Transport Energy Infrastructure Roadmap to 2050

HYDROGEN ROADMAP

Prepared for the LowCVP by Element Energy Ltd
Celine Cluzel & Alastair Hope–Morley

JUNE 2015

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Office for Low Emission Vehicles
Renewable Energy Association
Transport for London
Transport Scotland
UK Petroleum Association

Acknowledgements

The LowCVP, established in 2003, is a **public-private partnership** that exists to **accelerate a sustainable shift to lower carbon vehicles and fuels** and create opportunities for UK business.

LowCVP
Low Carbon Vehicle Partnership

The LowCVP aims to:

- Develop initiatives to promote the sale and supply of low carbon vehicles and fuels
- Provide input and advice on Government policy
- Provide a forum for stakeholders to share knowledge and information
- Ensure that UK motor, fuel and related businesses are best placed to capitalise on the opportunities in the low carbon markets of the future
- Contribute to the achievement of UK Government targets for road transport carbon reduction

Project Steering Committee

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BOC Limited
BEAMA
Calor Gas Ltd
EDF Energy
Electricity Networks Association
National Grid
Office for Low Emission Vehicles
Renewable Energy Association
Transport for London
Transport Scotland
UK Petroleum Association

Workshop attendees

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ULEMCo
UPS
Wales & West Utilities

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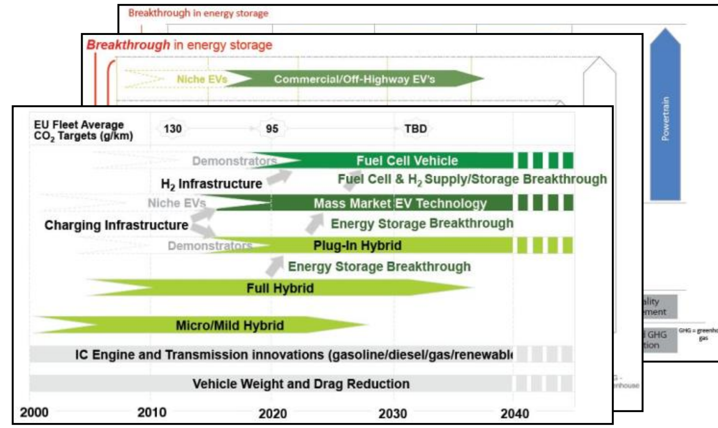
Background - a 'Transport Infrastructure roadmap' is needed to complement existing vehicle and fuel roadmaps

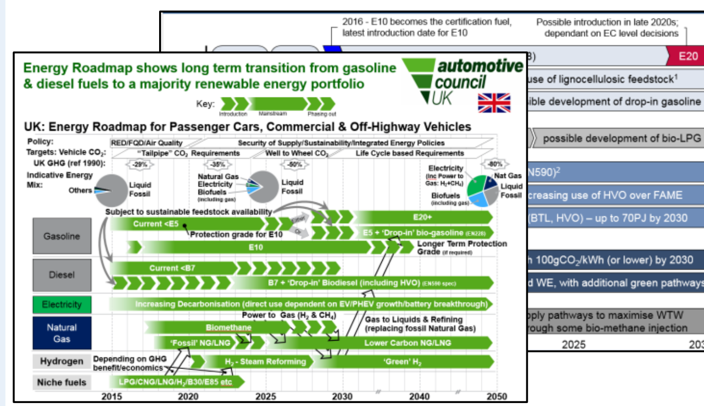
- In the context of the expected transition to lower carbon powertrains and fuels, the **Auto Council vehicle roadmaps** have proven to be a useful tool **to focus research, funding and policy**, bringing into one place the industry's views on future technology options, deployment steps and corresponding policy drivers.
- To complement these powertrain technologies roadmaps, the **LowCVP commissioned a Road Transport Fuels Roadmap in 2013-14**, which also proved successful in bringing clarity to the fuel options available and mapping the enabling milestones.
- This Infrastructure roadmap is the 'missing piece' that will support new powertrains and new fuels. This roadmap is all the more necessary as the **needs and barriers for deployment of electric, hydrogen and gas refuelling stations differ significantly** and refuelling/recharging infrastructure is a key enabler for low emission vehicles.
- The objectives of the Infrastructure Roadmap are to:
  - **Assess the infrastructure needs** and barriers for deployment of electric, hydrogen and gas refuelling stations to 2050, including impact on upstream distribution, as well as to consider 'conventional' liquid fuels
  - Make **recommendations for delivery** of infrastructure deployment, both at national and local government level.

Vehicle roadmaps



Source: Auto Council and LowCVP

Transport fuel roadmaps



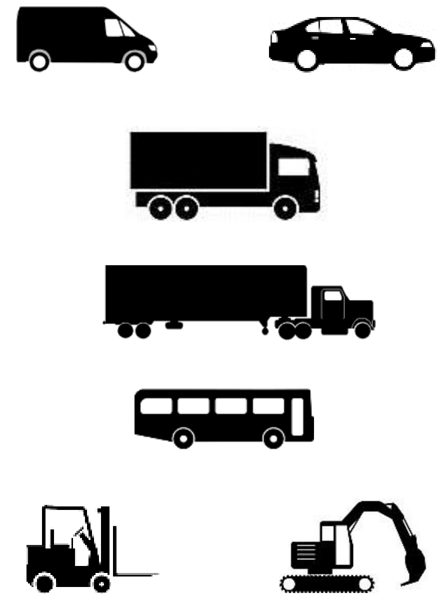
Source: Auto Council and Element Energy for the LowCVP

The Infrastructure Roadmap covers private and public infrastructure, for all main road vehicles and both current and future fuels

Fuels / energy vectors considered

- Zero tailpipe emission fuels: **electricity and hydrogen**
- 'Conventional' **liquid fuels**: gasoline (E5 to E20, in line with the Transport Fuels Roadmap), diesel, LPG/bio-propane
- **Methane**: Compressed Natural Gas (CNG), Liquefied NG (LNG) and biomethane
- Niche/future fuels: methanol, liquid air and a high bioethanol blend (E85)

Vehicle types



Refuelling infrastructure types

- Depot based refuelling for fleet operators and return to base operators
- Home recharging for private and (some) commercial vehicles
- Public forecourt refuelling/recharging

Drivers for change in the transport energy system

- The UK's legally binding target to **reduce total GHG emissions by at least 80% (relative to 1990 levels) by 2050**, and transport contributes to c. 25% of UK total GHG emissions;
- EU level regulations (gCO_2/km, **Air Quality targets** and EURO spec), Directives (Renewable Energy, Fuel Quality, Clean Power for Transport) and Transport White Paper

Source: Element Energy

The development of the Infrastructure Roadmap benefitted from input from a wide range of stakeholders, many consulted through workshops

Develop uptake scenarios for % sales of electric and ICE vehicles

ICE vehicles: diesel, petrol, LPG, gas vehicles
Electric vehicles: Battery (BEV), Plug-in Hybrid (PHEV), Range-Extended (RE-EV) and hydrogen fuel cell (FCEV)
Niche/future fuels considered: E85, methanol, liquid air

Input into Element Energy fleet model

Scrappage rate, stock and mileage inputs based on **DfT data/projections: c. 40% increase in stock and vkt by 2050 (39 million vehicles, 740 billion vkt)**; Vehicle efficiency based on **Committee on Climate Change modelling**

Output numbers of vehicles in the fleet and MJ used per energy vector

See full reports for further details of fuel uptake scenarios

Review existing literature on refuelling and upstream infrastructure

Industry consultation with LowCVP Fuels working group

Prepare Infrastructure Roadmap

Four dedicated fuel workshops were conducted

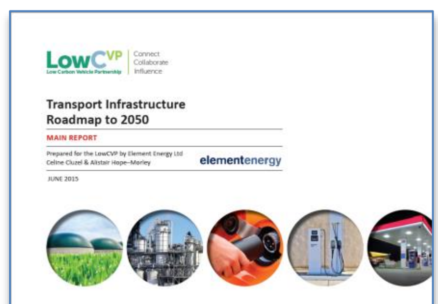
- Workshop themes: **electricity, liquid fuels, methane, hydrogen**
- **38 attendees included**: Infrastructure manufacturers, installers, operators, DNOs, energy companies, fuel suppliers, OEM / vehicle suppliers, end users, local government / regulator

