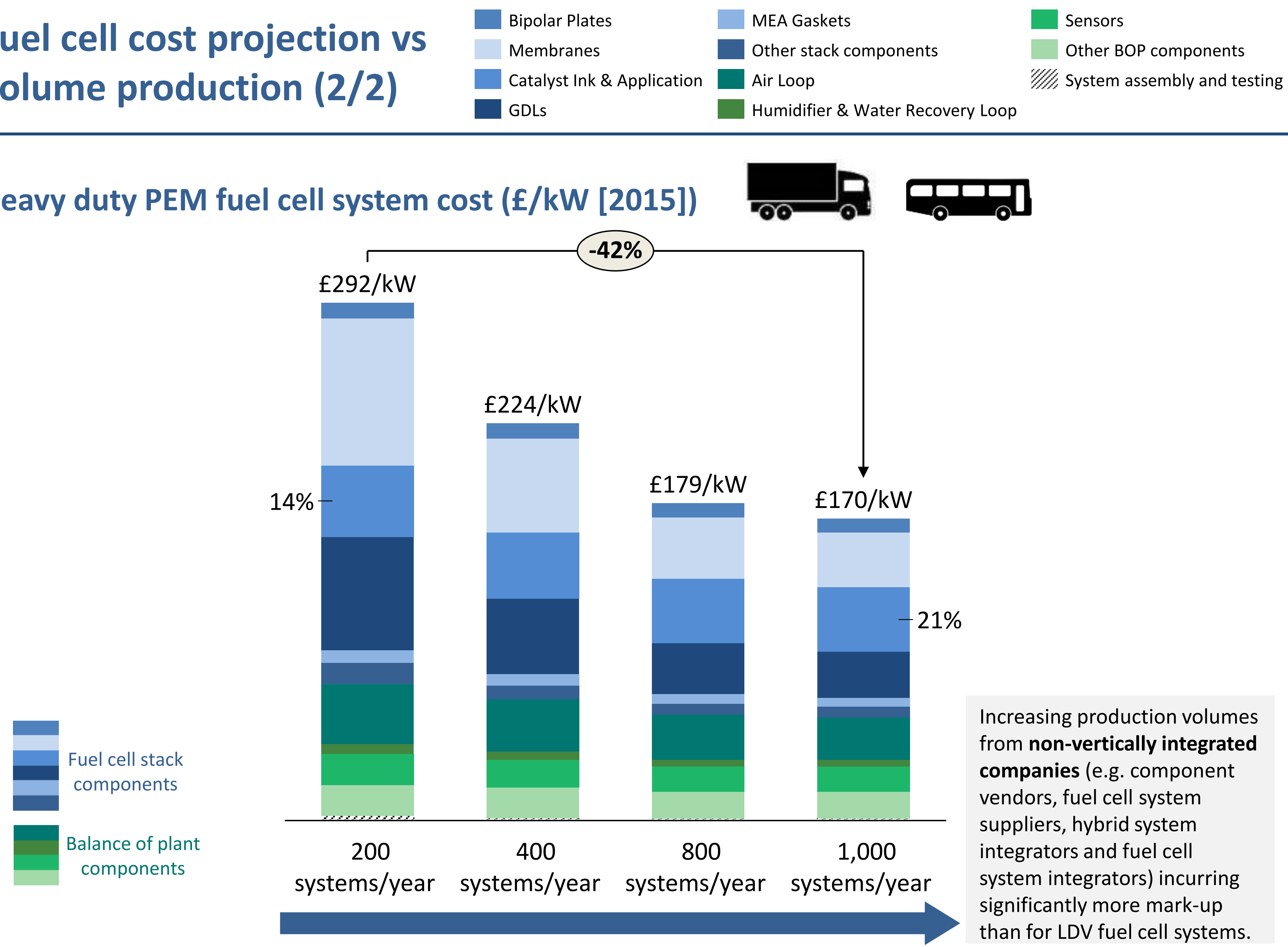


Increasing production volumes from **vertically integrated companies** conducting all manufacturing and assembly steps from raw materials to finished products to maximise cost efficiency and minimise mark-up.

Assumptions: fuel cell net power = 80 kW. Source: Strategy Analysis (2014), US DOE (2015).
'Other fuel cell components' includes gaskets, plates, current collectors, compression bands, stack insulation housing, stack assembly, stack conditioning.
'Other BOP components' includes high- and low-temperature coolant loop, fuel loop, system controller.

Fuel cell cost projection vs volume production (2/2)

Heavy duty PEM fuel cell system cost (£/kW [2015])



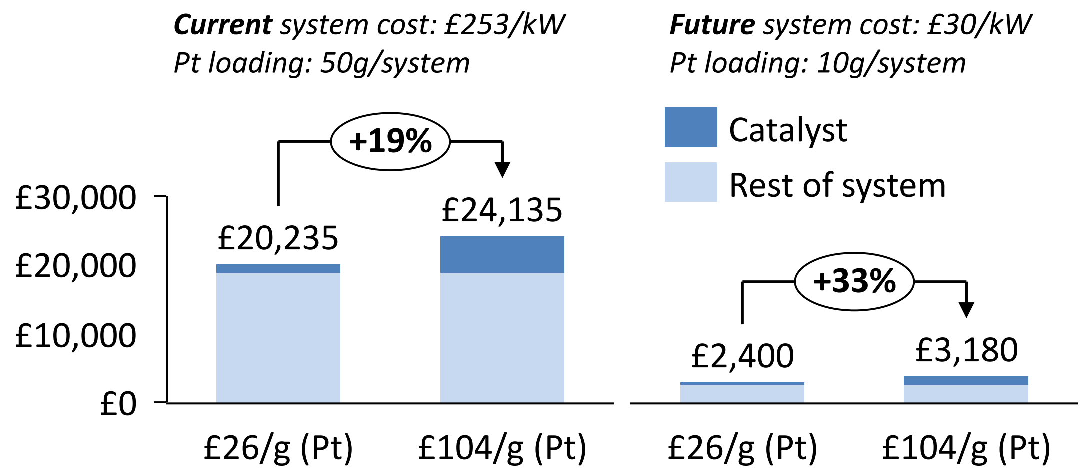
Increasing production volumes from **non-vertically integrated companies** (e.g. component vendors, fuel cell system suppliers, hybrid system integrators and fuel cell system integrators) incurring significantly more mark-up than for LDV fuel cell systems.

Assumptions: fuel cell net power = 160 kW. Source: Strategy Analysis (2014)
'*Other fuel cell components*' includes gaskets, plates, current collectors, compression bands, stack insulation housing, stack assembly, stack conditioning.
'*Other BOP components*' includes high- and low-temperature coolant loop, fuel loop, system controller.

Platinum material costs within fuel cells are expected to decrease over time, but will make up a higher proportion of total costs in future

- As previously outlined, large-scale production of relatively immature components (e.g. membranes, GDLs) is expected to drive significant cost reductions for these parts.
- Catalyst costs are linked to platinum commodity costs, and so higher platinum prices will increase fuel cell system costs. The platinum loading (in grams per stack) influences this exposure to changes in Pt prices.
- Catalyst loading in current fuel cell systems is uncertain but the general consensus is that today's LDV systems include c. 50 g of platinum per 80 kW stack and industry aims to reduce loading to c. 10 g per stack.
- Platinum loading in HDV stacks is much higher (100-200 g per stack) for increased durability.
- Under the current LDV loading, total platinum used makes up £1,300 per system and if the future specification target is achieved, total platinum costs would equate to £260 per system.

LDV fuel cell system costs with different levels of Pt loading

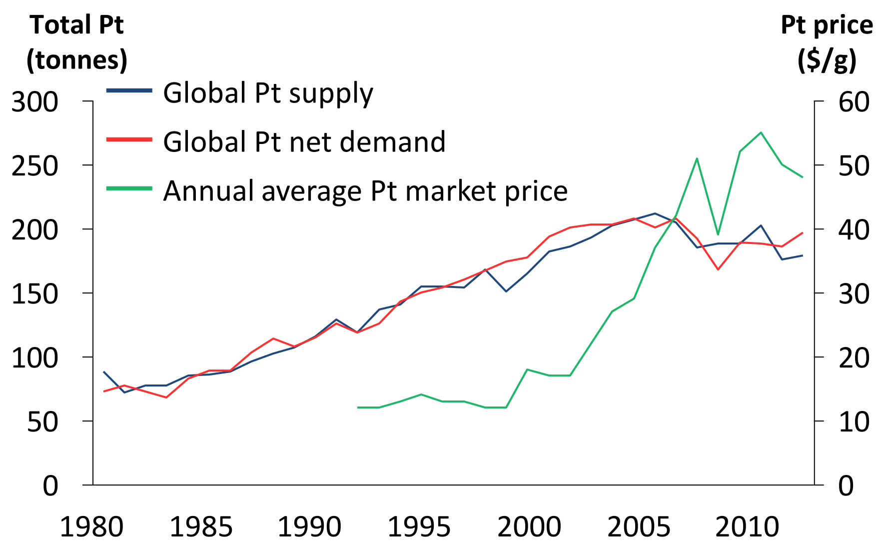


- Fuel cell system costs are not significantly exposed to Pt price volatility. For example, a doubling in platinum price today would have a minor impact on the overall system cost (↑ 6%).
- However, if future cost projections are achieved then quadrupling the Pt price will have a more significant impact of total system cost (↑ 33%).

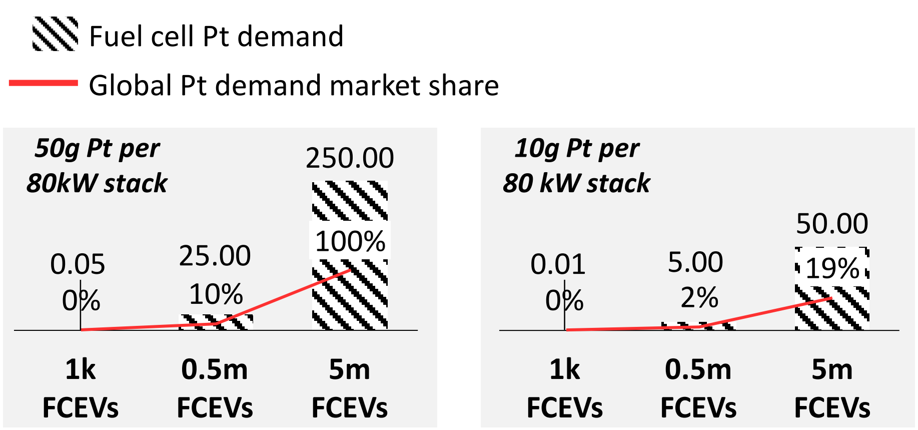
Assumptions: current platinum cost $1,133 per troy ounce = £26/g (Johnson Matthey)
Note: Toyota Mirai costs c. £60k in 2016

Future platinum use in fuel cells could significantly increase global demand, though falling Pt loading reduces the impact of future price changes on system costs

Pt supply and demand variation vs price volatility



FCEV volume dependent Pt demand (tonnes)



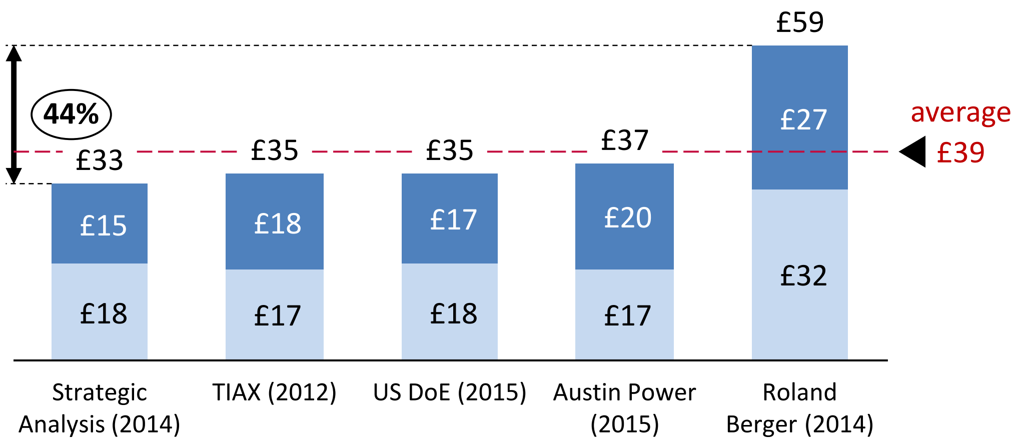
- Historically, global Pt supply has shown good flexibility in response to variations in global demand (annual supply and demand deviations of up to ± 15%).
- Significant proven global Pt reserves have been identified (>250 times annual demand), but capability of supply to meet demand with significant FCEV production ramp-up is unclear.
- Assuming current Pt content of 80 kW fuel cells (50g), annual production of 5 million FCEVs would double global Pt demand. However, if Pt content is reduced to 10g, annual production of 5 million cars would increase annual Pt demand by 19%.
- It should be noted that the expected fall in platinum loading reduces the impact of potential price rises, limiting the effect to £100s per stack rather than £1,000+ for current platinum loadings.

Sources: Statista (2015), Johnson Matthey (2015)

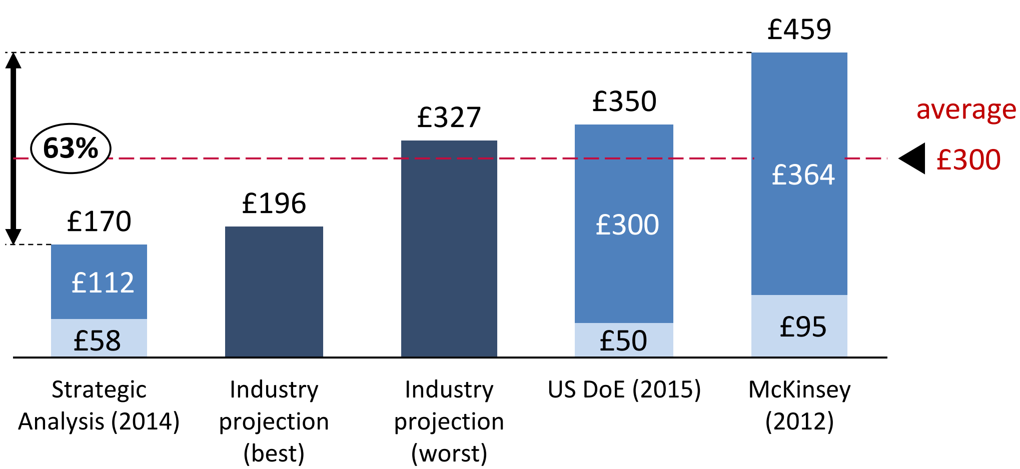
Existing analyses of LDV fuel cell cost projections are generally consistent but vary significantly for HDV costs

Stack
BOP and assembly
System

LDV PEM fuel cell system cost at production volumes of 500,000 units per year per manufacturer (£/kW [2015])



HDV PEM fuel cell system cost at production volumes of 1,000 – 1,500 units per year per manufacturer (£/kW [2015])



- Existing studies have employed different modelling methodologies and hold varying assumptions on how the market will develop.
- For LDV system costs, most studies (SA, TIAX, AP) are consistent with targets set by DoE. Conversely, the RB study is less optimistic, concluding that fuel cell technology will only reach full commercialisation if an alternative catalyst is developed in place of Pt.
- For HDV system costs, there is significant deviation between different studies (>60%).

Sources: Strategic Analysis (2014), US DOE (2015), TIAX (2011), Austin Power (2015), Roland Berger (2014), McKinsey (2012), industry consultation.
See references section for publication titles.

Using existing literature and industry consultation, we have developed three scenarios for LDV and HDV fuel cell cost reductions

- Performance improvements and cost reductions are essential to the commercialisation of fuel cells for transportation.
- Today, fuel cell systems are batch produced with many components assembled by hand. A number of opportunities exist to reduce fuel cell costs through improving design, materials (both quantity and type), manufacturing processes and system operation.
- Technical innovations are expected to be in advanced catalysis and flow field design. Common manufacturing innovations such as ordering parts in bulk, producing components in-house, using larger machinery and continuous production will help bring down fuel cell costs.
- A number of different fuel cell system cost projections have been illustrated in previous slides which are consistent with targets set by the US Department of Energy and have been validated through conversations with industry.
- Using existing literature and industry consultation, we have developed three scenarios for LDV and HDV fuel cell cost projections to 2050 which are linked to production volumes:
  - **Baseline** – average system cost from all sources at full scale production (500k for LDV, 1k for HDV).
  - **Slow reduction** – aligned with more conservative production volume and cost reduction estimates.
  - **Fast reduction** – aligned with more aggressive production volume and cost reduction estimates.
- When using the cost projections it is important to understand that some cost reductions will be possible simply by increasing the scale of production where as other cost reductions require interim learning and data to be collected to enable development of next generation technology. The balance between these two factors is not clear and has not be examined in detail in this study.

Fuel cell costs are directly linked to system production volumes – the scenarios capture several potential growth rates for fuel cell manufacture

- Fuel cell system cost projections are directly linked to specific system production volumes. To develop the scenarios, specific production volumes have been linked to particular years depending on the expected the rate of development.
- For example, LDV fuel cell system costs are expected to reach £60/kW at production volumes of 200,000 systems per year per fuel cell system manufacturer. This volume (and therefore cost) is achieved by 2020 in the *fast reduction* scenario, by 2025 in the *baseline* and not until 2035 in the *slow reduction* scenario.
- Large-scale production (500,000 systems per year) is achieved by 2040 in the *baseline* scenario with a system cost of £35/kW which is the average system cost from literature at large-scale production.
- Similarly, for HDV fuel cell systems, costs are expected to fall to £500/kW at production volumes of 200 systems per year which is achieved by 2020 in the *fast reduction* scenario, by 2025 in the *baseline* scenario and by 2035 in the *slow reduction* scenario.
- Large-scale production of HDV systems (1,500 systems per year) is achieved by 2050 in the *baseline* scenario with a system cost of £300/kW which, as for the LDV case, is the average system cost from literature.
- Tables below shows the years that particular fuel cell system costs are reached under the different scenarios.