Host stakeholder workshops

Review by Steering Committee

Prepare draft report

Complete final report



Report preparation
External input

Four separate reports have been developed – this report is dedicated to the case of hydrogen as a transport fuel

Four separate reports were produced to capture the differences between the energy vectors / fuels under consideration

This report

Final report summarising findings from each energy vectors

Structure of the report

- **Background and status quo**
  - Summary of current production and distribution system, and energy vector usage
  - Current supply pathways
  - Current dispensing technologies, geographical spread and key stakeholders
- **Future infrastructure requirements and barriers to deployment**
  - Future hydrogen transport demand and production pathways; the role of electrolysers
  - Quantification of refuelling station needs, by location and/or vehicle segment - based on projected demand, derived from validated uptake scenarios
  - Barriers to deployment of infrastructure *barriers to deployment of corresponding powertrains are not discussed– uptake of new powertrains/fuels is the starting assumption*
- **Summary roadmap and recommendations**
  - Roadmap schematic summarising the above findings
  - Recommendations for delivery (national, local, RD&D needs, funding shortfall)

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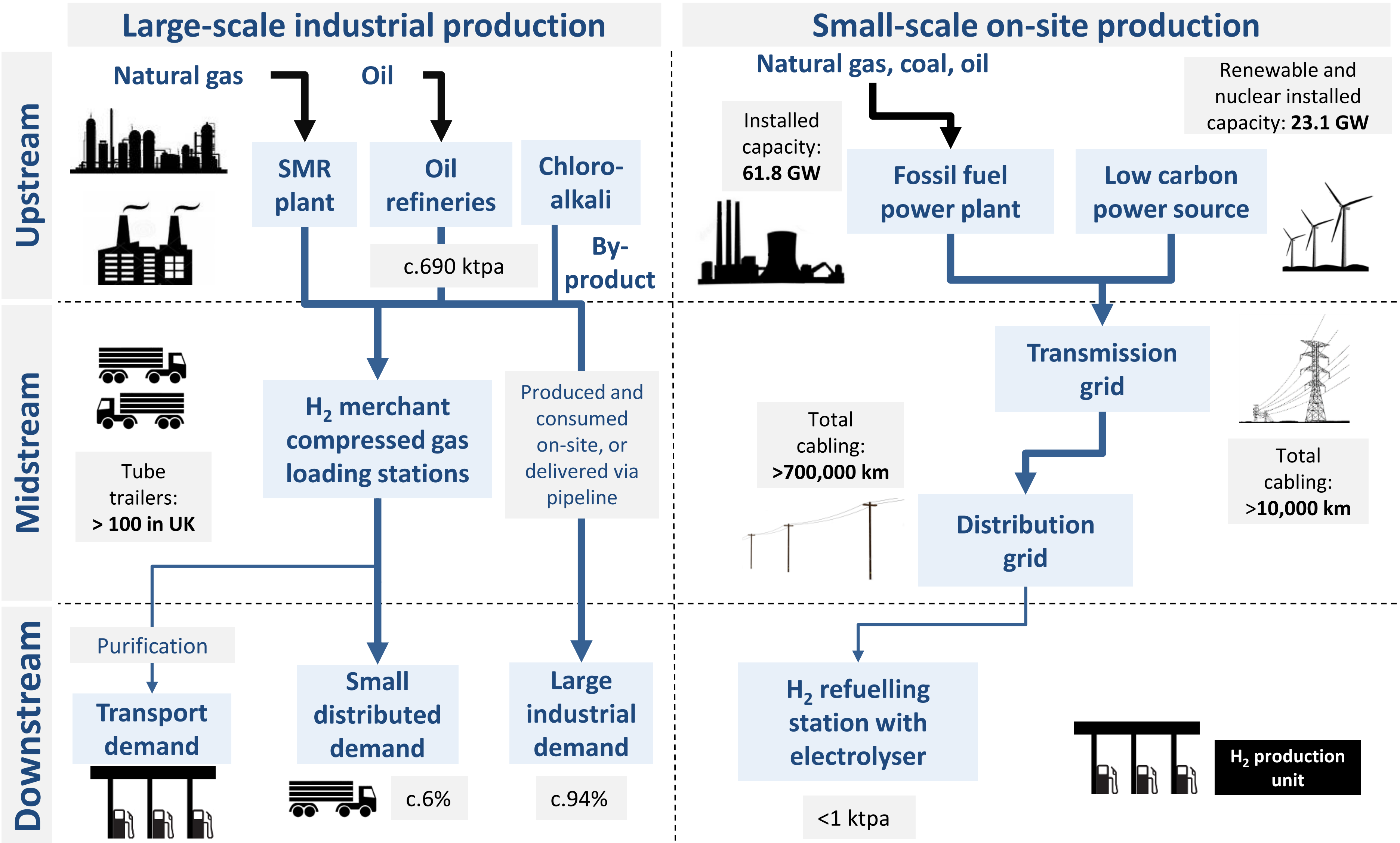
Until now, the UK hydrogen industry has been overwhelmingly geared towards meeting demand in refinery and industrial processes



Sources: All figures refer to the UK and are from DUKES (2014), DECC (2014), Roads2Hycom Deliverable 2.1 and 2.1a (2007)
Note: Some hydrogen is also imported to the UK

Several manufacturers plan to commercialise hydrogen vehicles in the coming years, with associated refuelling infrastructure requirements

Major vehicle OEMs

- **A range of OEMs have announced plans to bring FCEVs to market in the 2015-2018 period**, aiming to have 1,000's deployed by 2020:

Hyundai ix35 FCEV – launched 2014

Toyota Mirai – launched 2014/5

Honda FCV – launch 2016

Daimler next gen. FC – launch 2017

- These vehicles will **require extensive refuelling infrastructure** in their target markets, to offer an attractive consumer proposition
- They will be launched in markets where the best conditions exist in terms of customer demand and incentives, regulatory push and availability of infrastructure

Implications for refuelling infrastructure

- Hydrogen-powered vehicles will start to be deployed in the 2015-2020 period, with an expected ramp-up beyond 2020
- Depending on the deployment rate of passenger cars, other vehicle types may play an important role in increasing the utilisation of the early refuelling station network
- Consideration should be given to making refuelling stations compatible with a wide range of vehicles
- This **document summarises the likely infrastructure needs for hydrogen-fuelled vehicles in the 2015-2050 period**

Small manufacturers

- Several **non-OEM manufacturers are developing hydrogen (fuel cell or ICE)-based mobility concepts** across a range of segments, many already available:

Symbio FC range extended Kangoo – launched 2014

Symbio FC range-extended truck – launch c. 2017

Van Hool FC bus – launched 2013

Riversimple car – launch c. 2018

ULEMCo H_2-ICE Van – launched 2012

HyPulsion FC forklift – soft launch 2014

Expected to always require stand-alone refuelling facilities

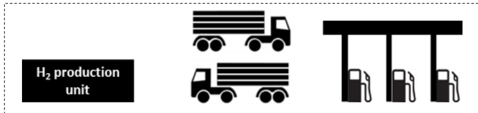
- Whilst some of these vehicles will rely on stand-alone depot-based refuelling infrastructure, **many will also rely on the availability of public refuelling networks**
- The non-OEM vehicles often have different refuelling requirements versus OEM cars (e.g. different refuelling pressures, refuelling frequency, tank size, etc.)
- There is therefore a **need to ensure H_2 infrastructure is compatible with all vehicle types from OEMs and other suppliers**

FC = Fuel Cell, FCEV = Fuel Cell Electric Vehicle

Source: Element Energy

Hydrogen refuelling stations (HRS) can be supplied by delivered or on-site produced hydrogen, with two main dispensing pressures

A) H_2 produced off-site and delivered to HRS



- Hydrogen is produced at a centralised, large scale plant via a series of available industrial pathways.[1]
- The hydrogen fuel must then be transported to a retail site via high pressure tube trailer, liquid H_2 trailer, manifold cylinder pack (MCP) or pipeline
- **E.g. Air Products has used both liquid and 500 bar tube trailers to supply TfL's Lea Interchange bus depot**