Year that LDV FC system cost projections are reached

	£260/kW	£60/kW	£35/kW
Baseline	2015	2025	2040
Fast reduction	2015	2020	2035
Slow reduction	2015	2035	>2050

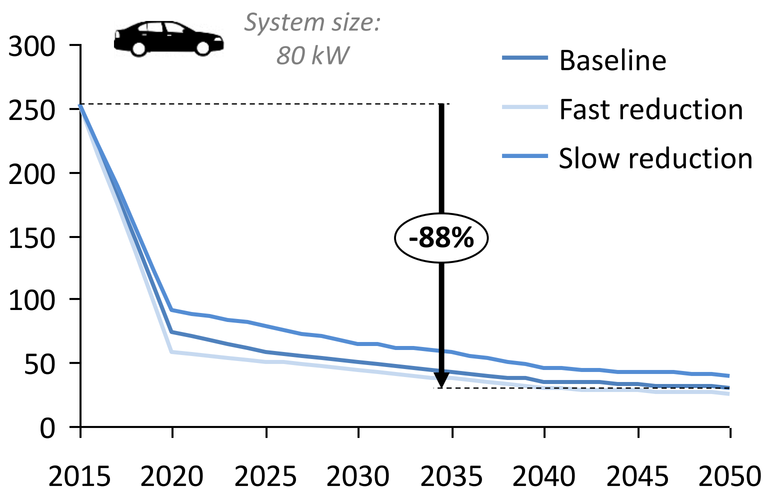
Year that HDV FC system cost projections are reached

	£1,500/kW	£500/kW	£300/kW
Baseline	2015	2025	2050
Fast reduction	2015	2020	2030
Slow reduction	2015	2035	>2050

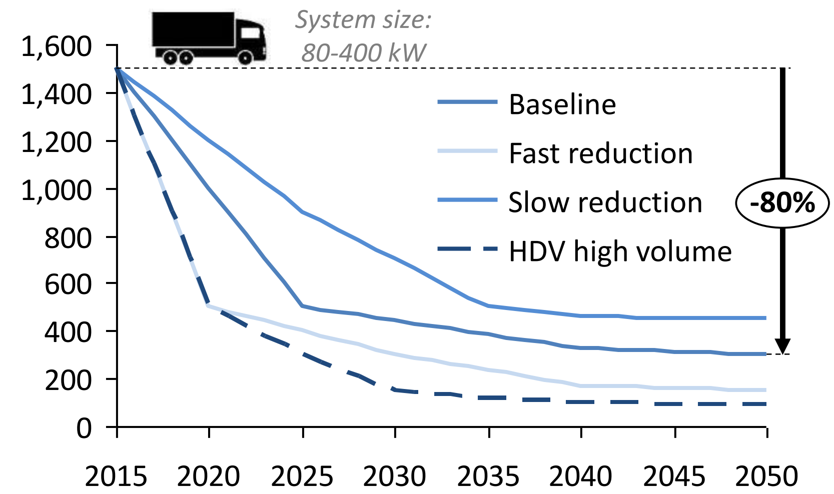
Source: OICA (2014), Element Energy analysis

LDV and HDV fuel cell system cost projections have been developed from existing literature and industry consultation

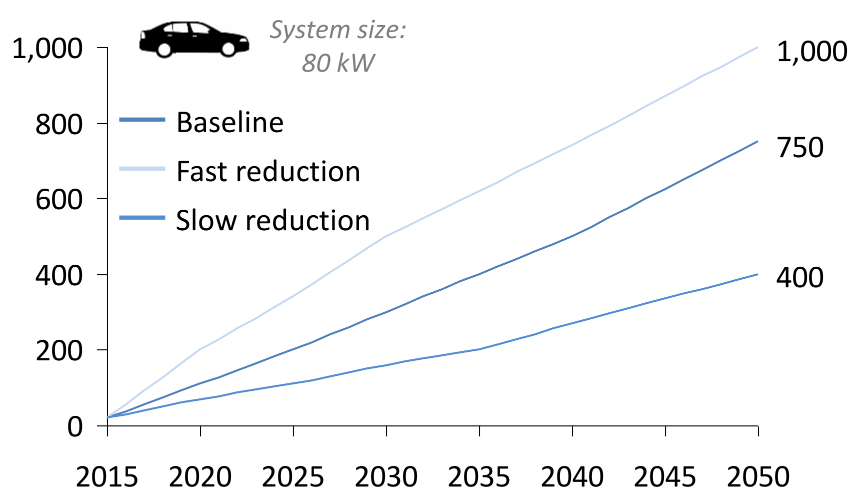
LDV PEM fuel cell system cost (£/kW [2015])



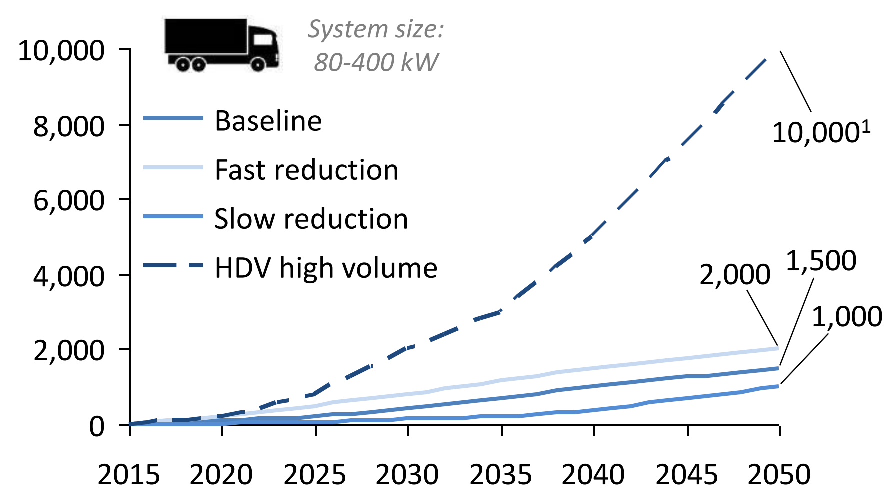
HDV PEM fuel cell system cost (£/kW [2015])



Total LDV FC systems produced annually (1000s/OEM)



Total HDV FC systems produced annually (systems/OEM)



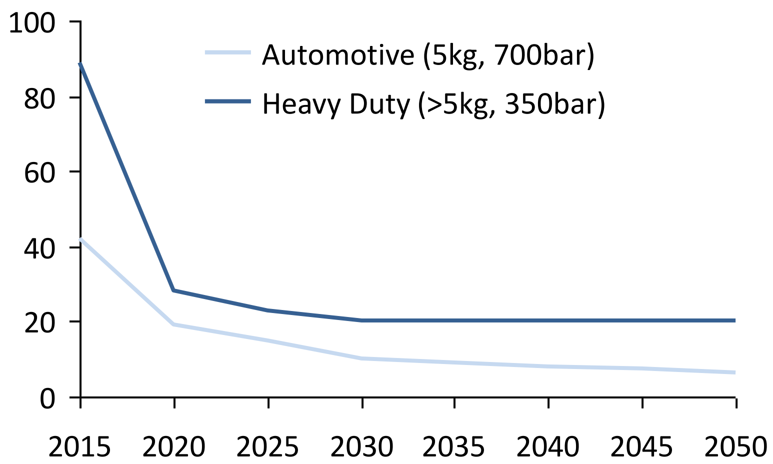
Source: Element Energy analysis informed by literature review (see previous slides). 1 – see next slide for basis of 10,000 volume scenario

We developed an additional scenario for HDV FC system costs to represent higher sales volumes in the truck sector compared to the bus industry

- Technical differences between LDV and HDV fuel cell systems are well understood and have been outlined in detail in the previous sections. However, the significant cost difference between LDV and HDV systems (£35/kW vs £300/kW) at high volume production levels suggest that HDV costs could benefit from factors driving LDV cost reduction.
- All HDV fuel cell cost projections to date focus on volumes expected in the bus sector of 1000s of units per year. This is due to the majority of demonstration activities to date being focused on the bus sector, where green procurement policies of public authorities have provided an easier route to market than in the truck sector. The consequence of this is that cost projections to date have not explored the potential cost reduction of higher volume production (in the 10,000s of units per year) and tighter supply chain integration in a scenario with successful mass market deployment of fuel cell trucks.
- To reflect this potential additional saving, we have developed an additional scenario – **HDV high volume** – to represent HDV fuel cell systems produced at volumes an order or magnitude higher than the current production projections (10,000 units per year vs 1,000 units per year).
- The **HDV high volume** scenario represents aggressive cost reductions achieved through fuel cell production volumes of 10,000 units per year and is derived by taking the LDV system cost at 10,000 units and replacing the LDV catalyst component with the HDV catalyst component to represent higher Pt loading (c. 100g per stack vs 10g per stack).

Hydrogen tank capital costs are expected to fall with volume production and technology innovation

Hydrogen tank cost projections (£/kWh [2015])



Tank production volumes per manufacturer per year are consistent with the baseline stack production volumes

- Tank costs are similarly linked to production volumes.
- Larger production volumes in the LDV sector and novel light-weight composite materials are expected to drive cost reductions in the hydrogen storage technology.
- 350 bar tanks for heavy duty applications have lower capital cost per tank but higher costs per kWh of stored hydrogen than 700 bar tanks due to lower volumetric density.
- Less emphasis has been placed on heavy duty tank costs compared with fuel cell costs in demonstrations to date. Discussions with powertrain integrators suggested a need for specific targets for HDV tanks on a cost per kilogram basis, and associated R&D initiatives to meet these targets.

Source: Element Energy analysis informed by literature review: IEA (2015), ECF (2015), McKinsey&Co (2012) .

Agenda

- Introduction
- **ZE vehicle component costs and trends**
  - Fuel cell technology and costs
  - **Battery technology and costs**
- Specification of existing diesel HDVs
- Market review of existing zero emission HDVs
- Specification of zero emission HDVs
- Results from design exercise
- Conclusions and potential for innovation
- References

For consistency, battery costs have been aligned with the CVEI project

We have aligned the battery costs used in the HDV powertrain modelling with the final Stage 1 outputs from the CVEI Project for consistency. These have been used in the model accompanying this report (Deliverable 9.1)

Agenda

- Introduction
- ZE vehicle component costs and trends
- **Specification of existing diesel HDVs**
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Technical specifications for vehicle archetypes are derived from leading OEM vehicles available to fleet operators today

- An extensive review of OEM technical data has been conducted to establish technical specifications for heavy duty vehicle ‘archetypes’ (i.e. representative ‘average’ vehicles in each size class).
- All relevant **heavy duty cycles** have been considered including service, urban delivery, municipal utility, regional delivery, long haul and construction for trucks and urban and inter-city for buses.
- Vehicle **weight categories** have been developed in-line with ETI’s existing categories:
  - Medium Goods Vehicles: 7-8 tonnes, 8-17 tonnes
  - Heavy Goods Vehicles: 17-25 tonne rigid, >25 tonne rigid, <33 tonne articulated, >33 tonne articulated
  - Buses: 6m minibus, 9m midibus, 12m single decker bus, 12m double decker bus, 12m 2-axle coach and 15m 3-axle coach
- Standard component configurations (e.g. single diesel tank, intermediate engine power) were collated across different leading vehicle developers and were used to develop archetype technical specifications.
- For heavy-duty trucks, specifications from Scania, MAN and Volvo have been assessed. For buses, specifications from Optare, Van Hool and Alexander Dennis were used.
- The following slides illustrate the data points extracted from technical brochures and show how the archetypes were developed.

Example technical specification of a long haul truck

Specification	Units	Volvo	Scania	MAN	Archetype
Model (engine type)	-	*FH 4x2 (D13c500)*	*R 410 4x2 (DC13-125)*	*TGX 4x2 (D2676LF46)*	*4x2, artic.*
Gross combined weight	*tonnes*	Up to 60 (40 in UK)	Up to 70 (40 in UK)	Up to 40	40[1]
Diesel ICE power	*kW*	368	360	323	350
Diesel ICE displacement	*L*	12.8	n/a	n/a	12.8
Diesel tank capacity	*L*	150-900	300	400	600
Fuel consumption	*L/100km*	Data not available	Data not available	Data not available	33.0[2]
Engine BTE (peak/average)	*%*	Data not available	Data not available	Data not available	44.5% / 42.7%[3]

[1]Consistent with the >33t articulated category based on ETI's internal classification. The maximum permissible gross weight in the UK is 44t, although 4x2 tractors are likely to operate at a maximum 40t gross weight
[2]Based on archetype fuel consumptions from existing studies from TIAX, ICCT and R-AEA.
[3]ICCT (2016).

Example technical specification of a single decker bus

Specification	Units	Optare	ADL	Van Hool	Archetype
Model	-	*Metrocity*	*Enviro300*	*A330*	-
Length	*m*	12	12	12	12
Diesel ICE power	*kW*	150	166	235	185
Diesel ICE displacement	*L*	6.7	6.7	n/a	6.7
Diesel tank capacity	*L*	200	250	260	200
Fuel consumption	*L/100km*	Data not available	Data not available	Data not available	39.0[1]
Peak engine BTE	*%*	Data not available	Data not available	Data not available	38%[2]

[1]Based on real-world fuel consumption data from consultations with multiple fleet operators in the UK.
[2]Fuel energy converted to brake power for archetype single decker bus engine (TIAX, 2011).

Agenda

- Introduction
- ZE vehicle component costs and trends
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A number of zero emission HGVs have been developed in the US for short mileage duty cycles (e.g. terminal and shuttling)

Developer	**Vision Corp**	**Vision Corp**	**TransPower**	**BAE Systems**
Model	Tyrano	Zero-TT	ElecTruck	Kenworth T370
Configuration	Fuel cell hybrid electric	Battery with FC range extender	Battery with FC range extender	Fuel cell hybrid electric (battery dominant)
Duty cycle	Terminal tractor	Terminal tractor	Terminal tractor	Terminal tractor
Gross weight	36 tonnes	60 tonnes	36 tonnes	36 tonnes
Fuel cell power	33 kW (Hydrogenics)	26.5 kW	2 x 30 kW (Hydrogenics)	80 kW (Ballard HD-7)
Battery capacity	*No data available*	*No data available*	120 kWh	100 kWh
Motor power	170 kW	170 kW	300 kW	360 kW
Range	*No data available*	*No data available*	160 km (H_2) 40 km (e)	*No data available*
H_2 storage capacity	20-40 kg @ 350 bar	15-20 kg @ 350 bar	20 kg @ 350 bar	30 kg @ 350 bar
Technology status	Vision Industries signed LoI in 2014 to supply 100 vehicles to TTSI but details of bankruptcy have slowed activity since late 2014.		Awarded R&D funding under ZECT II project (2015-2018)	

Source: Vision Corp, TransPower, BAE Systems

US Hybrid is developing a wide variety of different fuel cell electric hybrid trucks for different duty cycles with two currently in production

Developer	**US Hybrid**	**US Hybrid**	**US Hybrid**	**US Hybrid**
Model	H_2Tug	H_2Truck	H_2Cargo	H_2Ride
Configuration	Fuel cell plug-in electric	Fuel cell hybrid electric	Fuel cell plug-in electric	Fuel cell plug-in electric
Duty cycle	Tow tractor	Terminal tractor	Urban delivery	Shuttling
Gross weight	45 tonnes	36 tonnes	6 tonnes	10 tonnes
Fuel cell power	30 kW (Hydrogenics)	85 kW (US FuelCell)	30 kW (Hydrogenics)	30 kW (Hydrogenics)
Battery capacity	22 kWh Li-ion	22-36 kWh Li-ion	28 kWh Li-ion	28 kWh Li-ion
Motor power	240 kW	320 kW	120 kW	200 kW
Range	12 hrs (24 km/h max speed)	320 km (H_2) 8-24 km (e)	200 km (H_2) 31 km (e)	320 km (H_2) 24 km (e)
H_2 storage capacity	10 kg @ 350 bar	40 kg @ 350 bar	10 kg @ 350 bar	20 kg @ 320 bar
Technology status	In development	In development	In production	In production

Source: US Hybrid

For terminal tractor and urban delivery models, US Hybrid have developed both fuel cell hybrid and pure electric versions

Developer	US Hybrid		US Hybrid	
Model	H_2Truck	eTruck	H_2Cargo	eCargo
Configuration	Fuel cell hybrid electric	Plug-in battery electric	Fuel cell plug-in electric	Plug-in battery electric
Duty cycle	Terminal tractor	Terminal tractor	Urban delivery	Urban delivery
Gross weight	36 tonnes	36 tonnes	6 tonnes	4.5 tonnes
Fuel cell power	85 kW (US FuelCell)	-	30 kW (Hydrogenics)	-
Battery capacity	22-36 kWh Li-ion	240 kWh Li-ion	28 kWh Li-ion	36 kWh Li-ion
Motor power	320 kW	320 kW	120 kW	120 kW
Range	320 km (H_2) 8-24 km (e)	160 km (e)	200 km (H_2) 31 km (e)	120 km (e)
H_2 storage capacity	20-40 kg @ 350 bar	-	10 kg @ 350 bar	-
Technology status	In development	In development	In production	In production

Source: US Hybrid

Multiple examples of pure battery electric HGVs have also been developed for short range applications

Developer	BMW / Terberg	Mercedes
Model	YT202- EV	Urban eTruck
Configuration	Battery electric	Battery electric
Duty cycle	Short haul	Urban delivery
Gross Weight	36 tonnes	26 tonnes
Fuel cell power	-	-
Battery capacity	113 kWh LFMP	3 x 70 = 212 kWh Li-ion
Motor power	138 kW	2 x 125 kW
Range	100km	200 km
H_2 storage capacity	-	-
Technology status	Prototype demonstration in Berlin announced July 2016	Prototype unveiled July 2016

Two additional concepts from Tesla (pure battery) and Nicola (fuel cell hybrid) have been announced but no further details are currently available, hence they have been excluded from the table.

Source: BMW and Mercedes press releases

Agenda

We have developed a model to formulate technical specifications for different zero emission heavy duty vehicles

- For each diesel vehicle we have considered six approaches for developing a zero emission alternative with increasing efforts to minimise the overall cost, payload and packaging premium:
  1. **Parity** to diesel incumbent (e.g. equivalent driving range achieved with hydrogen storage) using baseline HDV fuel cell system costs in 2020. *title in tables and graphs: Parity FC truck (2020)*
  2. **Optimised** by making compromises where viable without affecting daily operation (e.g. reducing range but meeting daily driving needs). Important to avoid zero emission vehicle technical specifications with higher than necessary performance derived but prohibitive costs. *title: Optim. FC truck (2020)*
  3. **Hybridised**, changing the levels of hydrogen and battery storage and fuel cell sizing to reduce costs, whilst also maintaining optimised specification and baseline 2020 costs. *title: Optim. Hyb. FC truck (2020)*
  4. **High volume HDV** fuel cell production costs used to represent large-scale production volumes, again whilst maintaining optimised and hybridised specification and baseline 2020 costs. *title: Optim. Hyb., high vol. FC (2020)*
  5. **Future cost reductions**, by taking 2030 baseline fuel cell costs with the same optimisation and hybridisation assumptions. *title: Optim. Hyb. FC truck (2030)*
  6. **Future high volume HDV** production costs used with the same optimisation and hybridisation assumptions. *title: Optim. Hyb., high vol FC (2030)*

There are four main hybridisation archetypes for configuring fuel cell and battery technologies in zero emission drivetrains

Full FCEV ↓ Full BEV

Option	Fuel cell sizing	Battery sizing	Description	Example applications
1	Primary power (90%)	Energy Regen. (10%)	Large fuel cell (100-300 kW) provides the bulk of the energy to the electric motor with a small battery system to capture energy from regenerative braking and support high power demands (e.g. hill starts). Vehicle has one fuel source and does not need to be plugged-in.	Long haul: energy requirements of very long haul operations cannot be met with batteries and power
2	Mid-power (30%)	Mid-power (70%)	Balanced split between FC and battery capacity sizing. Allows smaller battery and greater hydrogen storage capacity to minimise overall payload penalty and allows longer operation at higher power.	Municipal utility: size FC to be utilised at constant load e.g. to charge battery during stop-start refuse collection duty cycle
3	Range extender (20%)	Primary power (80%)	Small fuel cell (20-50kW) provides additional energy to larger battery system to extend vehicle driving range. FC augments battery range rather than provide drivetrain power.	Urban delivery: ordinarily plugged-in and power is optimised for average duty cycle power.
4	(0%)	Full power (100%)	No fuel cell, only battery to provide energy and power to the electric motor. Eliminates the need for hydrogen storage and infrastructure	Urban delivery: hydrogen tank and fuel cell can be excluded if user is willing to accept a significant range penalty e.g. for short distance routes

- Boundary between options 2 and 3 is flexible
- As fuel costs decrease, hybridisation preference is likely to shift from range extender to mid-power

Agenda

- Introduction
- ZE vehicle component costs and trends
- Specification of existing diesel HDVs
- Market review of existing zero emission HDVs
- **Specification of zero emission HDVs**
    - Methodology
    - **ZE HDV examples**
- Results from design exercise
- Conclusions and potential for innovation
- References

7-8t service vehicle

Example 1

Specification for zero emission vehicle

Description		Parity FC truck (2020)	Optim. FC truck (2020)	Optim. Hyb. FC truck (2020)	Optim. Hyb., high vol. FC (2020)	Optim. Hyb. FC truck (2030)	Optim. Hyb., high vol FC (2030)
Motor power	*kW*	150	150	150	150	150	150
Fuel cell power	*kW*	135	135	45	45	45	45
Fuel cell cost	*£*	135000	135000	45000	22500	19890	6750
Fuel cell mass	*kg*	450	450	150	150	150	150
Fuel cell volume	*Litres*	675	675	225	225	225	225
Efficiency	*%*	0.50	0.50	0.50	0.50	0.50	0.50
H2 tank capacity	*kg*	29	15	10	10	10	10
H2 tank cost	*£*	26981	13490	9443	9443	6745	6745
H2 tank mass	*kg*	531	265	186	186	186	186
H2 tank volume	*Litres*	1659	830	581	581	581	581
Full tank mass	*kg*	560	280	196	196	196	196
Battery power	*kW*	15	15	105	105	105	105
Battery capacity	*kWh*	25	13	76	76	76	76
Battery cost	*£*	4730	4164	11708	11708	7695	7695
Batt. efficiency	*%*	0.95	0.95	0.95	0.95	0.95	0.95
Battery mass	*kg*	177	116	492	492	330	330
Battery volume	*Litres*	74	64	195	195	122	122
Range	*km*	938	469	469	469	469	469

Specification for diesel vehicle

Description		
Diesel ICE power	kW	150
Diesel ICE cost	£	8400
Diesel ICE mass	kg	484
Diesel ICE volume	L	753
Diesel tank cost	£	300
Full diesel tank mass	kg	158
Diesel tank capacity	L	150
Gearbox & clutch cost	£	2000
Gearbox & clutch mass	kg	100
Gearbox & clutch volume	L	250
Range	km	938

Sources: ICE costs (Ricardo-AEA, 2012), ICE mass and volume (average kg/kW and L/kW developed from publically available OEM specifications), tank cost (truckparts4u.com). Fuel cell mass and volume densities (industry consultation & literature (US Drive, 2013), (Argonne, 2010)), battery costs and densities (Element Energy, 2016).

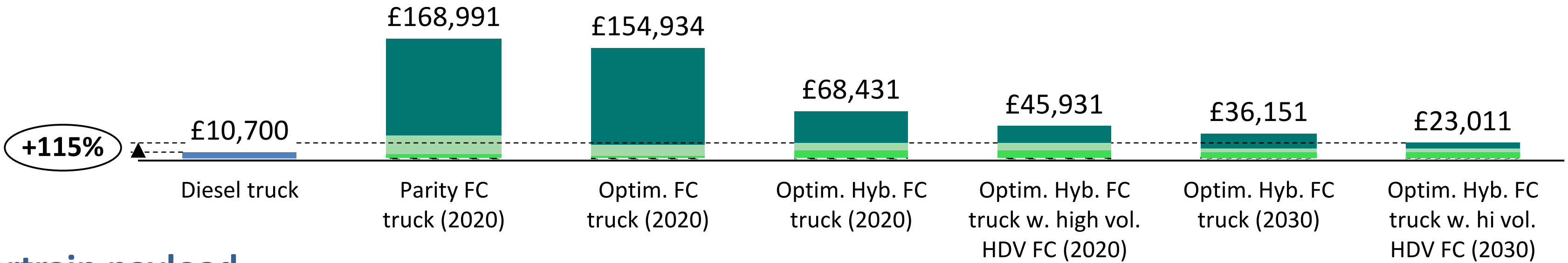
7-8t service vehicle

Example 1

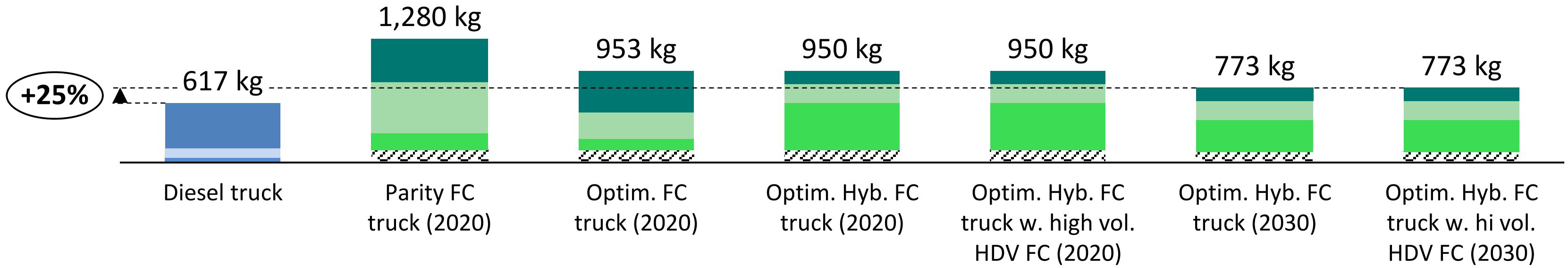
Diesel ICE
Gearbox & clutch
Diesel tank
Fuel cell
Hydrogen tank
Battery
Electric motor
Inverter

A Powertrain cost comparison

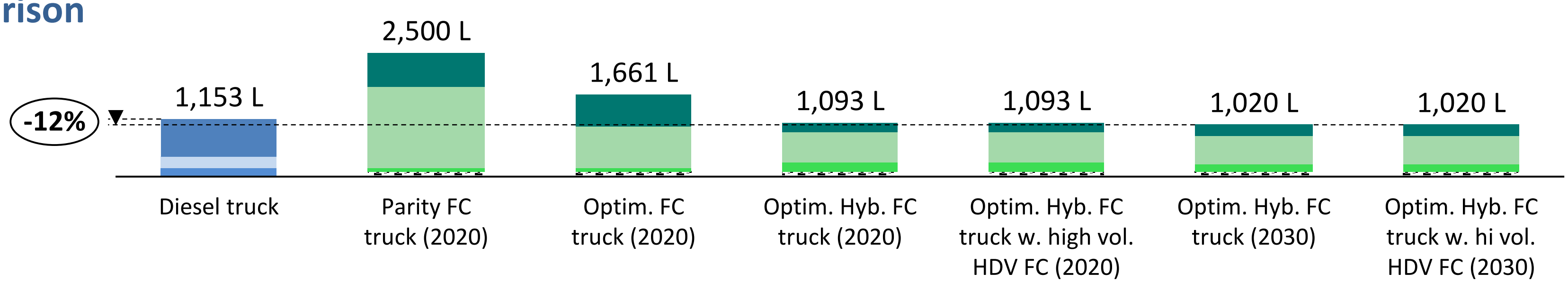
Optim. = Optimised performance with **50% driving range and 100% rated power** of diesel vehicle
Hyb. = Hybridised drivetrain with mid range power configuration with **30% power from FC, 70% power from battery**
High vol. HDV FC = FC costs based on the high volume HDV scenario (target of 10,000s per year by 2050) with £500/kW by 2020 and £150/kW by 2030.



B Powertrain payload comparison



C Powertrain packaging comparison



Example 2

17-25t regional delivery vehicle

Specification for zero emission vehicle Description		Parity FC truck (2020)	Optim. FC truck (2020)	Optim. Hyb. FC truck (2020)	Optim. Hyb., high vol. FC (2020)	Optim. Hyb. FC truck (2030)	Optim. Hyb., high vol FC (2030)
Motor power	*kW*	250	250	250	250	250	250
Fuel cell power	*kW*	225	225	75	75	75	75
Fuel cell cost	*£*	225000	225000	75000	37500	33150	11250
Fuel cell mass	*kg*	750	750	250	250	250	250
Fuel cell volume	*Litres*	1125	1125	375	375	375	375
Efficiency	*%*	0.50	0.50	0.50	0.50	0.50	0.50
H2 tank capacity	*kg*	52	26	18	18	18	18
H2 tank cost	*£*	48171	24086	16860	16860	12043	12043
H2 tank mass	*kg*	948	474	332	332	332	332
H2 tank volume	*Litres*	2962	1481	1037	1037	1037	1037
Full tank mass	*kg*	1000	500	350	350	350	350
Battery power	*kW*	25	25	175	175	175	175
Battery capacity	*kWh*	45	23	136	136	136	136
Battery cost	*£*	7612	4737	20903	20903	13738	13738
Batt. efficiency	*%*	0.95	0.95	0.95	0.95	0.95	0.95
Battery mass	*kg*	304	167	878	878	590	590
Battery volume	*Litres*	132	76	349	349	217	217
Range	*km*	791	395	395	395	395	395

Specification for diesel vehicle Description		
Diesel ICE power	kW	250
Diesel ICE cost	£	14000
Diesel ICE mass	kg	807
Diesel ICE volume	L	1254
Diesel tank cost	£	400
Full diesel tank mass	kg	200
Diesel tank capacity	L	200
Gearbox & clutch cost	£	2000
Gearbox & clutch mass	kg	100
Gearbox & clutch volume	L	250
Range	km	791

Sources: ICE costs (Ricardo-AEA, 2012), ICE mass and volume (average kg/kW and L/kW developed from publically available OEM specifications), tank cost (truckparts4u.com). Fuel cell mass and volume densities (industry consultation & literature (US Drive, 2013), (Argonne, 2010)), battery costs and densities (Element Energy, 2016).

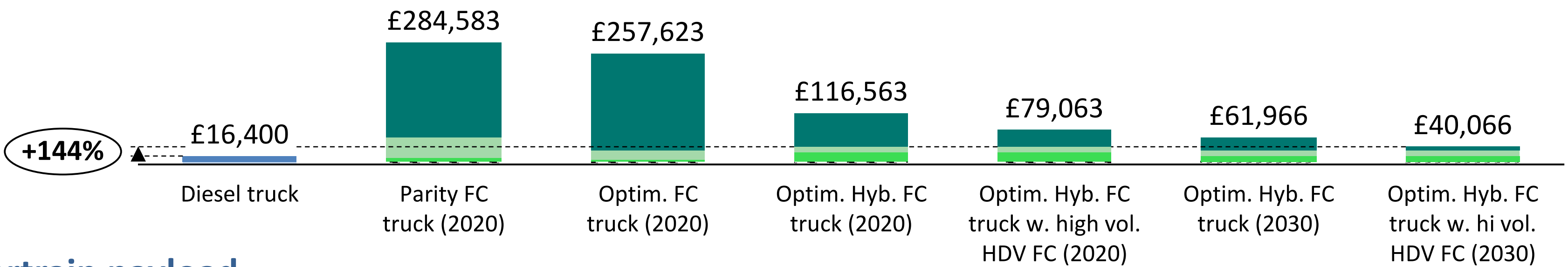
17-25t regional delivery vehicle

Example 2

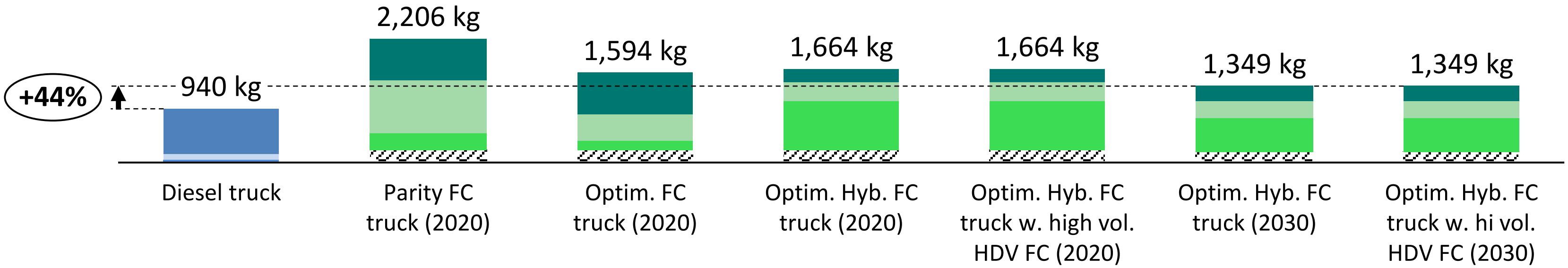
- Diesel ICE
- Gearbox & clutch
- Diesel tank
- Fuel cell
- Hydrogen tank
- Battery
- Electric motor
- Inverter

Optim. = Optimised performance with **50% driving range and 100% rated power** of diesel vehicle
Hyb. = Hybridised drivetrain with mid range power configuration with **30% power from FC, 70% power from battery**
High vol. HDV FC = FC costs based on the high volume HDV scenario (target of 10,000s per year by 2050) with £500/kW by 2020 and £150/kW by 2030.

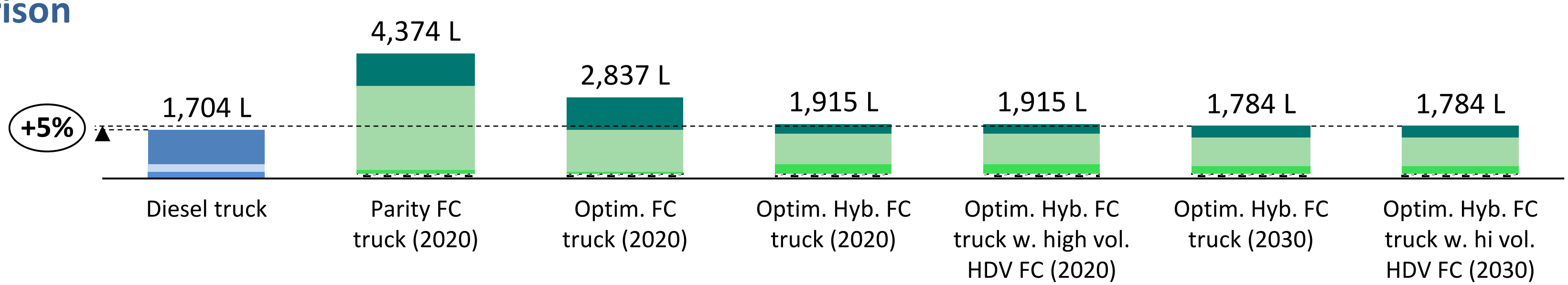
A Powertrain cost comparison



B Powertrain payload comparison



C Powertrain packaging comparison



Example 3

>25 tonne refuse collection vehicle

Specification for zero emission vehicle

Description		Parity FC truck (2020)	Optim. FC truck (2020)	Optim. Hyb. FC truck (2020)	Optim. Hyb., high vol. FC (2020)	Optim. Hyb. FC truck (2030)	Optim. Hyb., high vol FC (2030)
Motor power	*kW*	250	250	250	250	250	250
Fuel cell power	*kW*	225	225	75	75	75	75
Fuel cell cost	*£*	225000	225000	75000	37500	33150	11250
Fuel cell mass	*kg*	750	750	250	250	250	250
Fuel cell volume	*Litres*	1125	1125	375	375	375	375
Efficiency	*%*	0.50	0.50	0.50	0.50	0.50	0.50
H2 tank capacity	*kg*	78	39	27	27	27	27
H2 tank cost	*£*	72257	36128	25290	25290	18064	18064
H2 tank mass	*kg*	1422	711	498	498	498	498
H2 tank volume	*Litres*	4443	2222	1555	1555	1555	1555
Full tank mass	*kg*	1500	750	525	525	525	525
Battery power	*kW*	25	25	175	175	175	175
Battery capacity	*kWh*	68	34	204	204	204	204
Battery cost	*£*	10451	6333	31354	31354	20607	20607
Batt. efficiency	*%*	0.95	0.95	0.95	0.95	0.95	0.95
Battery mass	*kg*	439	237	1317	1317	885	885
Battery volume	*Litres*	174	99	523	523	325	325
Range	*km*	543	272	272	272	272	272

Specification for diesel vehicle

Description		
Diesel ICE power	kW	250
Diesel ICE cost	£	14000
Diesel ICE mass	kg	807
Diesel ICE volume	L	1254
Diesel tank cost	£	600
Full diesel tank mass	kg	301
Diesel tank capacity	L	300
Gearbox & clutch cost	£	2000
Gearbox & clutch mass	kg	100
Gearbox & clutch volume	L	250
Range	km	543

Sources: ICE costs (Ricardo-AEA, 2012), ICE mass and volume (average kg/kW and L/kW developed from publically available OEM specifications), tank cost (truckparts4u.com). Fuel cell mass and volume densities (industry consultation & literature (US Drive, 2013), (Argonne, 2010)), battery costs and densities (Element Energy, 2016).