B) H_2 produced on-site at the HRS

- Hydrogen is generated on-site via a co-located H_2 production unit, using water electrolysis, or small scale steam methane reforming
- This approach eliminates all fuel distribution costs but increases the HRS capital cost
- **E.g. BOC generates H_2 at Aberdeen City Council's Kittybrewster HRS via an on-site electrolyser**

Dispensing pressure levels available

- Two pressure levels available: **350 bar and 700 bar:**
  - Most **OEM vehicles have 700 bar** H_2 tanks but are compatible with both 350 and 700 bar dispensers, with the higher pressure required for a full tank fill (350 bar offers a c. 60% fill). OEM consensus favours 700 bar refuelling to maximise range however certain key players consider the higher pressure to not be essential for market development
  - **Currently most other vehicles**, e.g. H_2 buses, forklifts and some vans **use 350 bar** technology, to achieve lower refuelling station and tank costs - higher pressures may be required in future when space constrained vehicles are considered (double decker buses)

[1] Steam methane reforming (using methane or biogas feedstock), methanol reforming, autothermal reforming, chloralkali by-product, gasification (using waste, coal or biomass feedstock), centralised water electrolysis (using alkaline or PEM technology)

Today's early public HRS are generally based on containerised solutions; future HRS will be more fully integrated with existing forecourts

Current HRS layouts

- UK HRS are currently stand-alone or 'hosted' sites i.e. not fully integrated with conventional forecourts
- Dispenser is accessible to vehicle users, while hydrogen storage, compressors etc. are secured from public access
- Some sites use 'trailer swapping', where a hydrogen trailer acts as an on-site hydrogen store rather than offloading to other storage tanks

Characteristics of today's HRS

- Generally based on containerised solutions – typically standard ISO shipping containers
- They are often stand-alone stations on dedicated land
- HRS equipment is often in ISO (20 ft) shipping containers. Overall footprint of ~150m² depending on manoeuvring space etc.
- A local H_2 store in the form of compressed gas is generally present
- Refuelling nozzle is industry standard, safe, reliable and user friendly
- Refuelling takes a similar time to conventional fuel (3–4 minutes)

Future HRS will be integrated with existing forecourts

- It is envisaged that future HRS (e.g. beyond 2020) will increasingly be integrated within conventional existing petrol stations. Furthermore, the **coexistence of EV and FCEV infrastructure** should be considered
- This is likely to be the long-term solution once FCEVs reach commercialisation but will require well designed and fully integrated H_2 storage, distribution and safety systems, as well as developments in national regulations

- A number of fuel retailers have already trialled these solutions, and integrated stations are already present in Germany and California

Source: Air Products, www.hydrogen.energy.gov

HRS economics are strongly linked to station size and loading levels, which can be optimised by targeting multiple vehicle types

Three typical sizes defined for HRS

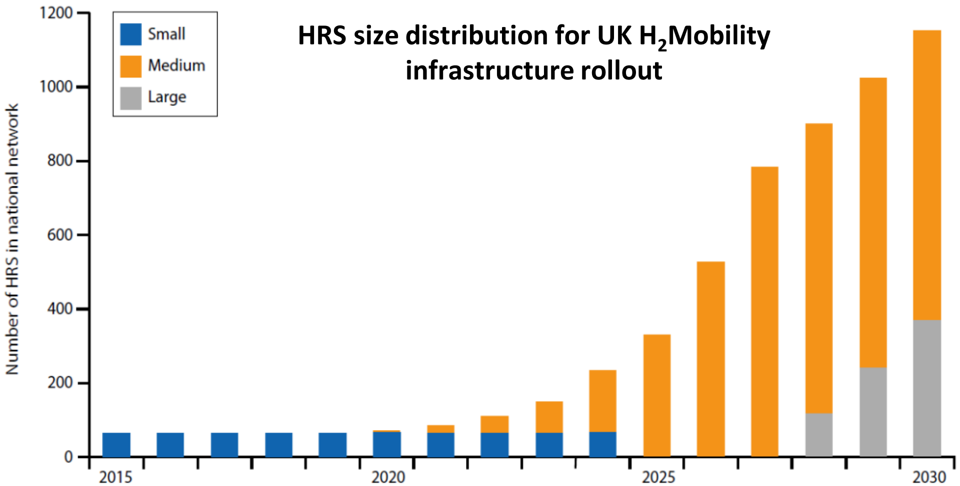
- It is useful to define HRS into three main size ranges, based on daily dispensing capacity:
- A number of very small options (e.g. <50kg/day) may also come to market

Small:	Medium:	Large:
<100kg/day	c. 500 kg/day	> 1,000 kg/day
< 20 cars/day	c. 100 cars/day	> 200 cars/day

Average commercial liquid fuel forecourt dispenses 11,400 Litres/day, equivalent to c.300-400 cars/day

The size of HRS deployed will evolve as demand grows

- Early HRS are likely to be in the 'small' range
- As vehicle numbers and demand grow, larger stations with superior economics will increasingly be deployed



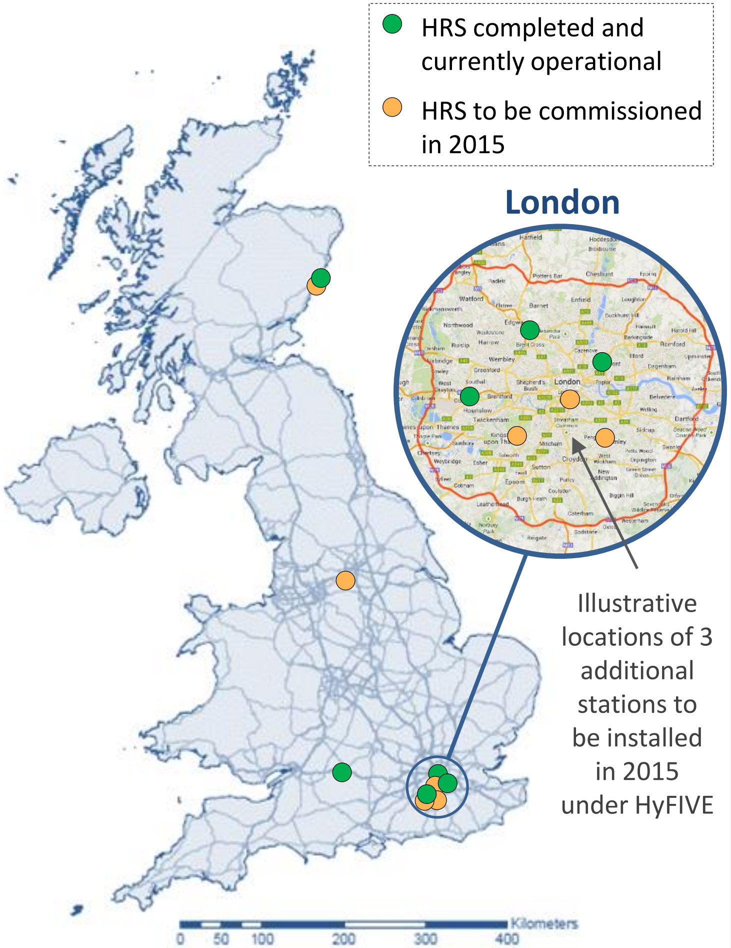
HRS economics are heavily influenced by size and demand from various vehicle types

- HRS capex does not vary linearly with dispensing capacity, as such **costs per kg are substantially higher for small stations with the same % loading**
- Station loading is critical in determining economics:
  - **'Small' stations require very high loading/ utilisation to break even, even with financial support e.g. capital funding**
  - Larger stations can break even at much lower loading levels
- Larger vehicles use significantly more hydrogen per day than passenger cars, and can make a useful 'base load' contribution to the hydrogen demand at a nearby station
- As such there is a **strong driver to ensure that HRS can meet technical requirements of as diverse a range of vehicles as possible** – this will ensure higher load factors (and favourable economics), as well as helping to de-risk any over-reliance on a single vehicle type.
- However, this must take into account **practical/ operational constraints that may prevent cars and large vehicles (e.g. buses) from sharing HRS**

Source: UK H_2Mobility Phase 1 (public report), Forecourt Trader Fuel Market Review (2014)

There are five operational HRS in the UK with a combined capacity of c. 1 tonne-H_2/day, with seven more planned by the end 2015

Hydrogen infrastructure in the UK today†



Key players active in hydrogen transport in the UK

Retailers, manufacturers, suppliers, installers, associated energy companies

BOC – A Member of The Linde Group; Sainsbury's; Air Products; Haskel; Hydrogenics – Shift Power | Energize Your World; ITM Power – Energy Storage | Clean Fuel; Air Liquide; SSE

OEMs, vehicle suppliers, end users, local authorities

ULEMCo; Hyundai; Riversimple; Symbio FCell; Stagecoach; Toyota; Transport for London; Honda; Tower Transit; Commercial Group; Aberdeen City Council

Evolution of hydrogen vehicle/HRS deployments in the UK

Key milestones

2008 – 2009 – 2010 – 2011 – 2012 – 2013 – 2014 – 2015 – 2016

- UK H_2 Mobility: *Development of national rollout plans begun for H_2 infrastructure and passenger vehicles*
- CHIC: *Eight fully operational FC buses and one HRS deployed* ★
- Aberdeen Hydrogen Project: *Ten FC buses and one HRS deployed in Aberdeen*
- HyTEC: *One publicly accessible HRS, five FC taxis, and a fleet of FC passenger cars* ★
- *One publicly accessible HRS installed alongside a supermarket forecourt, a fleet of H_2 vans and FCEVs* ★
- *First publicly accessible HRS with on-site production of 'green' H_2 in Swindon*

- HyFIVE – Hydrogen for Innovative Vehicles: *Three new public HRS and c.50 new FCEVs to be deployed in London over three years* ★

UK activities exclusively based in London: ★

†: Note this does not include small-scale HRS in Birmingham, Coventry, Glamorgan, Isle of Lewis, Loughborough, Nottingham, University of South Wales. It does not include HRS funded under the 2015 OLEV scheme (2 new HRS and 2 mobile refuellers)

Many H_2 production pathways exist with varying costs and CO_2 emission rates – most options are available to the UK today or in the future

Hydrocarbon-based production

- The **most common form of industrial H_2 production** today
- Involves reforming methane or other hydrocarbons to produce syngas and subsequently using the water-gas-shift reaction to extract hydrogen
- Highly mature technology allowing **low-cost, large-scale** production
- Pathway can potentially be decarbon-ised with carbon capture and storage

Large production capacity in the UK

Water electrolysis

- Mature technology but further developments needed for widespread transport use
- Allows on-site production at HRS
- Requires access to low cost electricity to achieve affordable H_2 costs
- Using renewable electricity produces **'green' hydrogen**
- Potential for use in refinery processes if sufficiently low cost

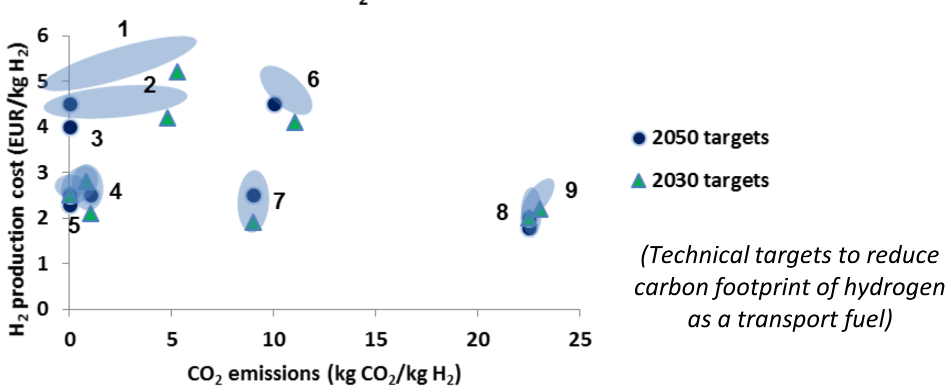
Several suppliers based in the UK

Biogas, CCS & novel routes

- H_2 can be produced from **various alternative sources**, including waste gasification, from anaerobic digestion, or as an industrial or CCS by-product
- Some technologies would produce **large quantities of cheap, 'green' H_2** if developed, e.g. CCS
- Industry will only consider developing novel pathways when a strong, reliable energy sector demand is established

Techs. at various development stages

Technologies available for H_2 production, their costs and CO_2 emissions



Technology type[1]

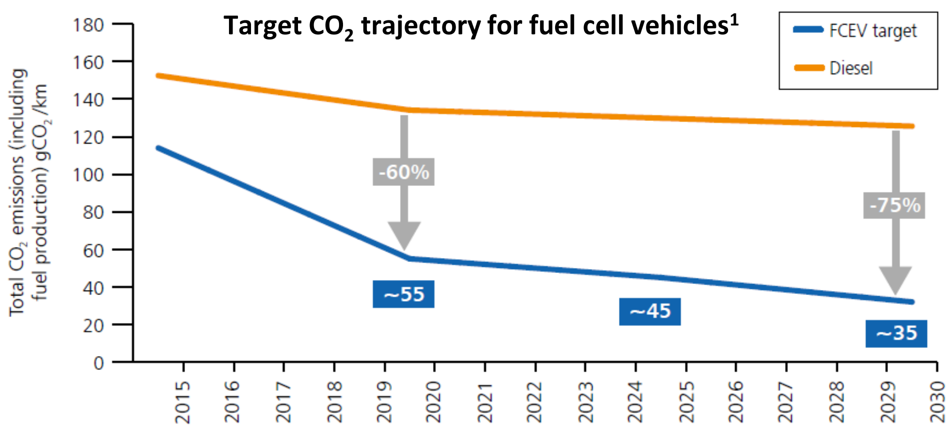
1. Distributed water electrolysis
2. Conventional water electrolysis
3. Coal gasification + CCS
4. Centralised SMR + CCS
5. IGCC + CCS
6. Distributed SMR
7. Conventional SMR
8. IGCC
9. Coal gasification

Source of graph: A portfolio of power-trains for Europe: a fact-based analysis, McKinsey & Co, 2011

CCS = carbon capture and storage, SMR = steam methane reforming 1 Assumes access to green electricity for electrolysers

Likely production mix will be of methane-based and electrolytic 'green' H_2 in the medium-term, with more 'green' sources in the longer term

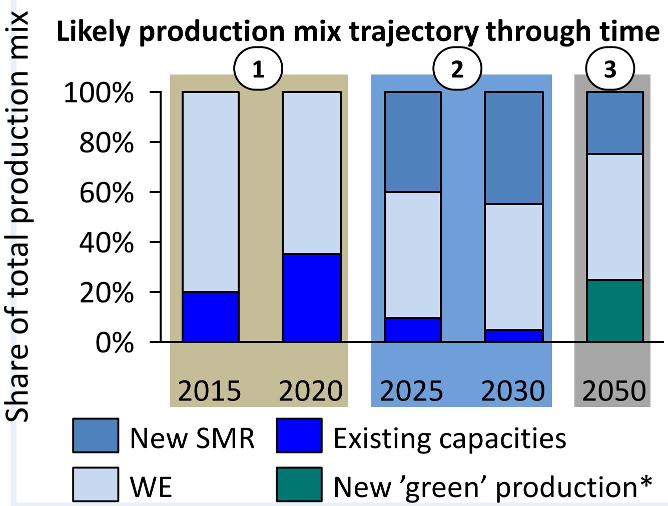
'Green' hydrogen transition trajectory



From 2015 to 2030, a **mix of methane-based and 'green' water electrolysis hydrogen production** will dominate:

- UK H_2Mobility presents a plan to achieve a low carbon trajectory for the fuel (implying use of renewable electricity for electrolysers), whilst ensuring the fuel is affordable (leading to the use of fossil hydrocarbons)
- The strategy **matches the CO_2 performance of plug-in hybrids** as the grid decarbonises, whilst identifying a least cost production mix– leading to a **roughly equal mix of methane and electrolysis options**
- Similar Well to Wheel performance expected beyond 2030

Various sources are likely to be relevant to H_2 production going forward



1 A lack of well-developed distribution systems for high-purity hydrogen will lead to the initial dominance of WE using on-site production → As guaranteed purity becomes more prevalent from existing centralised sources and demand can justify investment in high-capacity distribution, the dominance of WE is reduced from 2020, as existing H_2 sources are tapped

2 In the 2020-2030 period, overall demand will exceed existing spare capacity and a mixture of new on-site/centralised WE and centralised SMR will be developed, with associated distribution infrastructure. Clear policy will be needed to deliver green H_2