40% of energy converted from fuel in refuse trucks is used by hydraulic machinery, leaving 60% for driving. Therefore 50% range optimisation has a smaller effect than for other vehicle types.

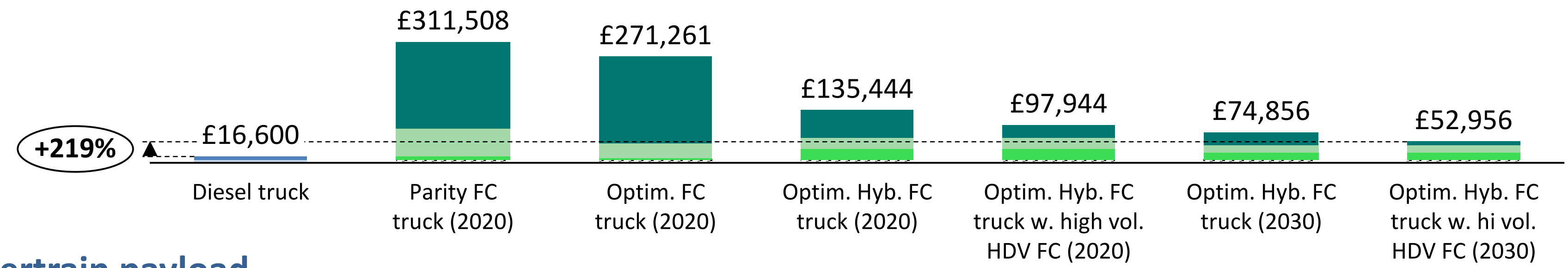
>25 tonne refuse collection vehicle

Example 3

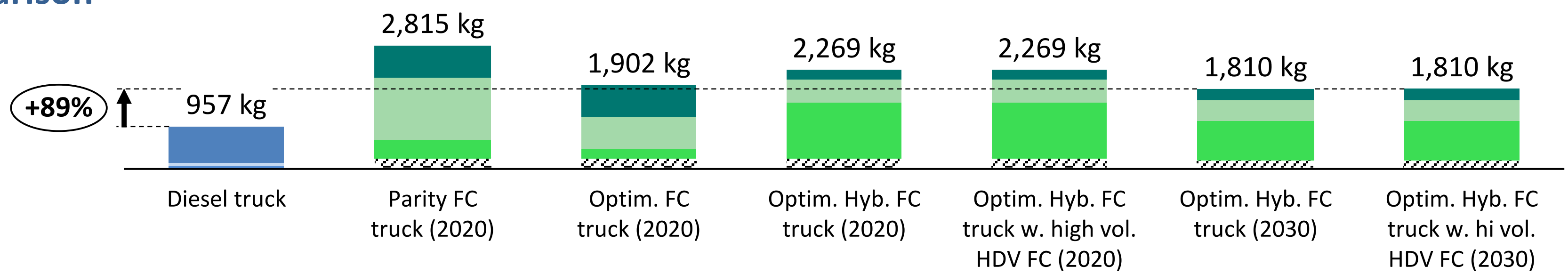
- Diesel ICE
- Gearbox & clutch
- Diesel tank
- Fuel cell
- Hydrogen tank
- Battery
- Electric motor
- Inverter

Optim. = Optimised performance with **50% driving range and 100% rated power** of diesel vehicle
Hyb. = Hybridised drivetrain with mid range power configuration with **30% power from FC, 70% power from battery**
High vol. HDV FC = FC costs based on the high volume HDV scenario (target of 10,000s per year by 2050) with £500/kW by 2020 and £150/kW by 2030.

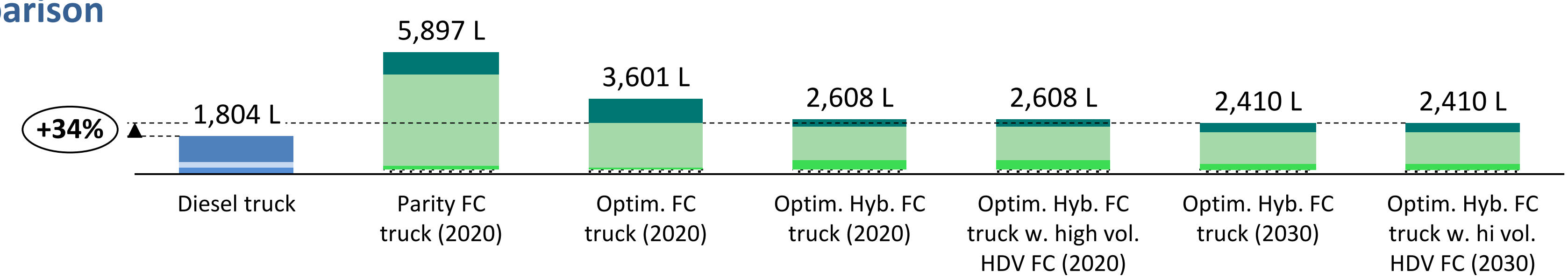
A Powertrain cost comparison



B Powertrain payload comparison



C Powertrain packaging comparison



>33 tonne articulated long haul vehicle

Specification for zero emission vehicle

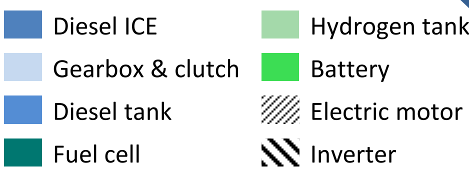
Description		Parity FC truck (2020)	Optim. FC truck (2020)	Optim. Hyb. FC truck (2020)	Optim. Hyb. FC truck w. OEM HDV FC (2020)	Optim. Hyb. FC truck (2030)	Optim. Hyb. FC truck w. OEM HDV FC (2030)
Motor power	*kW*	350	315	315	315	315	315
Fuel cell power	*kW*	315	284	95	95	95	95
Fuel cell cost	*£*	315000	283500	94500	47250	41769	14175
Fuel cell mass	*kg*	1050	945	315	315	315	315
Fuel cell volume	*Litres*	1575	1418	473	473	473	473
Efficiency	*%*	0.50	0.50	0.50	0.50	0.50	0.50
H2 tank capacity	*kg*	178	45	31	31	31	31
H2 tank cost	*£*	164472	41118	28783	28783	20559	20559
H2 tank mass	*kg*	3236	809	566	566	566	566
H2 tank volume	*Litres*	10114	2528	1770	1770	1770	1770
Full tank mass	*kg*	3414	854	598	598	598	598
Battery power	*kW*	35	32	221	221	221	221
Battery capacity	*kWh*	155	39	232	232	232	232
Battery cost	*£*	23790	6497	35685	35685	23453	23453
Batt. efficiency	*%*	0.95	0.95	0.95	0.95	0.95	0.95
Battery mass	*kg*	1000	260	1499	1499	1007	1007
Battery volume	*Litres*	397	112	595	595	370	370
Range	*km*	1818	455	455	455	455	455

Specification for diesel vehicle

Description		
Diesel ICE power	kW	350
Diesel ICE cost	£	19600
Diesel ICE mass	kg	1129
Diesel ICE volume	L	1756
Diesel tank cost	£	1200
Full diesel tank mass	kg	601
Diesel tank capacity	L	600
Gearbox & clutch cost	£	2000
Gearbox & clutch mass	kg	100
Gearbox & clutch volume	L	250
Range	km	1818

Sources: ICE costs (Ricardo-AEA, 2012), ICE mass and volume (average kg/kW and L/kW developed from publically available OEM specifications), tank cost (truckparts4u.com). Fuel cell mass and volume densities (industry consultation & literature (US Drive, 2013), (Argonne, 2010)), battery costs and densities (Element Energy, 2016).

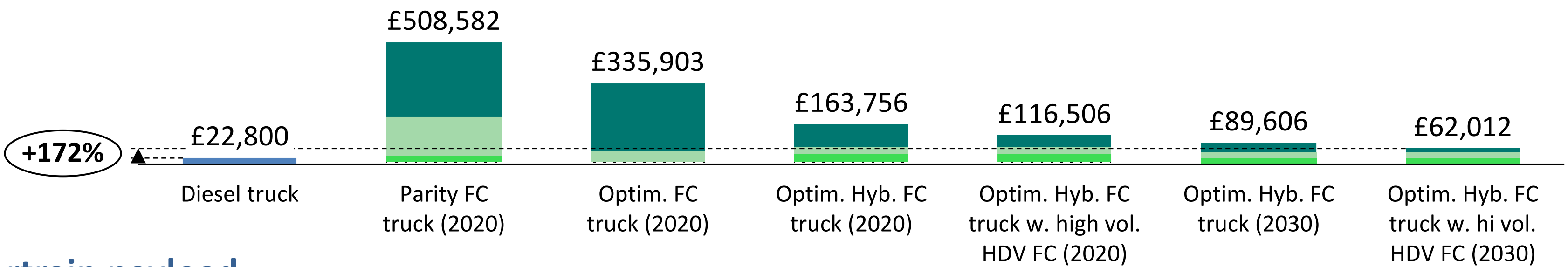
>33 tonne articulated long haul vehicle



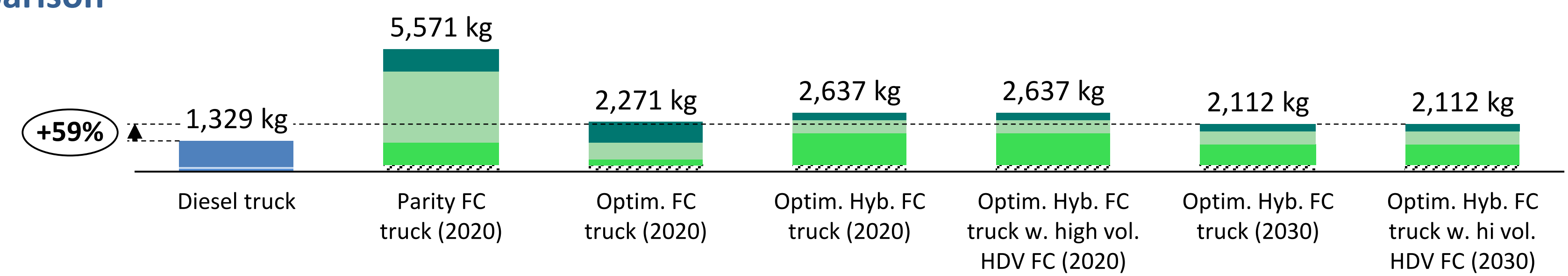
Example 4

Optim. = Optimised performance with **25% driving range and 90% rated power** of diesel vehicle
Hyb. = Hybridised drivetrain with mid range power configuration with **30% power from FC, 70% power from battery**
High vol. HDV FC = FC costs based on the high volume HDV scenario (target of 10,000s per year by 2050) with £500/kW by 2020 and £150/kW by 2030.

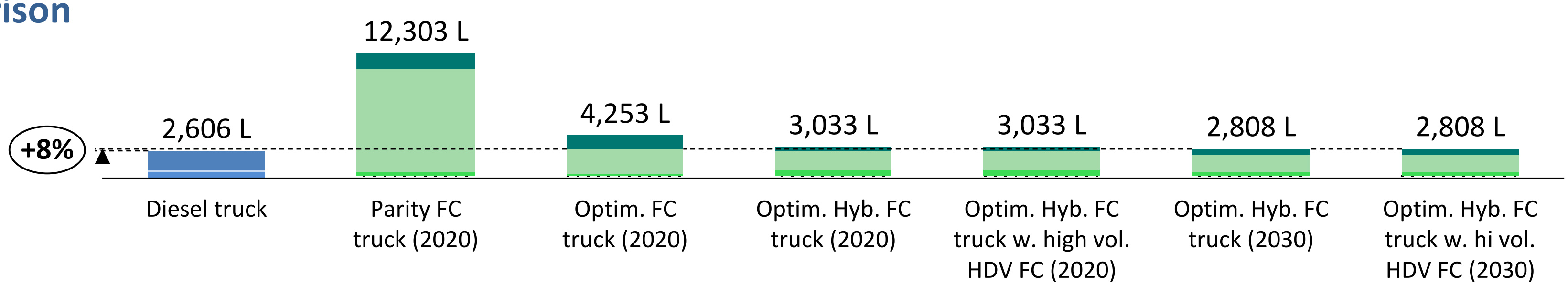
A Powertrain cost comparison



B Powertrain payload comparison



C Powertrain packaging comparison



12m single-decker urban bus

Example 5

Specification for zero emission vehicle

Description		Parity FC bus (2020)	Optim. FC bus (2020)	Optim. Hyb. FC bus (2020)	Optim. Hyb., high vol. FC (2020)	Optim. Hyb. FC truck (2030)	Optim. Hyb., high vol FC (2030)
Motor power	*kW*	185	185	185	185	185	185
Fuel cell power	*kW*	167	167	56	56	56	56
Fuel cell cost	*£*	166500	166500	55500	27750	24531	8325
Fuel cell mass	*kg*	555	555	185	185	185	185
Fuel cell volume	*Litres*	833	833	278	278	278	278
Efficiency	*%*	0.50	0.50	0.50	0.50	0.50	0.50
H2 tank capacity	*kg*	58	29	20	20	20	20
H2 tank cost	*£*	53592	26796	18757	18757	13398	13398
H2 tank mass	*kg*	1055	527	369	369	369	369
H2 tank volume	*Litres*	3295	1648	1153	1153	1153	1153
Full tank mass	*kg*	1113	556	389	389	389	389
Battery power	*kW*	19	19	130	130	130	130
Battery capacity	*kWh*	50	25	151	151	151	151
Battery cost	*£*	8469	4697	23255	23255	15284	15284
Batt. efficiency	*%*	0.95	0.95	0.95	0.95	0.95	0.95
Battery mass	*kg*	339	176	977	977	656	656
Battery volume	*Litres*	146	74	388	388	241	241
Range	*km*	513	256	256	256	256	256

Specification for diesel vehicle

Description		
Diesel ICE power	kW	185
Diesel ICE cost	£	10360
Diesel ICE mass	kg	597
Diesel ICE volume	L	928
Diesel tank cost	£	400
Full diesel tank mass	kg	200
Diesel tank capacity	L	200
Gearbox & clutch cost	£	2000
Gearbox & clutch mass	kg	100
Gearbox & clutch volume	L	250
Range	km	513

Sources: ICE costs (Ricardo-AEA, 2012), ICE mass and volume (average kg/kW and L/kW developed from publically available OEM specifications), tank cost (truckparts4u.com). Fuel cell mass and volume densities (industry consultation & literature (US Drive, 2013), (Argonne, 2010)), battery costs and densities (Element Energy, 2016).

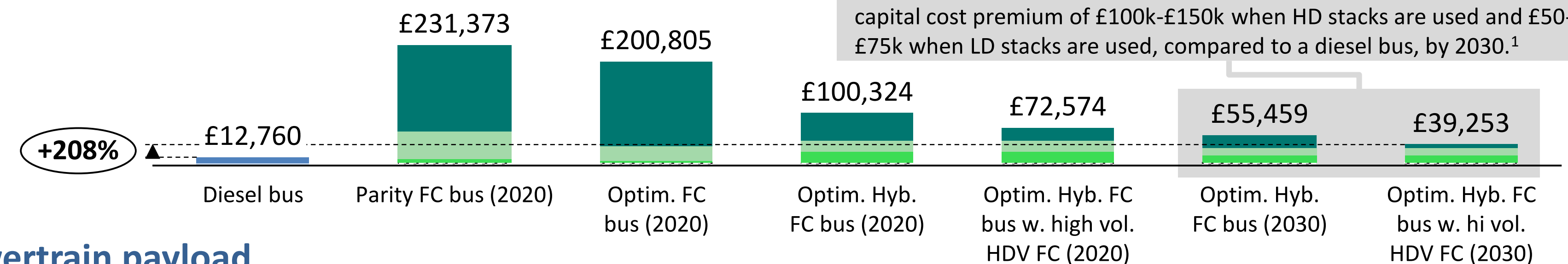
12m single-decker urban bus

Example 5

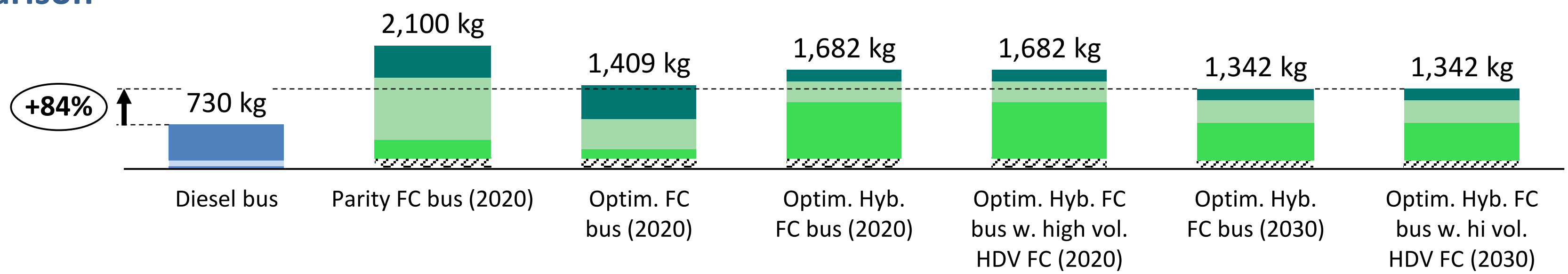
(A) Powertrain cost comparison

Optim. = Optimised performance with **50% driving range and 100% rated power** of diesel vehicle
Hyb. = Hybridised drivetrain with mid range power configuration with **30% power from FC, 70% power from battery**
High vol. HDV FC = FC costs based on the high volume HDV scenario (target of 10,000s per year by 2050) with £500/kW by 2020 and £150/kW by 2030.

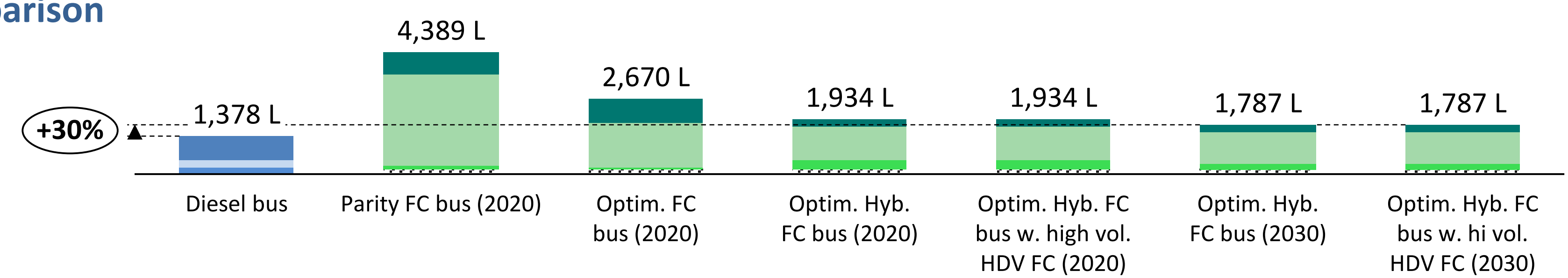
Recent study assessing fuel cell bus market uptake in Europe suggested a capital cost premium of £100k-£150k when HD stacks are used and £50-£75k when LD stacks are used, compared to a diesel bus, by 2030.[1]



(B) Powertrain payload comparison



(C) Powertrain packaging comparison



[1] Roland Berger (2015). LD systems are designed to have shorter lifetimes (5,000 hrs vs 20,000 hrs) with reduced Pt loading, durability. However, if LD system costs fall significantly below HD system costs then installing an LD system into a vehicle for HD application and including multiple stack replacements in the TCO could be more cost effective than installing an HD system.

Agenda

- Introduction
- ZE vehicle component costs and trends
- Specification of existing diesel HDVs
- Market review of existing zero emission HDVs
- Specification of zero emission HDVs
- **Results from design exercise**
- Conclusions and potential for innovation
- References

Indicative fuel cell vehicle drawings were prepared in order to understand packing constraints for zero emission trucks

Objectives

- Element Energy subcontracted ULEMCo (alternative powertrain specialists) to investigate hydrogen storage packaging constraints for new vehicle technical specifications described in the previous sections of this report.
- Specifically, we explored packaging constraints for **three vehicle types**:
  1. 4x2 tractor unit (long haul)
  2. 25t heavy rigid truck (regional distribution)
  3. 7.5t light rigid truck (service)
- **Three hybridisation options** are shown for each vehicle type: full power, mid power and range extender fuel cell.
- The outputs were solid models depicting the arrangement of hydrogen tanks and battery packs on the vehicles with the assumption made that the fuel cell and electric motor would be housed in the space beneath the cab where the diesel engine and gearbox would traditionally be situated.

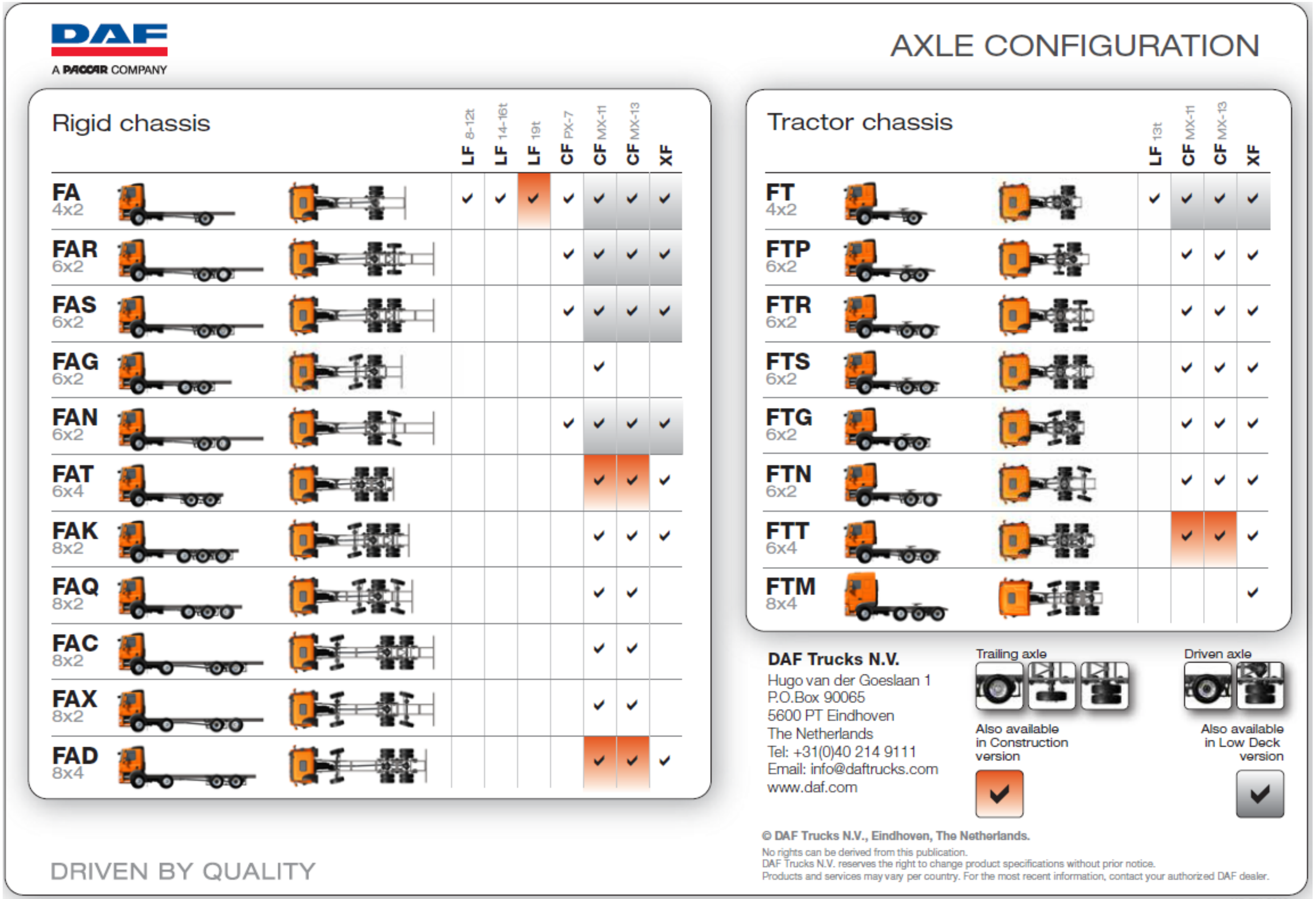
Methodology

- Appropriate cab and chassis models for each vehicle type were taken from the DAF Bodybuilder portal.[1] The models are 'visualisations' and have correct overall dimensions.
- Hydrogen cylinder specifications were selected from the Luxfor G-Stor range of Type III[2] cylinders that are used by ULEMCo on their hydrogen dual-fuel ICE vehicles (see next slide).
- Element Energy provided ULEMCo with the volume required for the batteries (in litres) for each vehicle type based on 2030 figures, from which ULEMCo were able to estimate the maximum hydrogen containment on each vehicle.
- All drawings were prepared using Sketchup software.

[1]www.dafbbi.com

[2]Type III: seamless and gas tight metal liner, full exterior composite reinforcement

The DAF Bodybuilder database was used to obtain vehicle dimensions – full range of available chassis configurations are shown below



Rigid chassis

	LF 8-12t	LF 14-16t	LF 19t	CF PX-7	CF MX-11	CF MX-13	XF
FA 4x2	✓	✓	✓	✓	✓	✓	✓
FAR 6x2				✓	✓	✓	✓
FAS 6x2				✓	✓	✓	✓
FAG 6x2					✓		
FAN 6x2				✓	✓	✓	✓
FAT 6x4					✓	✓	✓
FAK 8x2					✓	✓	✓
FAQ 8x2					✓	✓	
FAC 8x2					✓	✓	
FAX 8x2					✓	✓	
FAD 8x4					✓	✓	✓

Tractor chassis

	LF 13t	CF MX-11	CF MX-13	XF
FT 4x2	✓	✓	✓	✓
FTP 6x2		✓	✓	✓
FTR 6x2		✓	✓	✓
FTS 6x2		✓	✓	✓
FTG 6x2		✓	✓	✓
FTN 6x2		✓	✓	✓
FTT 6x4		✓	✓	✓
FTM 8x4				✓

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www.daf.com

Specifications of three hydrogen cylinder sizes were used from the Luxfor G-Stor Type III cylinder range[1]

Part number	H2 capacity	Diameter	Length	Water volume	Tank weight	Total weight tank and fuel
	kg	*mm*	*mm*	*L*	*kg*	*kg*
W100N	2.41	415	1168	100	51.5	53.9
W205N	4.93	415	2110	205	95	99.9
W322N	7.72	415	2190	322	141	148.7

1. http://www.luxfercylinders.com/products/alternative-fuel/gstorh2

Three DAF truck models were used as a basis for the technical drawings

The vehicle configuration was influenced in part by the models readily available from DAF but also by some practical considerations as described below:

Tractor unit (long haul)

- The most commonly used type of tractor unit in UK haulage is 6x2 vehicle which has a driven and a lift axle, and can operate up to a GVW of 44 tonnes with a 3-axle trailer.[1] However, it was clear that this platform would not have enough available space to house a suitable amount of hydrogen tanks. Therefore, a 4x2 tractor was chosen for this analysis which can operate up to 40 tonnes GVW with a 3-axle trailer.[1]
- 6x2 tractors are more prevalent in the UK due to residual value considerations (selling to owner drivers who need maximum operational flexibility) even if 40t GVW is sufficient for the first owner.
- 3.6m wheelbase tractors are most common in the UK and therefore have been selected for this assessment.
- Up to 4.0m wheelbases are available but the additional 0.4m is not enough to allow additional hydrogen storage with commercially available cylinders compared to the 3.6m tractor.

Heavy rigid truck (regional distribution)

- The configuration modelled is based on a DAF FAN chassis (steerable rear axle).
- This vehicle can be loaded up to a GVW of 25 tonnes, and in combination with a 3 axle drawbar trailer, a 3 axle rigid can haul up to 44 tonnes.

Light rigid truck (service)

- The configuration modelled is a DAF FL cab on an FT chassis. This configuration is typical of light trucks used in the UK and has a GVW of up to 8.5 tonnes.

[1]Based on UK truck weight regulations: https://www.gov.uk/government/publications/guide-to-lorry-types-and-weights

The technical drawings focus on the placement of hydrogen and battery storage with the specific constraints of each vehicle

Hydrogen storage tank design

- Initial drawing work found that hydrogen tanks cannot be housed behind the cab due to trailer swing clearance (for tractors) or limited load space (for rigid trucks).
- Furthermore, we have ensured provision of space for a drive shaft to the drive axle in order to maintain ground clearance and stay within the overall vehicle width.
- Brackets, under trays and any pipework shown are purely for illustrative purposes.

Battery pack design

- Battery packs were modelled as solid blocks as per the technical specifications outlined in earlier sections of this report.
- The same width and height constraints were respected as for the hydrogen tanks in respect of ground clearance and overall vehicle width.
- Some smaller packs were mounted across the chassis frame behind the cab where this was acceptable from a packaging point of view.

Drawings for the three vehicle types with three different hybridisation options are presented in the upcoming slides

Vehicle drawing methodology continued

Presentation of technical drawings

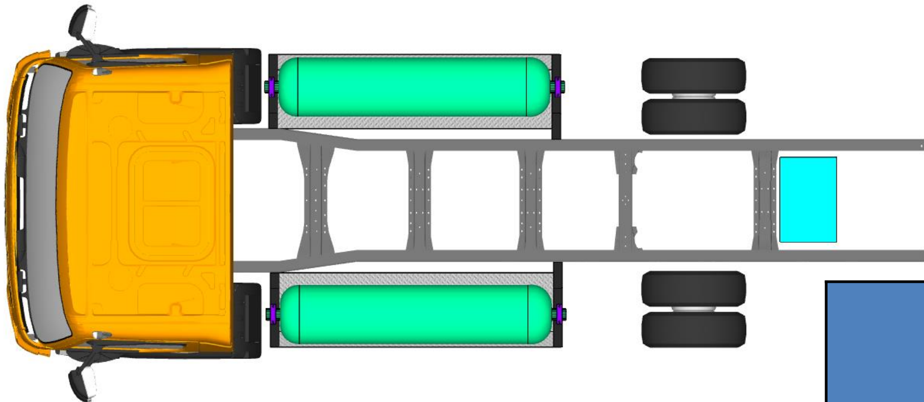
- Three vehicle types and three hybridisation options have been assessed. A technical drawing has been produced for each hybridisation option of each vehicle giving a total of nine technical drawings.
- Each slide shows the technical drawings for a given vehicle and hybridisation option, and includes a table summarising the battery specification (capacity and volume) and volume (in water litres) of hydrogen capable of being stored at 350 bar based on the Luxfor G-Stor Type 3 cylinder range, with implied range and payload difference with respect to the diesel incumbent.
- The table also includes an estimate of the amount of hydrogen that could be stored at 700 bar and in liquid form based on the available volume.
- Volumetric and gravimetric densities can be found in the Excel model (Deliverable 9.1) for 700 bar storage.
- For liquid hydrogen storage, 20 wt. % gravimetric density and 14.1 L/kg-H_2 have been assumed.[1]
- A summary slide has been included to combine the tables from each hybridisation option and identify the most appropriate hybrid for each vehicle type.

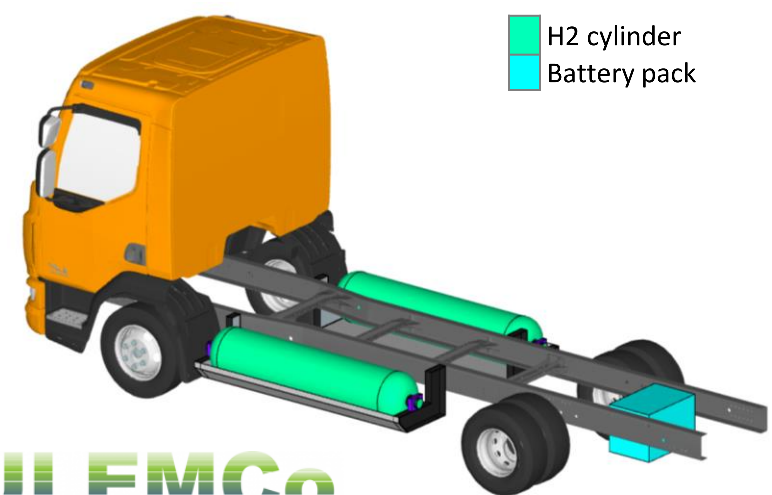
[1] *Hydrogen Production and Storage - R&D Priorities and Gaps* (IEA, 2006)

Light rigid (7-8t) truck with full power fuel cell powertrain

Vehicle specification

Chassis: DAF CF 6x2 Rigid, FAN Chassis, 4.8m Wheelbase H2
H2 storage: 2 x W205N cylinders
Battery: 1 x 54 Litre pack





H2 cylinder
Battery pack

		Hydrogen storage method		
		Gaseous 350 bar	Gaseous 700 bar	Liquid hydrogen
Battery capacity	kWh	13	13	13
Battery volume[1]	Litres	54	54	54
Maximum H2 tank volume[2]	Litres	410	410	410
Implied storage	kg-H2	9.9	16.7	29.1
Implied vehicle range	km	340	562	959
Vehicle payload difference[3]	kg	88	210	74

Key findings

- In this configuration, the two 350 bar cylinders provide sufficient hydrogen storage for a 340km real world range.
- More dense 700 bar storage enables a higher daily driving range (>500 km) but has an associated 200 kg payload penalty.
- Liquid hydrogen enables a very long range without significant payload loss.

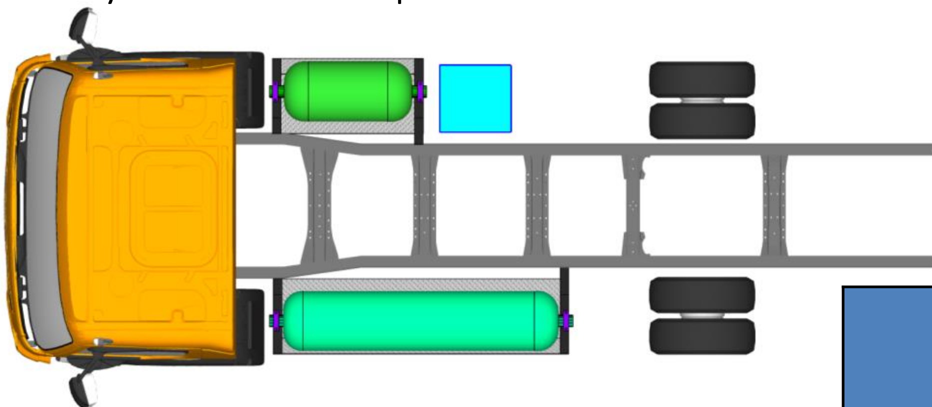
ULEMCo

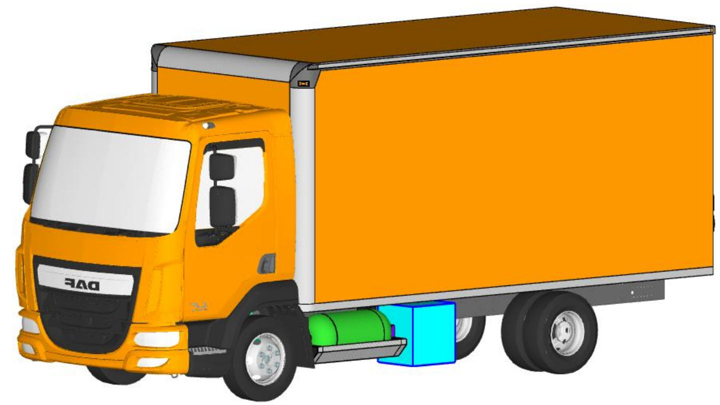
[1]Based on 2030 energy density figures. [2]Maximum quantity of hydrogen storage that could be installed on the vehicle. Volume is in water litres. [3]Overall payload difference compared to incumbent diesel vehicle (ZE – ICE).