3 Beyond 2030, 'green' H_2 will increasingly dominate due to climate change/CO_2 targets. → A wider variety of sources are likely to become available, e.g. waste gasification, CCS with the choice of source being specific to the costs in specific locations, rather than a single technology dominating

[1]: UK H_2Mobility Phase 1, public report

*: New 'green' production could include waste gasification, CCS, etc. The development pathway for these technologies will strongly influence the 2050 production mix

In 2014, the European Commission issued a directive to help harmonise technical specifications for hydrogen refuelling equipment

- The **Clean Power for Transport** programme, initiated in 2013, aims to facilitate the development of a single market for alternative fuels for transport in Europe
- The resulting **2014/94/EU directive** on 'the deployment of alternative fuels infrastructure' aims to:
  1) Harmonise technical specifications for recharging and refuelling stations
  2) Develop clear, transparent fuel price comparison methodologies
  3) Ensure Member States develop national policy frameworks to support the deployment of alternative fuel technologies and infrastructure
- Clarity on use of 700/350 bar or dual-pressure refuelling remains not fully addressed by the Directive, as conformity is possible at 700 bar or 350 bar pressures

From Nov 2017, all public HRS in the EU must be compliant with the technical specification

- Hydrogen refuelling points shall employ compliant fuelling algorithms and equipment → **ISO/TS 20100** Gaseous Hydrogen Fuelling specification
- Hydrogen purity dispensed by hydrogen refuelling points → **ISO 14687-2** Hydrogen Purity Standard
- Connectors for motor vehicles for the refuelling of gaseous hydrogen → **ISO 17268** Gaseous Hydrogen Motor Vehicle Refuelling Connection Devices Standard

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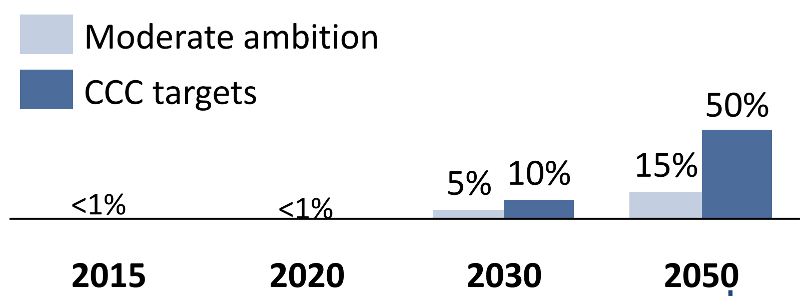
FCEV uptake has been projected to quantify the hydrogen demand in transport and corresponding requirements for HRS

In consultation with the LowCVP Fuels Working Group, we derived uptake scenarios for new powertrains/fuels, they are policy led, typically based on CCC targets. Scenarios are used to forecast infrastructure required to match transport policy ambition and estimate the corresponding upfront costs of this infrastructure

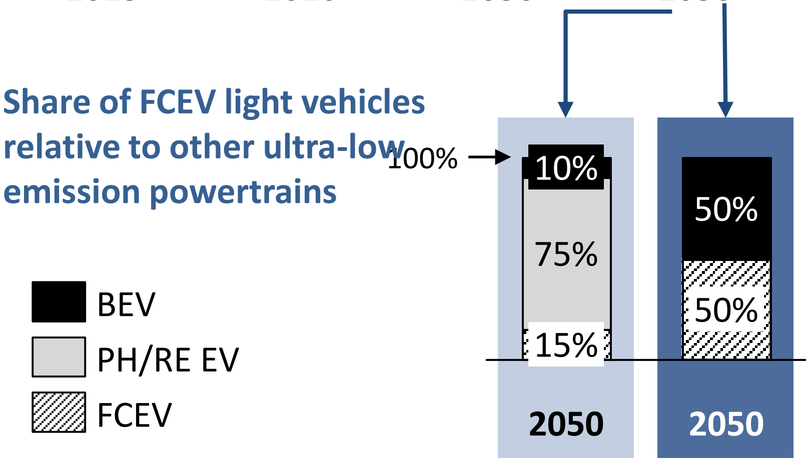
Uptake of FCEVs is mainly in the light vehicle segments

- **Two scenarios** for cars & vans,
  - '**CCC targets**': FCEVs reach 10% market share by 2030 and Zero Emission vehicles reach 100% of market share before 2050
  - '**Moderate ambition**': the 2030 CCC targets are not met, FCEV uptake represents 5% of new sales; by 2050 FCEVs represent 15% of new sales but the wider category of EVs represent 100% of sales
- An increase of sales of **fuel cell HGVs** (mostly under 7t GVW) to <1% in 2020, 1% in 2030 and 20% in 2050
- An increase of sales of **fuel cell buses** 1-2% in 2020, 5% in 2030 and 50% in 2050
- Vehicle stock numbers were calculated using Element Energy's UK vehicle fleet model. H_2 consumption was based on manufacturer data and observations from UK and EU vehicle trials

Market share of FCEV cars and vans (new sales)



Share of FCEV light vehicles relative to other ultra-low emission powertrains



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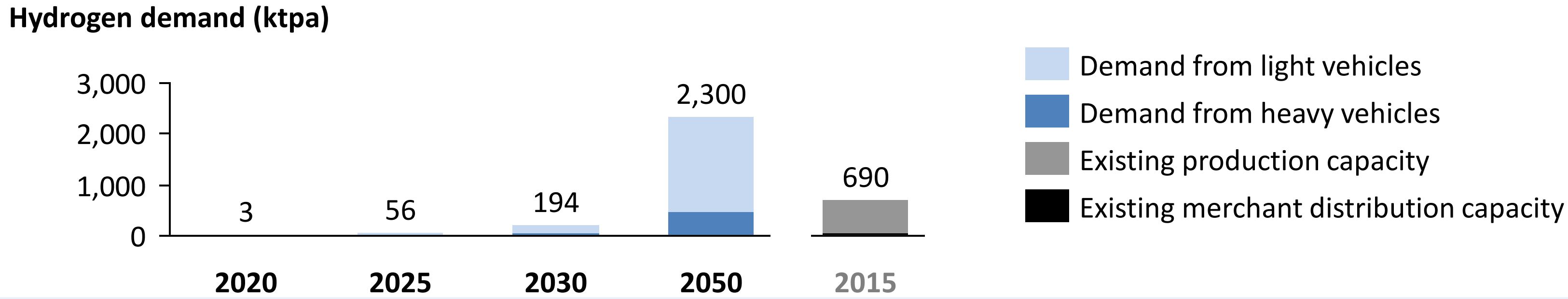
Growth in hydrogen demand to 2050 from transport will require significant capacity, particularly in low carbon production routes

Projected growth in hydrogen demand for use in transport (High uptake case reaching a parc of c. 10 million vehicles by 2050)



Hydrogen demand today and in 2050

- Under the high uptake case hydrogen demand for transport will **exceed existing production capacity** in the 2030s
  - Existing production capacity stands at c. 690 kt/year of which 650 kt/year is dedicated to use by heavy industry, leaving 41 kt/year that is distributed by tube trailer
  - Total demand from transport by 2050 equates to c. 2,300 kt/year under the high uptake scenario
- This additional demand presents a **significant challenge in terms of both production and distribution capacity**:
  - A quadrupling of existing production capacity would be required: additional production is equivalent to c. 23 large SMR plants[1], or c. 15 GW of grid-connected electrolysers[2]
  - If this hydrogen was all produced centrally, this would likely require around 2,000 tube trailers, based on existing technology (1.1 t per trailer, 500 bar) and two trips per day, compared to <100 trailers today.
  - Alternatively, higher demand could attract large gas companies to deploy centralised liquefaction facilities and develop liquid hydrogen logistics networks benefitting from greater vehicle capacity (c.3t per trailer)
  - *The case of electrolysis production (which can be centralised or on-site) is detailed on the next slide*

Source: UK H_2Mobility Phase 1 public report, Roads2Hycom Deliverable 2.1 and 2.1a, Element Energy
1: Based on 100ktpa (largest current UK SMR plant) 2: Based on 70% efficiency and 80% load factor

Once commercially proven, H_2 from water electrolysis (WE) is expected to see significant growth to 2030, driven initially by the transport sector