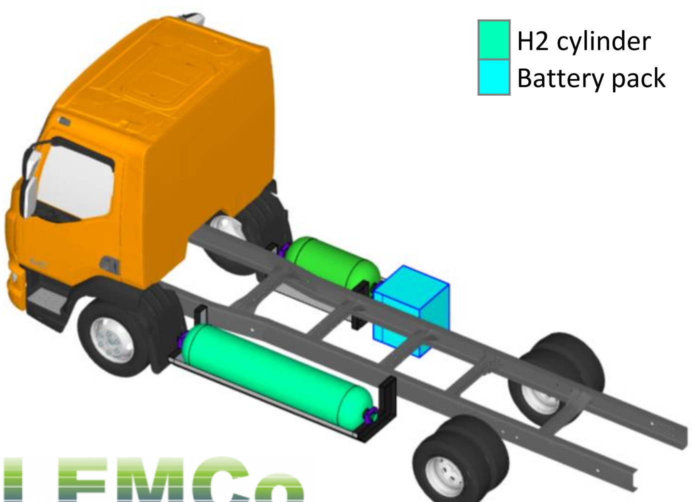
Light rigid (7-8t) truck with mid power fuel cell powertrain

Vehicle specification

Chassis: DAF CF 6x2 Rigid, FAN Chassis, 4.8m Wheelbase H2
H2 storage: 1 x W205N and 1 x W100N cylinders
Battery: 1 x 122 Litre pack







H2 cylinder
Battery pack

ULEMCo

		Hydrogen storage method		
		Gaseous 350 bar	Gaseous 700 bar	Liquid hydrogen
Battery capacity	kWh	76	76	76
Battery volume[1]	Litres	122	122	122
Maximum H2 tank volume[2]	Litres	305	305	305
Implied storage	kg-H2	7.3	12.4	21.7
Implied vehicle range	km	376	540	836
Vehicle payload difference[3]	kg	-15	75	-26

Key findings

- With more energy stored in the battery in this hybridisation option, 350 bar storage enables greater range than full power FC hybridisation but range is still constrained.
- 700 bar storage enables a daily driving range of more than 500 km with only an associated 50 kg payload penalty.
- Liquid hydrogen enables ample range without significant payload loss.

[1]Based on 2030 energy density figures. [2]Maximum quantity of hydrogen storage that could be installed on the vehicle. Volume is in water litres. [3]Overall payload difference compared to incumbent diesel vehicle (ZE – ICE).

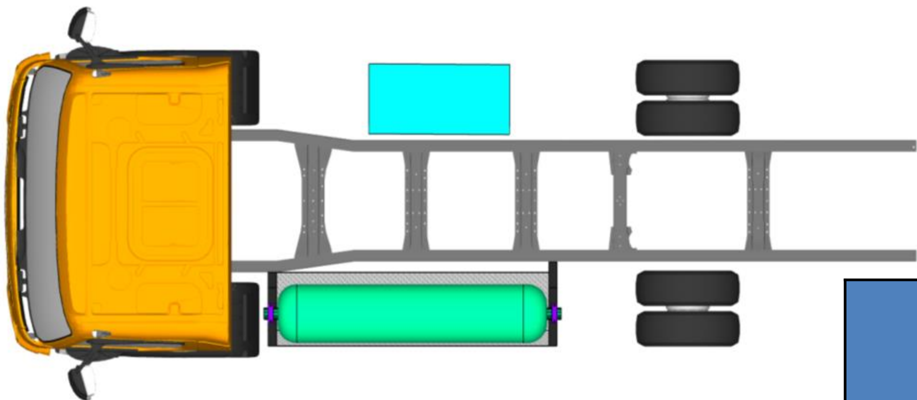
Light rigid (7-8t) truck with range extender fuel cell powertrain

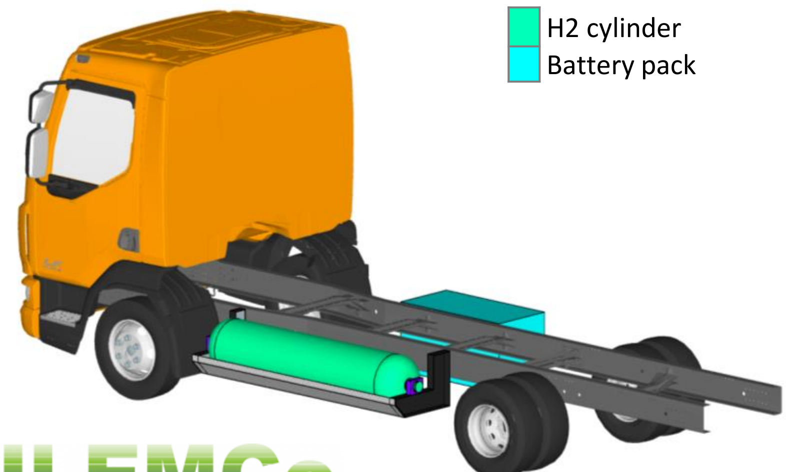
Vehicle specification

Chassis: DAF CF 6x2 Rigid, FAN Chassis, 4.8m Wheelbase H2

H2 storage: 1 x W205N cylinder

Battery: 1 x 263 Litre pack





H2 cylinder

Battery pack

		Hydrogen storage method		
		Gaseous 350 bar	Gaseous 700 bar	Liquid hydrogen
Battery capacity	kWh	165	165	165
Battery volume[1]	Litres	263	263	263
Maximum H2 tank volume[2]	Litres	205	205	205
Implied storage	kg-H2	4.9	8.4	14.6
Implied vehicle range	km	463	574	772
Vehicle payload difference[3]	kg	274	335	267

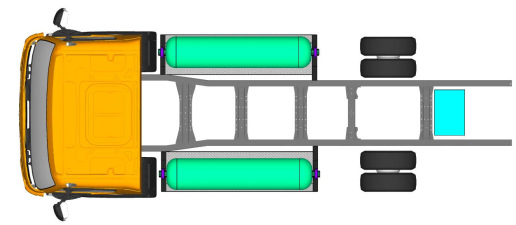
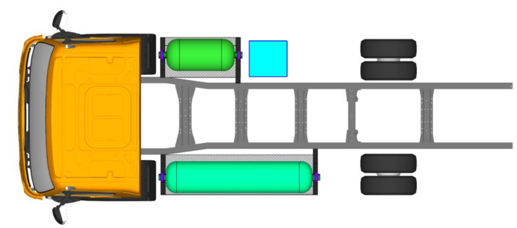
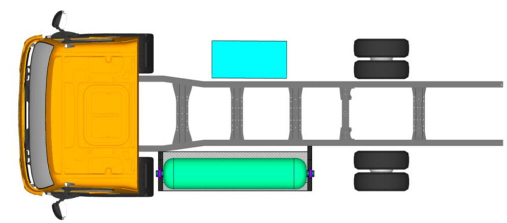
Key findings

- Further increasing the battery size in a range-extended configuration increases the driving range to 463km when using 350 bar gaseous hydrogen.
- Although volumetric battery energy density is very high in 2030, the mass density is not sufficiently high to avoid an increased vehicle mass of nearly 300kg relative to the diesel ICE version.

[1]Based on 2030 energy density figures. [2]Maximum quantity of hydrogen storage that could be installed on the vehicle. Volume is in water litres. [3]Overall payload difference compared to incumbent diesel vehicle (ZE – ICE).

Light rigid (7-8t) truck – summary of hybridisation options

H2 cylinder
Battery pack

Hybridisation option			Hydrogen storage method: Gaseous 350 bar	Gaseous 700 bar	Liquid hydrogen	Technical drawings
Full power fuel cell	Battery capacity	kWh	13	13	13	
	Battery volume[1]	Litres	54	54	54	
	Maximum H2 tank volume[2]	Litres	410	410	410	
	Implied storage	kg-H2	9.9	16.7	29.1	
	Implied vehicle range	km	340	562	959	
	Vehicle payload difference[3]	kg	88	210	74	
Mid power fuel cell	Battery capacity	kWh	76	76	76	
	Battery volume[1]	Litres	122	122	122	
	Maximum H2 tank volume[2]	Litres	305	305	305	
	Implied storage	kg-H2	7.3	12.4	21.7	
	Implied vehicle range	km	376	540	836	
	Vehicle payload difference[3]	kg	-15	75	-26	
Range extender fuel cell	Battery capacity	kWh	165	165	165	
	Battery volume[1]	Litres	263	263	263	
	Maximum H2 tank volume[2]	Litres	205	205	205	
	Implied storage	kg-H2	4.9	8.4	14.6	
	Implied vehicle range	km	463	574	772	
	Vehicle payload difference[3]	kg	274	335	267	

Key findings

- Available space on the light rigid truck is restricted by a low chassis clearance and short wheel base.
- Packaging the full amount of hydrogen storage required by the zero emission vehicle technical specification was not feasible with 350 bar pressure storage but utilising more energy dense hydrogen storage systems (700 bar pressure or liquid hydrogen) enables sufficient driving mileage. However, it should be noted that 340km of daily range may already be sufficient for some urban operators
- Based on range, payload and packaging considerations the mid power fuel cell hybridisation option is best suited to this vehicle type.

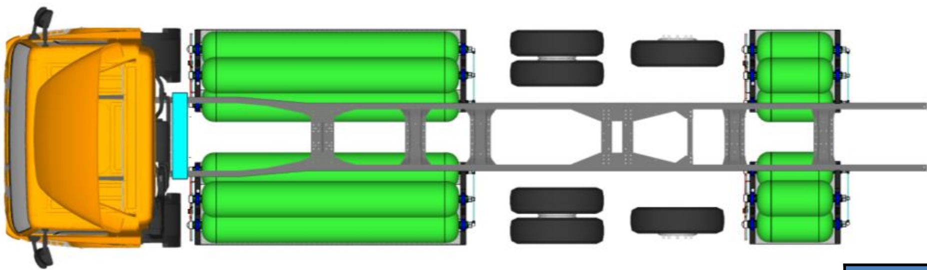
Heavy rigid (25t) with full power fuel cell powertrain

Vehicle specification

Chassis: DAF CF 6x2 Rigid, FAN Chassis, 4.8m Wheelbase

H2 storage: 6 x W322N and 6 x W100N cylinders

Battery: 1 x 61 Litre pack



		Hydrogen storage method		
		Gaseous 350 bar	Gaseous 700 bar	Liquid hydrogen
Battery capacity	kWh	23	23	23
Battery volume[1]	Litres	61	61	61
Maximum H2 tank volume[2]	Litres	2532	2532	2532
Implied storage	kg-H2	60.9	103.4	179.7
Implied vehicle range	km	943	1588	2745
Vehicle payload difference[3]	kg	1106	1855	1017

Key findings

- For the full power hybridisation, the battery pack is small enough to be housed behind the cab, allowing up to 12 350 bar cylinders to be stored on the vehicle with a large driving range of almost 1,000 km.
- Increasing the energy density of the hydrogen storage to 700 bar enables significant range increases but has a large payload penalty.

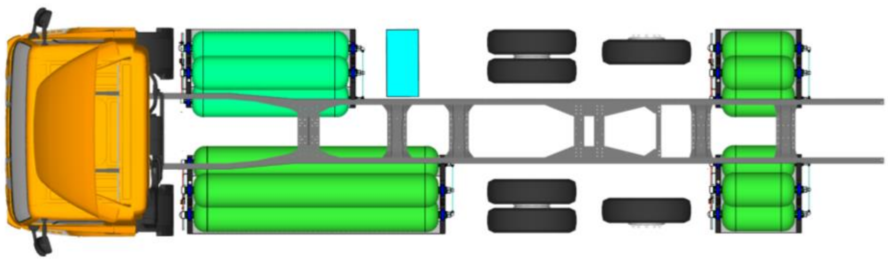
ULEMCo

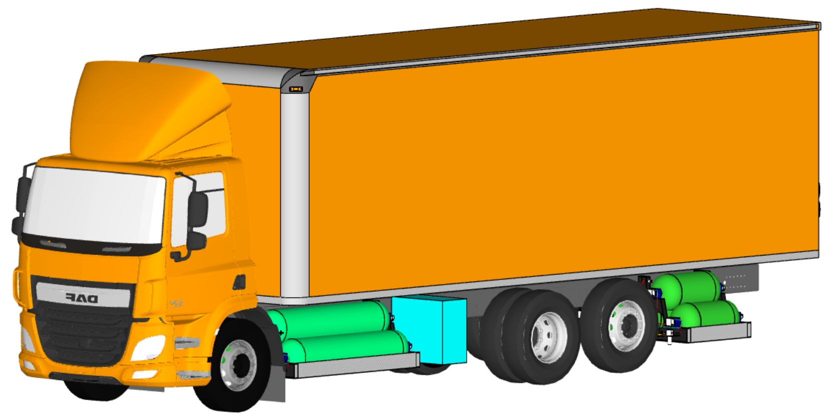
[1]Based on 2030 energy density figures. [2]Maximum quantity of hydrogen storage that could be installed on the vehicle. Volume is in water litres. [3]Overall payload difference compared to incumbent diesel vehicle (ZE – ICE).

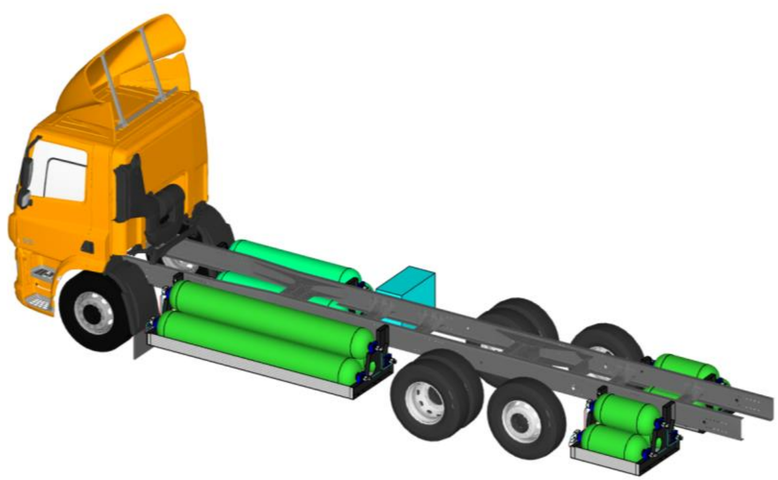
Heavy rigid (25t) with mid power fuel cell powertrain

Vehicle specification

Chassis: DAF CF 6x2 Rigid, FAN Chassis, 4.8m Wheelbase
H2 storage: 6 x W322N and 6 x W100N cylinders
Battery: 1 x 217 Litre pack







		Hydrogen storage method		
		Gaseous 350 bar	Gaseous 700 bar	Liquid hydrogen
Battery capacity	kWh	136	136	136
Battery volume[1]	Litres	217	217	217
Maximum H2 tank volume[2]	Litres	2181	2181	2181
Implied storage	kg-H2	52.4	89.0	154.8
Implied vehicle range	km	914	1468	2466
Vehicle payload difference[3]	kg	916	1561	839

Key findings

- For the mid power hybridisation, the battery pack cannot be stored behind the cab and instead is located between the wheels.
- With 350 bar storage, sufficient driving range is enabled with a moderate c.900kg payload penalty.
- Increasing the storage pressure to 700 bar yields a significant range increase but has a large 1.5 tonne payload penalty.

ULEMCo

[1]Based on 2030 energy density figures. [2]Maximum quantity of hydrogen storage that could be installed on the vehicle. Volume is in water litres. [3]Overall payload difference compared to incumbent diesel vehicle (ZE – ICE).

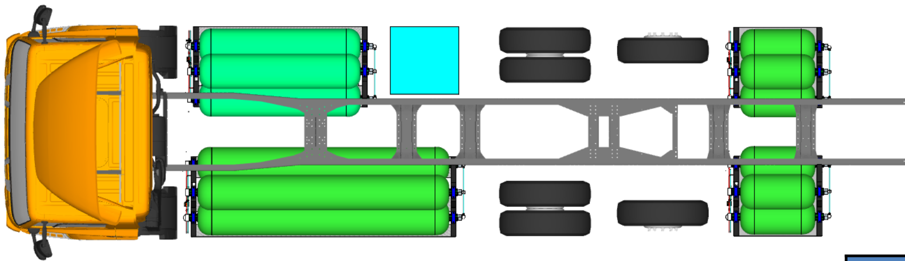
Heavy rigid (25t) truck with range extender fuel cell powertrain

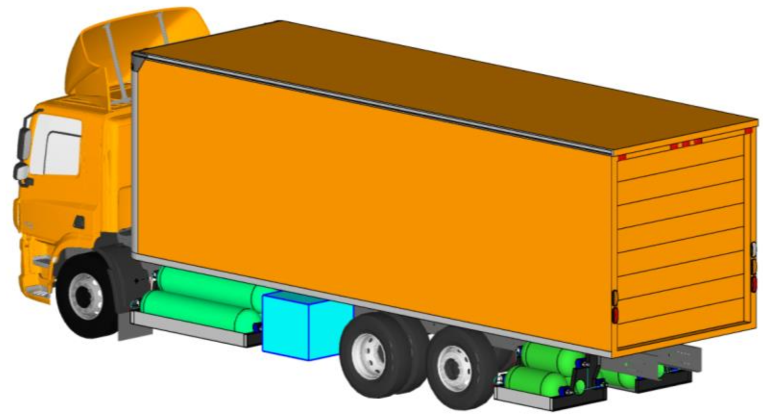
Vehicle specification

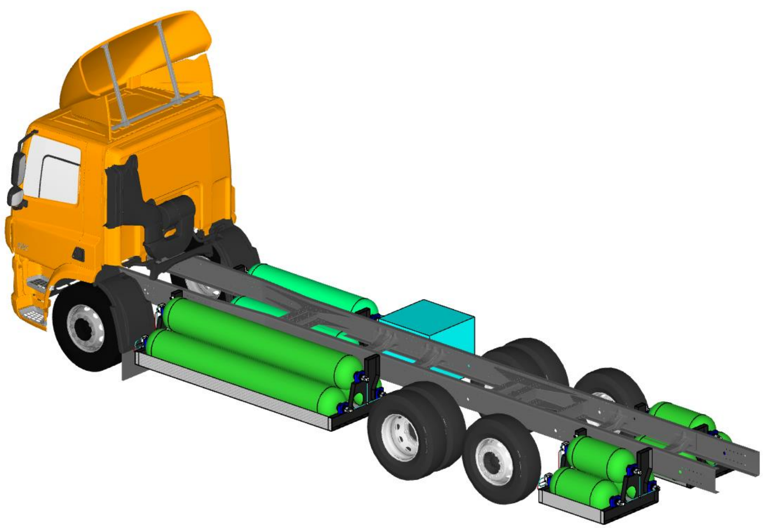
Chassis: DAF CF 6x2 Rigid, FAN Chassis, 4.8m Wheelbase H2

H2 storage: 3 x W322N, 3 x W205N and 6 x W100N cylinders

Battery: 1 x 470 Litre pack







		Hydrogen storage method		
		Gaseous 350 bar	Gaseous 700 bar	Liquid hydrogen
Battery capacity	kWh	294	294	294
Battery volume[1]	Litres	470	470	470
Maximum H2 tank volume[2]	Litres	2181	2181	2181
Implied storage	kg-H2	52.4	89.0	154.8
Implied vehicle range	km	1052	1607	2605
Vehicle payload difference[3]	kg	1521	2166	1444

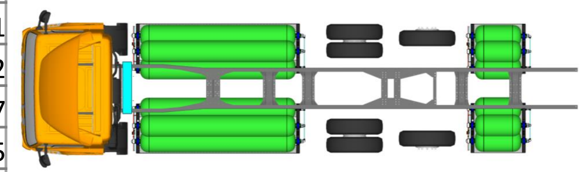
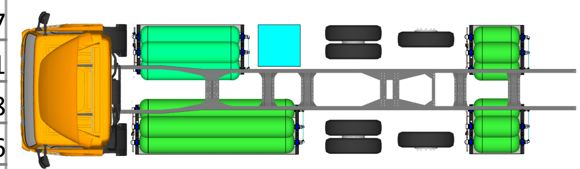
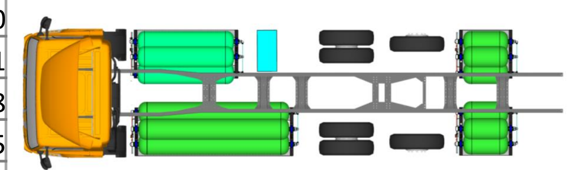
Key findings

- For the range extended hybridisation option, 350 bar pressure provides ample storage for the required driving range.
- However, the lower gravimetric energy density of the battery pack becomes significant with the large 294 kWh pack with a 1.3 tonne payload penalty.

[1]Based on 2030 energy density figures. [2]Maximum quantity of hydrogen storage that could be installed on the vehicle. Volume is in water litres. [3]Overall payload difference compared to incumbent diesel vehicle (ZE – ICE).

Heavy rigid (25t) truck – summary of hybridisation options

H2 cylinder
Battery pack

Hybridisation option			Hydrogen storage method: Gaseous 350 bar	Hydrogen storage method: Gaseous 700 bar	Hydrogen storage method: Liquid hydrogen	Technical drawings
Full power fuel cell	Battery capacity	kWh	23	23	23	
	Battery volume[1]	Litres	61	61	61	
	Maximum H2 tank volume[2]	Litres	2532	2532	2532	
	Implied storage	kg-H2	60.9	103.4	179.7	
	Implied vehicle range	km	943	1588	2745	
	Vehicle payload difference[3]	kg	1106	1855	1017	
Mid power fuel cell	Battery capacity	kWh	136	136	136	
	Battery volume[1]	Litres	217	217	217	
	Maximum H2 tank volume[2]	Litres	2181	2181	2181	
	Implied storage	kg-H2	52.4	89.0	154.8	
	Implied vehicle range	km	914	1468	2466	
	Vehicle payload difference[3]	kg	916	1561	839	
Range extender fuel cell	Battery capacity	kWh	294	294	294	
	Battery volume[1]	Litres	470	470	470	
	Maximum H2 tank volume[2]	Litres	2181	2181	2181	
	Implied storage	kg-H2	52.4	89.0	154.8	
	Implied vehicle range	km	1052	1607	2605	
	Vehicle payload difference[3]	kg	1521	2166	1444	

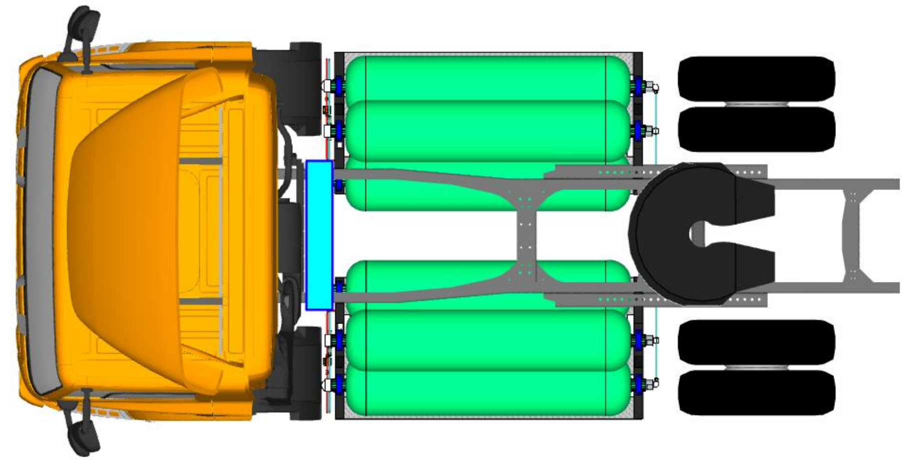
Key findings

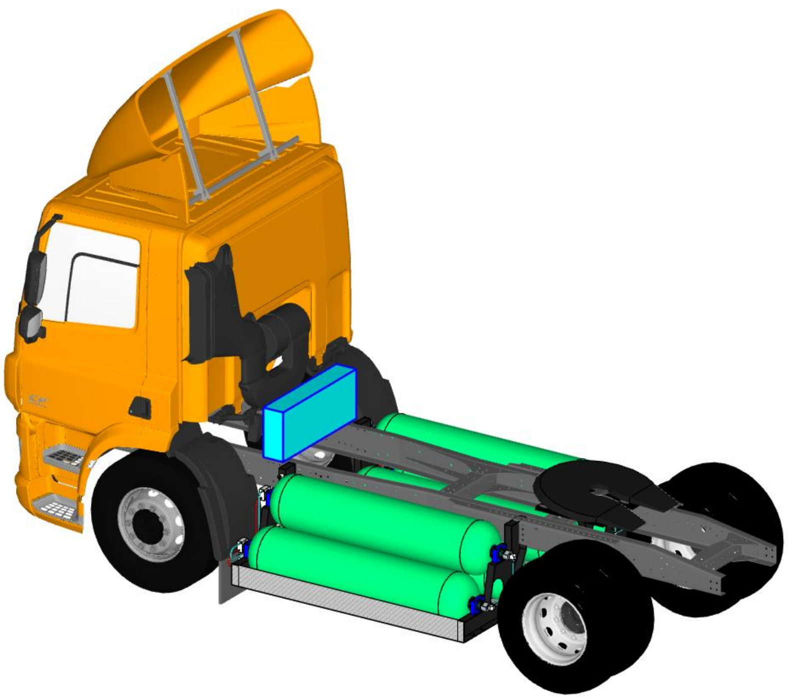
- Longer vehicle length enabled the required battery and hydrogen storage to be packaged on the heavy rigid truck with no constraint.
- For all hybridisation options, installing the maximum feasible amount of hydrogen storage would enable extended vehicle ranges, even with the least energy dense storage mechanism (350 bar pressure).
- From a technical perspective (before costs are considered), the full power fuel cell option is most appropriate.

Tractor unit (long haul) with full power fuel cell powertrain

Vehicle specification

Chassis: DAF CF 4 x 2 Tractor Unit, 3.6m wheelbase
H2 storage: 6 x W205N cylinders
Battery: 1 x 70 Litre pack





		Hydrogen storage method		
		Gaseous 350 bar	Gaseous 700 bar	Liquid hydrogen
Battery capacity	kWh	39	39	39
Battery volume[1]	Litres	70	70	70
Maximum H2 tank volume[2]	Litres	1230	1230	1230
Implied storage	kg-H2	29.6	50.2	87.3
Implied vehicle range	km	325	536	915
Vehicle payload difference[3]	kg	79	443	36

Key findings

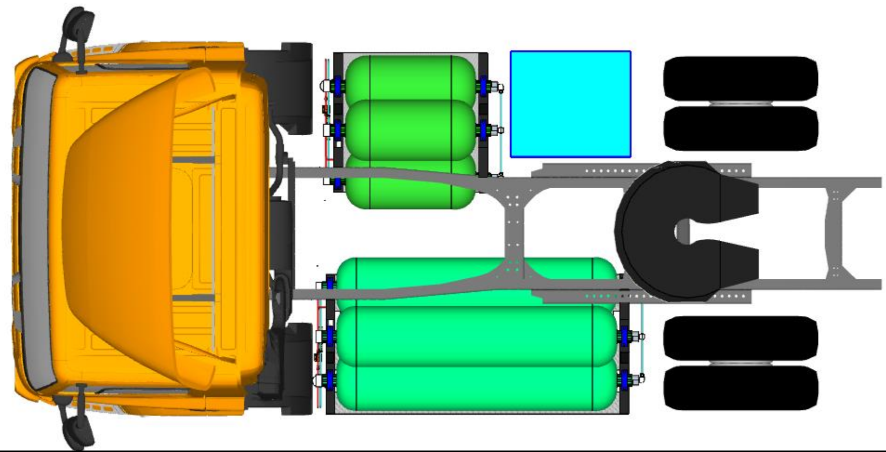
- The chosen 4x2 tractor is smaller than a 6x2 tractor but has been selected as an extreme case for this assessment.
- Only 21.6 kg of hydrogen can be stored on-board the vehicle with 350 bar storage, restricting the driving range to 325 km.
- 700 bar storage enables over 50 kg of hydrogen to be stored and enables an acceptable driving range, over 500 km.

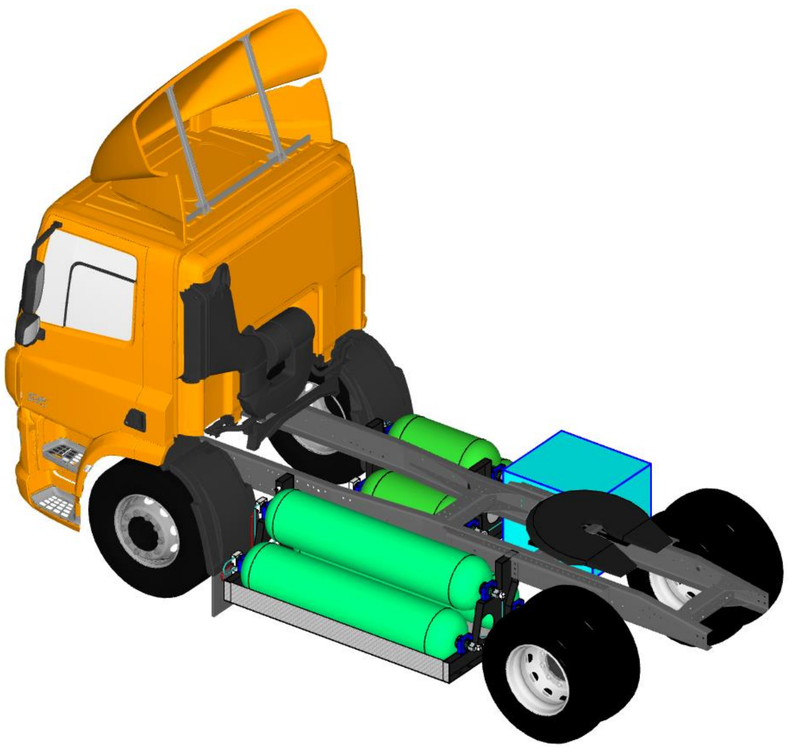
[1]Based on 2030 energy density figures. [2]Maximum quantity of hydrogen storage that could be installed on the vehicle. Volume is in water litres. [3]Overall payload difference compared to incumbent diesel vehicle (ZE – ICE).

Tractor unit (long haul) with mid power fuel cell powertrain

Vehicle specification

Chassis: DAF CF 4 x 2 Tractor Unit, 3.6m wheelbase
H2 storage: 3 x W205N and 3 x W100N cylinders
Battery: 1 x 370 Litre pack





		Hydrogen storage method		
		Gaseous 350 bar	Gaseous 700 bar	Liquid hydrogen
Battery capacity	kWh	232	232	232
Battery volume[1]	Litres	370	370	370
Maximum H2 tank volume[2]	Litres	915	915	915
Implied storage	kg-H2	22.0	37.3	65.0
Implied vehicle range	km	361	518	800
Vehicle payload difference[3]	kg	137	408	105

Key findings

- For the mid power hybridisation, the battery pack is too large to be housed behind the cab so is located between the wheel base, reducing available space for hydrogen storage.
- 350 bar storage is not suitable for the required driving ranges.
- Sufficient driving range is enabled by 700 bar storage albeit with a moderate c. 400 kg payload penalty.

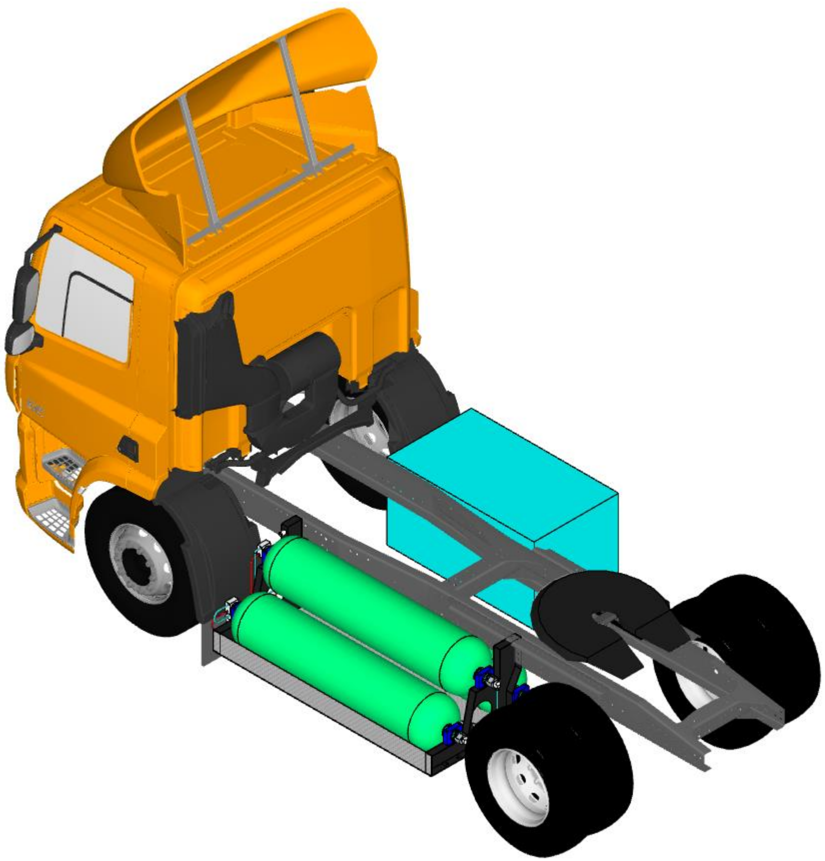
ULEMCo

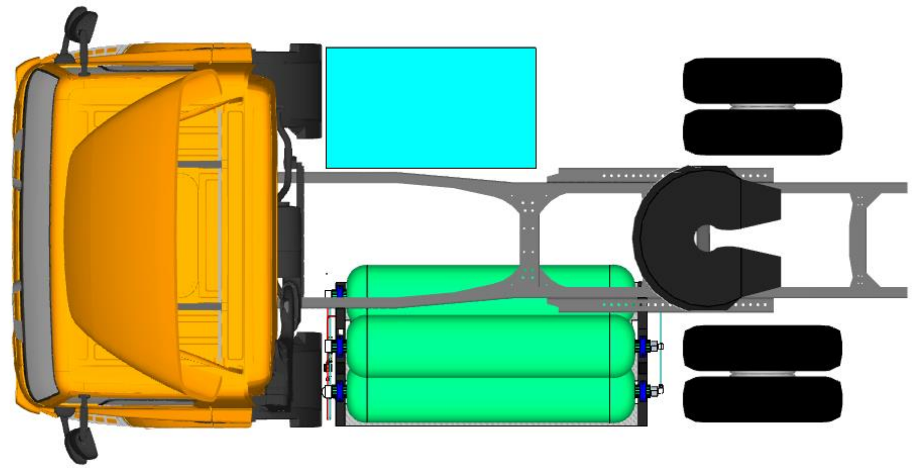
[1]Based on 2030 energy density figures. [2]Maximum quantity of hydrogen storage that could be installed on the vehicle. Volume is in water litres. [3]Overall payload difference compared to incumbent diesel vehicle (ZE – ICE).