Optimised economics are key

1. Access to low-cost electricity
2. Ability to access payments from energy network operators from provision of grid services

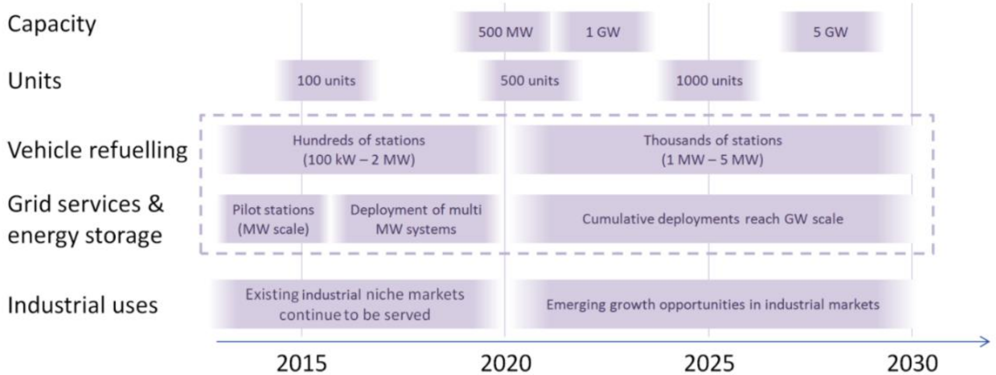
Improvements in performance and capex also required

- Improvements in **capex, system size, efficiency** and **lifetime** will be required to improve overall economics
- These incremental changes will be key to the widespread rollout of WE

Growth in electrolysis is expected assuming the right conditions are met

- It is expected that **growth in electrolyser numbers will be led by a number of applications**:
  - The **commercialisation of FCEVs** in the 2015-2025 period, leading to a demand for high-purity, low carbon H_2
  - Other markets for electrolysis may open in the **power to gas and chemicals sectors** in parallel to transport

Expected development of electrolyser applications through time



- On-site electrolysis (as opposed to centralised production) is **likely to dominate in short term** as there is a better match with the scale of demand at refuelling stations. Groups of on-site electrolysers can provide grid services through pooling/aggregation
- In the medium term, choice of on-site versus centralised production **will depend on economies of scale, access to low electricity prices versus distribution costs and possible colocation with other demands** (e.g. power to gas, pre-combustion carbon capture and storage)
- Green H_2 could also **displace conventional H_2 in refinery processes** if available at sufficiently low cost

Source: Development of Water Electrolysis in the European Union, FCH JU, 2014

1 The main component of the cost of hydrogen production from electrolysis is the variable electricity input costs

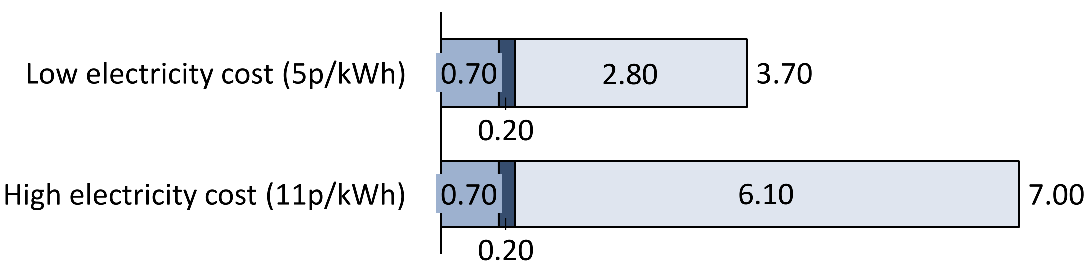
New applications for electrolytic H_2 are emerging

- Only **4% of existing global H_2 production** (mainly for industrial use) is **based on WE**,[1] due to the higher costs of WE in most markets compared to alternatives e.g. SMR, or industrial by-products
- More recently, **increasing demand for lower carbon content and higher purity H_2** for transport applications is leading to **increased demand for H_2 from WE** (which produces very pure H_2, can be deployed on-site, and can be powered by renewable electricity)
- This new demand ties in well with the **emergence of WE as a solution for energy storage and grid balancing** applications

The cost of hydrogen production is made up of a number of components, dominated by variable costs

Capital costs (capex)	Fixed operating costs (fixed opex)	Variable operating costs (variable opex)
All capital costs (including finance costs) spread over each kg of H_2 delivered	Includes servicing, maintenance, insurance, land rent etc.	Dominated by electricity cost, but also includes water feedstock

Illustrative H_2 production cost from water electrolysis, £/kg



Cost structure is dominated by variable costs[2]. Low electricity prices are required to be competitive with petrol/diesel on a per km basis, which is approximately £7/kg equivalent including the HRS

Variable operating costs, i.e. **electricity input costs make up the largest portion of the levelised cost of H_2 production**

1 MW alkaline WE system 2015 costs from FCH JU electrolyser study (2014): capex = £760/kW, opex = £27/kW (excludes stack replacement), electricity price range = £0.05-0.11/kWh (lower-bound corresponds to electrolyser providing e.g. grid balancing services, etc. or private wire connection to a renewables generator, upper-bound corresponds to using retail electricity prices), interest rate = 7%, lifetime = 15 years, WE consumption = 55 kWh/kgH_2, utilisation = 80%, excludes redundancy costs

Source: Element Energy analysis [1]IEA (2007), [2]This assumed a well-utilised electrolyser. As utilisation decreases, capex and fixed operating costs become a larger proportion of the overall cost of H_2 produced

The economics of H_2 from electrolysis are heavily dependent on the ability to access affordable electricity and to provide services to the grid

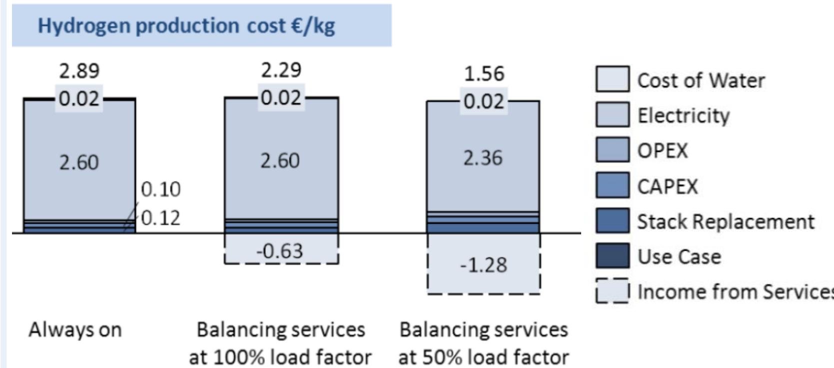
Options for minimising dominant variable costs

In the UK, two main ways to lower variable costs can be envisaged:

- Reducing the cost of electricity purchased, through e.g. avoiding distribution network charges – this can be achieved through **connecting the electrolyser directly to a renewable generator**, without going via the distribution/transmission grid
- Accessing **payments from the grid operator to help balance the grid** by storing energy at times of high production/low demand, or providing frequency response services – the **H_2 produced** from energy storage **can be used for transport, re-electrified via a fuel cell, or injected into the gas grid**

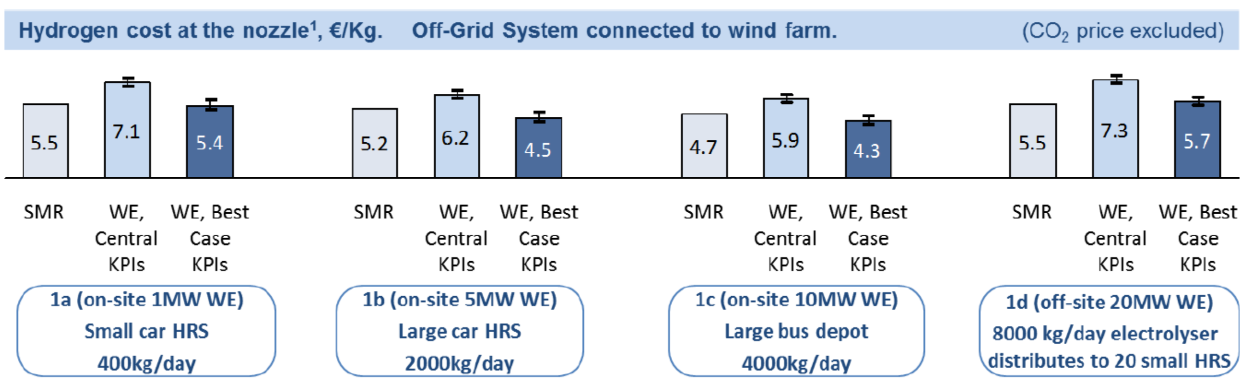
Grid services impact

2030 H_2 production cost in Germany under full- and part-load operating strategies, offering balancing services



Impact of off-grid connection for electrolyser

2030 H_2 cost at the nozzle for transport applications in the UK



Resulting H_2 economics

- Savings from **using a private wire connection can lead to attractive economics vs. SMR in 2030**
- **Additional savings (e.g. c €1/kg) can be made from offering grid balancing services** – provided the right balancing payments regime is in place

Source: Development of Water Electrolysis in the European Union, FCH JU, 2014

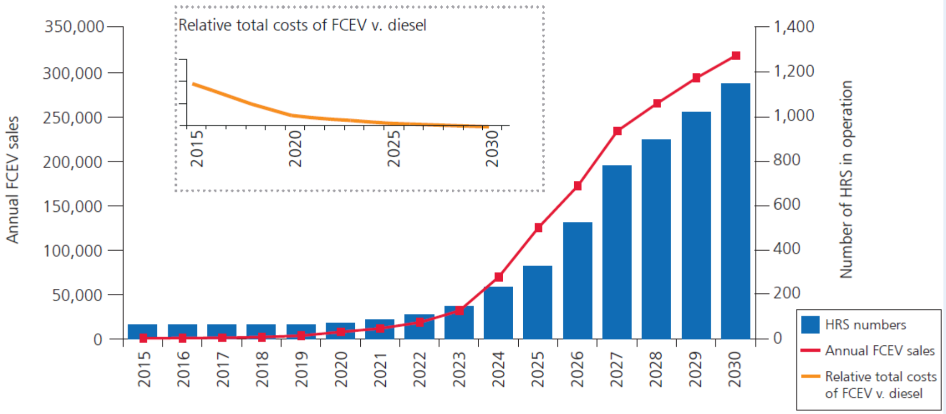
Contents

Early publicly accessible HRS are likely to require public funding, beyond 2020 HRS will offer increasingly attractive investment propositions

hydrogen

FCEV passenger car rollout will occur slowly pre-2020

- FCEV costs are likely to be higher than diesel and plug-in vehicles until 2nd gen. in ~2020 or beyond
- FCEV car sales of 100s-1000s expected before 2020
- Based on current uptake, pre-2020 deployments are likely to be concentrated in major urban centres
- **HRS deployments likely to be 10s of relatively small stations**, with low utilisation in early years
- Vans/captive fleet vehicles could help provide a base load demand for HRS. Locations of these vehicles will be driven by local customer demand



A Pre-2020 HRS are likely to require public funding

- HRS investments will be required early in order to ensure early FCEVs have access to hydrogen, despite **challenging economics** of small, under-utilised HRS
- In most cases (except e.g. heavily-loaded captive fleet HRS) **European, national or regional government intervention** will be **required to bridge the funding gap**
- A range of funding sources is available – next slide

B Post-2020, HRS will offer improving economics

- As FCEV numbers ramp up post-2020, larger, more profitable HRS can be built
- With more vehicles providing higher load factors, these HRS will offer more **favourable economics**
- At this point, a **commercially sustainable rollout is possible**, with increasing interest from existing petrol station operators or new entrants.
- Funding no longer needed on a per station basis

Source: UK H_2 Mobility Phase 1 report

A range of public funding sources will support hydrogen refuelling infrastructure deployments in the pre-2020 period

Funding body	Description	Funding rate	Timescales
FCH JU (FCH 2 JU) FUEL CELLS AND HYDROGEN JOINT UNDERTAKING	Public-private partnership between EC and industry, to advance the commercialisation of hydrogen and fuel cells	Up to 70% of project value under Horizon 2020	Annual calls for proposals 2014-20
EU Structural Funds	EU funds for encouraging development across a range of thematic objectives (total ~€10.7bn 2014-2020 for the UK)	Up to 60% of project value	Annual calls for proposals 2014-20
EU TEN-T/CEF Funding TEN-T	Funding to improve key transport corridors in Europe, across a range of modes (total €26.3bn 2014-2020 across Europe)	Varies up to 50% depending on type of project	Annual work programmes 2014-2020
UK Government Office for Low Emission Vehicles	UK Government Ultra-Low Emissions Strategy (£500m) includes funding to support H_2 infrastructure in the UK (announced October 2014)	Initial funding: £11m inc. new HRS (£7m), upgrades (£2m) and vehicles (£2m)	• First £5.5m call: closed 6th March 2015 • Future calls uncertain
Innovate UK Innovate UK Technology Strategy Board	UK Government-run body to help fund innovation in a range of technology areas	Up to 50% of project value (60% for SMEs)	Regular calls for proposals

Some uncertainty remains around the end of public support beyond 2020

- Multiple funding sources are available to support new refuelling infrastructure in the early years of FCEV commercialisation, up to 2020, however **beyond 2020 it is unclear which sources of funding will be renewed**
- There may be a **need to review public funding around 2018**, to evaluate the need for funding/policies/other support mechanisms beyond 2020 and ensure that adequate support is in place for hydrogen transport commercialisation to continue beyond 2020

Source: Element Energy

The hydrogen sector is working to address several barriers to allow the transition from demonstration activities to a commercial rollout

Barrier	Description	Example solution
Cost and reliability of HRS	Today's HRS are produced in low volumes, with bespoke, low volume components. Reliability not yet equal to petrol forecourts	▪ Introduction of series production and standardised designs ▪ Reduced cost and standardisation of compression/pre-cooling components ▪ Mobile back-up stations to give network redundancy
Customer experience	Consistent customer experience e.g. 'look and feel' of stations, ease of payment, pricing etc. not yet established	▪ Industry-agreed guidance for customer experience ▪ Apps to help navigate sparse early network
Regulatory and approvals process	Regulatory regimes often differ between sites, with no standardised approvals process yet defined	▪ Introduction of EU-wide regulations for safe design of HRS ▪ Standardised and streamlined approvals processes
Safety restrictions	Static hydrogen storage regulations restrict sizing of refuelling stations	▪ Amend COMAH (and other) regulations to reflect the needs of the hydrogen transport sector
Station siting	Challenging to find suitable sites in space-constrained urban areas	▪ Development work to reduce station footprints ▪ Involvement of fuel retailers/site hosts required
H_2 quality assurance and metering	Quality assurance procedures to meet ISO-defined purity limits not yet finalised Accurate H_2 fuel metering technology is immature	▪ Development of standardised, low-cost, in-line fuel quality measurement techniques ▪ Simplified H_2 purity regulations from OEMs ▪ Volume-produced H_2 metering technology

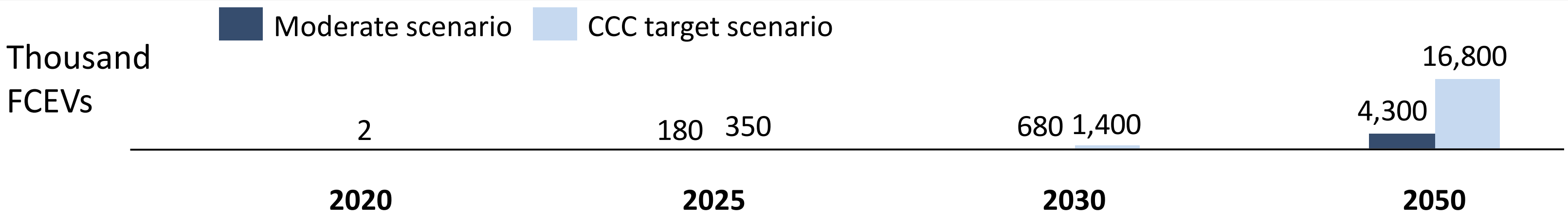
AD = Anaerobic digestion

Contents

Passenger cars - full national coverage for hydrogen refuelling for cars is expected by 2030, to support increasing FCEV numbers