Tractor unit (long haul) with range extender fuel cell powertrain

Vehicle specification

Chassis: DAF CF 4 x 2 Tractor Unit, 3.6m wheelbase
H2 storage: 3 x W205N Cylinders
Battery: 1 x 802 Litre pack





		Hydrogen storage method		
		Gaseous 350 bar	Gaseous 700 bar	Liquid hydrogen
Battery capacity	kWh	502	502	502
Battery volume[1]	Litres	802	802	802
Maximum H2 tank volume[2]	Litres	615	615	615
Implied storage	kg-H2	14.8	25.1	43.7
Implied vehicle range	km	446	552	741
Vehicle payload difference[3]	kg	1068	1250	1047

Key findings

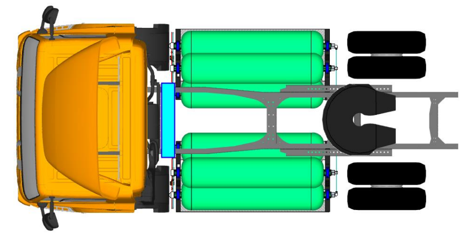
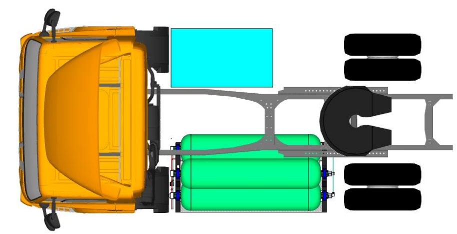
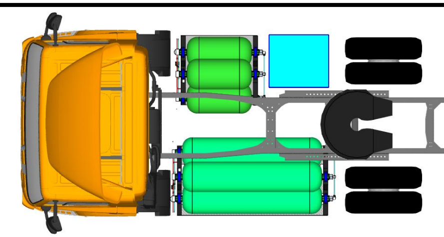
- For the range extender fuel cell hybridisation option, three 350 bar hydrogen cylinders and a large battery pack comprise the standard energy storage configuration, achieving 446 km driving range.
- Replacing the cylinders with 700 bar storage enables >500km driving range with a moderate payload penalty of 181 kg.
- Liquefied H2 range remains high, but lower than in full power version

ULEMCo

[1]Based on 2030 energy density figures. [2]Maximum quantity of hydrogen storage that could be installed on the vehicle. Volume is in water litres. [3]Overall payload difference compared to incumbent diesel vehicle (ZE – ICE).

Heavy rigid (25t) truck – summary of hybridisation options

H2 cylinder
Battery pack

Hybridisation option			Hydrogen storage method: Gaseous 350 bar	Hydrogen storage method: Gaseous 700 bar	Hydrogen storage method: Liquid hydrogen	Technical drawings
Full power fuel cell	Battery capacity	kWh	39	39	39	
	Battery volume[1]	Litres	70	70	70	
	Maximum H2 tank volume[2]	Litres	1230	1230	1230	
	Implied storage	kg-H2	29.6	50.2	87.3	
	Implied vehicle range	km	325	536	915	
	Vehicle payload difference[3]	kg	79	443	36	
Mid power fuel cell	Battery capacity	kWh	232	232	232	
	Battery volume[1]	Litres	370	370	370	
	Maximum H2 tank volume[2]	Litres	915	915	915	
	Implied storage	kg-H2	22.0	37.3	65.0	
	Implied vehicle range	km	361	518	800	
	Vehicle payload difference[3]	kg	137	408	105	
Range extender fuel cell	Battery capacity	kWh	502	502	502	
	Battery volume[1]	Litres	802	802	802	
	Maximum H2 tank volume[2]	Litres	615	615	615	
	Implied storage	kg-H2	14.8	25.1	43.7	
	Implied vehicle range	km	446	552	741	
	Vehicle payload difference[3]	kg	1068	1250	1047	

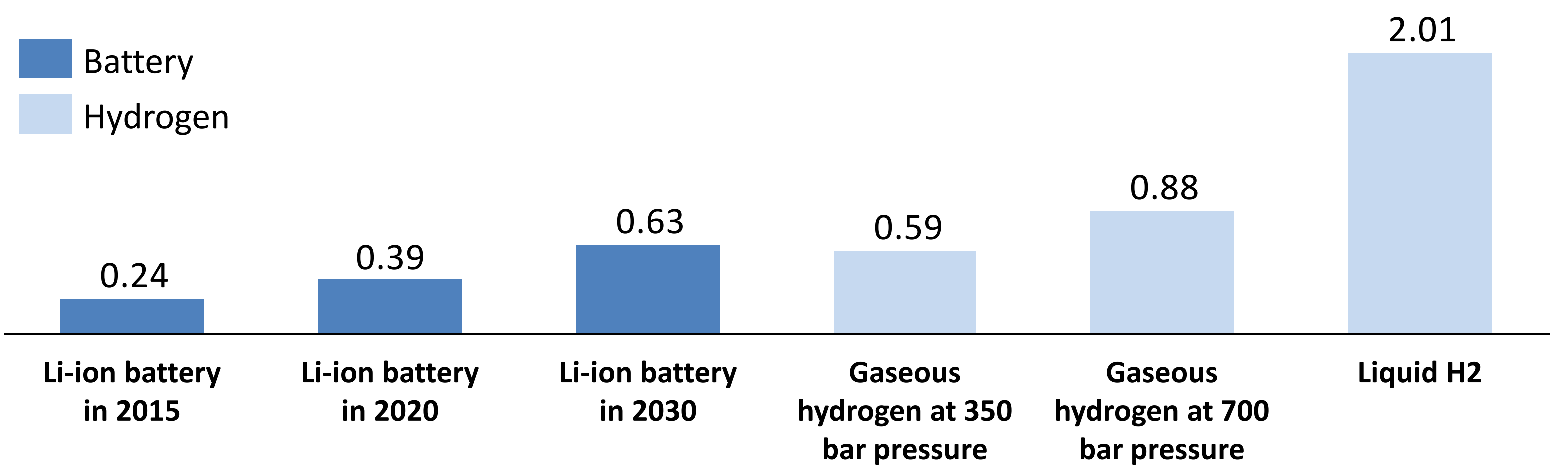
Key findings

- A 4x2 long haul tractor chassis was selected for the analysis due to the additional space between the axles relative to a 6x2 tractor.
- Constrained by the short wheel base, 350 bar storage is insufficient for long haul use in all hybridisation options.
- 700 bar storage enables adequate driving ranges, and from a technical perspective, the range extended fuel cell option has the lowest payload penalty.

The design results highlight effects of changing performance of batteries and hydrogen storage systems

- Analysis shows that by 2030, through technology advancement, Li-ion batteries could be more energy dense (volumetrically) than 350 bar hydrogen storage, as shown in the graph below.
- If fuel cell efficiency is considered (50%), battery energy density will exceed the energy density on a delivered energy basis from 350 bar hydrogen storage by 2020. This is explains the slightly higher driving ranges in the range-extended powertrains, since proportionately more of the total energy stored is in the battery rather than the hydrogen storage
- 350 bar compressed hydrogen as a an energy storage method would still have a number of advantages over more volumetrically energy dense batteries. E.g. faster refill times compared to recharging batteries, avoided grid constraints at large depots and smaller payload penalties due to higher gravimetric energy density of hydrogen storage at 350 bar.

Volumetric energy density (kWh/L) of battery and hydrogen storage technologies



Agenda

- Introduction
- ZE vehicle component costs and trends
- Specification of existing diesel HDVs
- Market review of existing zero emission HDVs
- Specification of zero emission HDVs
- Results from design exercise
- **Conclusions and potential for innovation**
- References

Innovation opportunities exist in fuel cell system designs and production methods (1/2)

- Fuel cell systems consist of two distinct groups of components: the stack and the balance of plant. Improving cost, durability and performance of the stack (particularly for light duty stacks) are the most significant technical challenges.
- For HDV and LDV fuel cells, the balance of plant generally includes well established, commercially available technologies (e.g. humidifiers, air loops, etc.) with minimal innovation opportunities compared to the stack.
- Several innovations are available at a stack level (see next page) to reduce costs and improve lifetime. This is particularly important for light duty stacks currently used in passenger cars, as their lower costs relative to HDV stacks make them attractive for use in trucks and buses but they cannot currently meet the demanding durability needs.
- For HDV stacks, the contribution of platinum to total costs is relatively low (for example £5000 out of a £100,000-200,000 system cost)
- Since current HDV designs are already close to meeting durability requirements (with demonstration units reaching 20,000 hours of operation), high costs per kilowatt remain the primary barrier to deployment. In other words, the systems are already technically suitable for their intended uses, as evidenced by the numerous buses and light/medium duty vehicles in successful operation in funded US and EU demonstration projects
- The current high costs will be addressed primarily by strongly increasing production volumes, which allow continuous production process for fuel cell stacks and the component parts (e.g. the membrane electrode assemblies). Joint procurement exercises underway across Europe for fuel cell buses aim to reduce the cost of a standard 12m bus from £1m in 2010 to c. £500,000 or below. Further cost reductions will be necessary to meet acceptable levels for truck operators, except where they are willing to pay a high premium for zero emission mobility e.g. refuse collection, deliveries in cities with traffic restrictions to control air pollution.

Innovation opportunities exist in fuel cell system designs and production methods (2/2)

Innovations in fuel cell technology

- The stack includes multiple components that fuel cell developers are currently working to improve including catalysts, membranes, gas diffusion layers and bipolar plates.
- Opportunities for stack design innovation include:
  - **Catalysts and electrodes**: develop platinum-group-metal (PGM)-free catalysts, increase catalyst activity by increasing surface area e.g. via dispersion techniques or creating nanoparticle structures.
  - **Membranes/electrolytes**: develop ion transport membranes with improved conductivity over a wider temperature and humidity range, explore membrane designs with reduced BOP (e.g. without humidifiers as Toyota have done for the Mirai fuel cell), improve identification of degradation mechanisms.
  - **Bipolar plates**: improve flow-field design to maximise air flow and increase stack power density
- Stack cost and durability are both currently to the quantity (loading) of platinum catalyst therefore strategies to improve cost will have detrimental effects to durability, necessitating a design trade-off, until suitable PGM-free catalysts are developed, which is one of DOE's four innovation priorities for hydrogen.[1]
- Additional research on the mechanisms of catalyst loss and fuel cell degradation is required to identify potential solutions (such as new membrane materials with higher catalyst stability) that could improve durability while also allowing reduced catalyst loadings
- Incorporation of these improvements in future designs will be needed to deliver further cost reductions (beyond those available from production volume effects), as they will reduce the mass and cost of materials required per kilowatt of output.

[1]https://energy.gov/eere/articles/energy-department-announces-30-million-investment-innovation-hydrogen-and-fuel-cell

Innovations are also being pursued in hydrogen storage to enable use in large, long-range vehicles

- For most truck and bus requirements, 350 bar hydrogen storage provides sufficient range at acceptable packaging volumes. Innovation should therefore focus on reducing cost, through a combination of improved designs reducing carbon fibre requirements per kilogram stored, and increased production volumes
- Cryo-compressed hydrogen storage technology, developed for transport applications by Lawrence Livermore National Laboratory,[1] combines the benefits of regular compressed hydrogen and liquid hydrogen storage methods.
- BMW have developed two on-board hydrogen storage methods (700 bar gaseous and cryo-compressed) for the 5 Series GT FCEV prototypes operated in the EU-funded HyFIVE project.
- Compared to regular compressed hydrogen storage, cyro-compressed hydrogen offers several advantages across the hydrogen supply chain:
  - Distribution: larger quantities of hydrogen can be stored on distribution trailers delivering to refuelling stations.
  - Dispensing: cryo-compressed hydrogen is dispensed via cryo-pumps which have higher flow rates than gaseous hydrogen dispensers.
  - On-board storage: cryo-compressed hydrogen can be stored on-board fuel cell vehicles with vacuum insulated tanks that have 30-40% less carbon fibre per kg of hydrogen, reducing payload and packaging penalties.
- Compared to liquid hydrogen storage, cryo-compressed hydrogen storage tanks are pressurised to 50 bar which minimises hydrogen boil-off losses.
- Liquid hydrogen tanks are cheaper and take up less space. However, the relationship between volume and mass density and hydrogen capacity is non-linear for cryo-compressed tanks, i.e. a cryo-compressed tank with 50 kg-H_2 capacity has a proportionately smaller volume and mass premium compared to a tank with 5 kg-H_2 capacity.
- There is uncertainty over the timescales for larger scale deployments for cryo-compressed hydrogen, given that 350bar and 700 bar gaseous storage (for heavy and light vehicles respectively) have become the standard used by refuelling station providers and vehicle manufacturers.

[1]G. Petitpas et al. (2014)

Opportunities to reduce fuel consumption by up to 35% through improved vehicle design (unrelated to engine) have been explored for trucks in the US

Innovations in overall truck efficiency

- Given the fundamentally lower energy density of batteries and hydrogen storage relative to diesel vehicles, reducing the energy used per kilometre will be highly beneficial in terms of maximising range for a given amount of on-board storage
- Opportunities for reducing truck fuel consumption by 30-40%[1] through improving powertrain and road load technologies have been explored in detail for heavy-duty vehicles in the US.[2]
- The SuperTruck program aims to develop new advanced technologies to further reduce long haul truck fuel consumption by up to 50%.[3]
- Zero emission trucks will not benefit from engine related improvements, but research has found non-engine related improvements could deliver 35.3%[2] fuel consumption reductions for a Class 8 line-haul truck in the US by 2020-2030:
    - 22.2% reductions from aerodynamic drag improvements to tractor-trailer design (e.g. side skirts, gap reducers)
    - 9.6% reductions from using low rolling resistance tyres on both the tractor and trailer
    - 3.5% reduction from lightweighting (e.g. chassis and trailer optimisation)
- Class 8 line-haul trucks have greater weight and length due to different regulations in the US compared to the UK for long haul trucks. However, the reduction figures described above give show the approximate potential savings from improved road load technologies for trucks in the UK.
- These improvements would increase the driving range available from a given quantity of hydrogen or battery energy storage.

[1]compared to 2010 fuel consumption levels, [2]ICCT (2015b), [3]ICCT (2014)

Further design and demonstration work should be carried out on zero emission trucks, particularly on larger, long-range configurations

Recommendations

- The 26 tonne rigid truck appears very promising in terms of packaging traction batteries and hydrogen storage to give a high driving range. *Further work to develop and demonstrate a fuel cell truck in this size range is recommended. Ideally this would be led by a truck OEM rather than only an conversion exercise based on an ICE truck. Discussions are already in progress with the FCH JU to fund this type of activity in 2017*.
- There are on-going discussions to amend EU Directive 2015/719 (which defines truck length and weight regulations) but current proposals are to increase vehicle length limits by only 50 cm to allow for safer fronts and aerodynamic devices to be fitted. *The results of this design exercise should be used in discussions with regulators to highlight the benefits of increased flexibility for zero emission vehicles, particularly due to the current constraints for EU tractor units compared with US models*
- Long haul tractors are required to drive significant mileage but traditionally have short wheel bases compare to rigid trucks, and zero emissions options appear to be fundamentally range constrained unless liquid hydrogen is used. *We recommend engagement with fleet operators and/or freight associations to understand the potential impacts of these range constraints, such as the proportion of operations that could be carried out even with range-limited tractor units, or the feasibility of new configurations (such as increased use of rigid trucks with drawbar trailers) to overcome these limitations.*

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References

Author, publication year	Publication title
Argonne, 2010	Technical Assessment of Compressed Hydrogen Storage Tank Systems for Automotive Applications
Austin Power, 2015	PEM Fuel Cell System Manufacturing Cost Analysis for Automotive Applications
CAFEE, 2014	HDV diesel engine efficiency evaluation energy audit
Carbon Trust, 2012	Polymer Fuel Cells – Cost reduction and market potential
DVSA, 2013	Guide to lorry types and weights
ECF, 2015	Private work for European Climate Foundation
Element Energy, 2016	Consumers, Vehicles and Energy Integration (CVEI) - project is on-going
G. Petitpas et al., 2014	A Comparative Analysis of the Cryo-compression 2 and Cryo-adsorption Hydrogen Storage Methods
ICCT, 2014	The U.S. Super Truck Program Expediting the Development of Advanced Heavy-Duty Vehicle Efficiency Technologies
ICCT, 2015a	Cost effectiveness of advanced efficiency technologies for long haul tractor trailers
ICCT, 2015b	Advanced tractor-trailer efficiency technology potential in the 2020–2030 timeframe
ICCT, 2016	On-going work
IEA, 2015	Technology Roadmap – Hydrogen and Fuel Cells
IEA, 2006	Hydrogen Production and Storage - R&D Priorities and Gaps
Johnson Matthey, 2015	Forecast of Platinum Supply and Demand
L. Rudnick, 2005	Synthetics, Mineral Oils, and Bio-Based Lubricants: Chemistry and Technology, Second Edition
Mckinsey & Co, 2012	Urban Buses: Alternative Powertrains for Europe
OICA, 2014	World Motor Vehicle Production
Ricardo-AEA, 2012	A review of the efficiency and cost assumptions for road transport vehicles to 2050
Ricardo-AEA, 2011	Reduction and Testing of Greenhouse Gas (GHG) Emissions from Heavy Duty Vehicles – Lot 1: Strategy
Roland Berger, 2014	Fuel cells: A realistic alternative for zero emission?
Roland Berger, 2015	Fuel Cell Electric Buses - Potential for Sustainable Transport in Europe
Statista, 2015	Platinum-group metal reserves worldwide by country
Strategic Analysis, 2014	Mass Production Cost Estimation of Direct H2 PEM Fuel Cell Systems for Transportation Applications
TIAX, 2011	European Union Greenhouse Gas Reduction Potential for Heavy-Duty Vehicles
TIAX, 2009	Direct Hydrogen PEMFC Manufacturing Cost Estimation for Automotive Applications
US DOE, 2015	Fuel cell System Cost
US DOE, 2016	Medium and Heavy Duty Fuel Cell Electric Truck Targets
US Drive, 2013	Fuel Cell Technical Team Roadmap