Total FCEVs in the vehicle parc beyond 2020

H_2 demand (ktpa): *2* *18-34* *65-130* *340-1300*



2015-2020

- First 10-15 HRS deployed in 2015
- Gradual ramp-up to 65 by 2020 before further deployments Likely mostly 'small' (< 100kg / day) – HRS supported by public funding
- Dominated by stand-alone HRS, some forecourt integration

2020-2025

- Ramp-up post-2020 with 2nd gen. FCEVs
- >300 HRS deployed by 2025
- Shift to larger, profitable stations
- Shift to forecourt stations and market entry by major retailers

2025-2030

- Further mass-market vehicle growth
- Rapid rollout of large, forecourt-integrated HRS
- Full national coverage achieved by 2030, with >1,000 HRS deployed
- Intervention to ensure sufficient green H_2 in production mix

2030-2050

- Continued growth in line with FCEV sales, which are expected to make up 20-50% of the vehicle parc by 2050
- Hydrogen a 'standard' offer at majority of refuelling stations during this phase

Source: UK H_2Mobility Phase 1 public report, DECC 2050 pathways analysis

The initial focus for the passenger car-led HRS rollout is likely to be dense urban centres, with rapid expansion beyond 2020 to the rest of UK

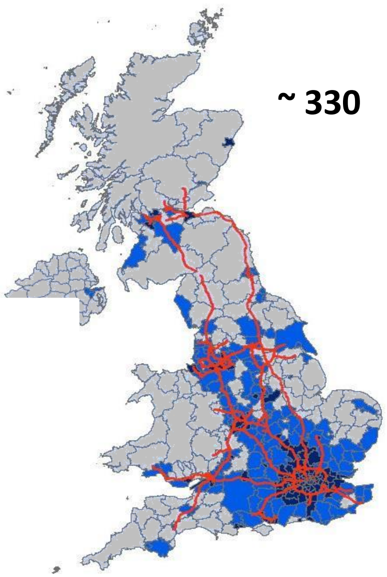
First 65 HRS for passenger cars deployed by 2020

- Initially, OEM vehicles will not be available in all showrooms. Instead, vehicles will only be made available from a few strategically chosen areas predominantly in South East England
- Geographic strategy for first stations not yet finalised, though focus on South East is expected given current HRS deployment trends and high costs of supporting small numbers of vehicles across national dealer network
- Some coverage of major roads and secondary urban clusters as HRS numbers grow – 'primitive' national driving by 2020

> 300 HRS across the UK by 2025

- All major roads and major cities covered by 2025
- Coverage to enable 'close-to-home' refuelling for 50% of the population, as well as long-distance travel

Areas covered by HRS deployed in:
- 2015-2020
- 2021-2025
- 2026-2030

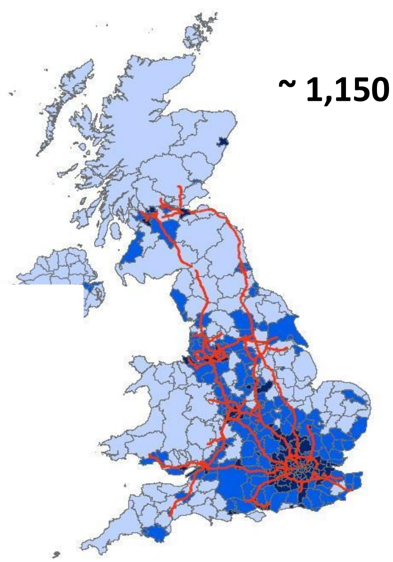


2025 illustrative

> 1,000 HRS across the UK by 2030

- Full UK coverage, defined as 'close-to-home' refuelling for the whole UK population, including less-populated regions

Areas covered by HRS deployed in:
- 2015-2020
- 2021-2025
- 2026-2030



2030 illustrative

Source: UK H_2Mobility Phase 1, public report, industry input at workshop in March 2015

Vans - use of passenger car stations, with a small number of dedicated HRS at depots by 2030

Growth in hydrogen vans expected beyond 2025 as more vehicles become available and prices drop

2015-2020	2020-2025	2025-2050
Most H_2 vans deployed in relatively small numbers, reliant on fully public infrastructure	Additional H_2 van options likely available, e.g. from OEMs → greater penetration amongst fleet operators	As costs approach diesel parity, rapid growth in adoption of H_2 vans in applications that cannot be met by battery electric vans

2015-2020

- Use of public HRS preferable to provide 'base load' H_2 demand
- Some vans currently require 350 bar refuelling – dual-pressure HRS may be needed where this is justified by local vehicle demand
- Avoid depot-based refuelling where possible, deploying vehicles in fleets able to use the emerging public infrastructure
- Maximise public availability

2020-2025

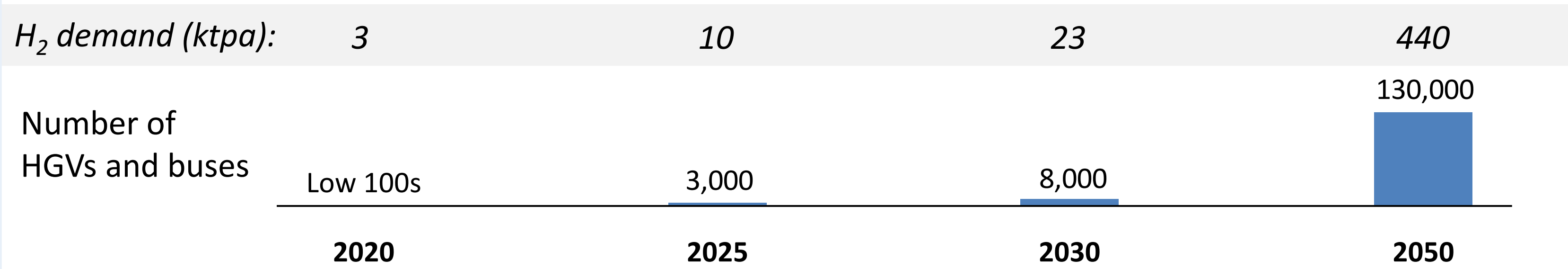
- Increased deployments of vans, particularly driven by urban air quality restrictions
- Continued use of public refuelling where possible
- Emergence of depot-based refuelling where needed for operational reasons and for large fleets
- Potential shift to 700bar tanks reducing the need for dual-pressure stations

2025-2030

- Widespread deployment of hydrogen vans
- Strong utilisation of HRS by cars reduces importance of non-depot refuelling for vans (i.e. base load demand is already present)
- Use of depot-based fuelling wherever more convenient for fleet operators

Buses (+ trucks) - significant numbers of depot-based HRS are expected by 2030, likely focused in major urban centres

Total FCEV buses and HGVs in the UK fleet



2015-2020

- Up to c. 5 depot-based 350 bar HRS with up to c. 1tpd
- Unlikely to be publicly accessible
- Locations driven by local political ambition and air quality targets
- Limited demonstrations of H_2 light trucks

2020-2025

- Further deployments of e.g. 20 buses (1-2 routes) in leading cities. 1 depot HRS per city (~1tpd)
- Reduced public funding for refuelling infrastructure
- Increasing use of H_2 in light trucks to complement EVs for longer duty cycles

2025-2030

- Multiple routes using fuel cell buses in leading cities
- Larger ~2-5tpd HRS in depots
- Novel engineering solutions required for these larger depots
- Growing role for H_2 in larger trucks, likely using depot based refuelling

2030-2050

- Hydrogen becomes one of the dominant fuels for buses alongside other ULEV powertrains
- Widespread availability of high-capacity 350 bar HRS developed in depots across the country
- Widespread use of H_2 in trucks

Forklifts - the forklift HRS market is likely to grow rapidly beyond 2020, provided the technology can compete on economic terms in the UK

hydrogen

Growth in hydrogen forklifts expected beyond 2025 as more vehicles become available and prices drop

2015-2020	2020-2025	2025-2050
Small number of deployment projects to 2020 to test the cost-effectiveness of fuel cell forklifts in the UK market	If fuel cell forklifts can prove their cost-effectiveness relative to electric/hybrid in the UK market, deployments in larger numbers will occur	Continued rollout of hydrogen forklifts to existing customers, until all their major logistic centres have been covered

2015-2020

- Trial fleets using 350 bar indoor HRS, capacities up to 50kg/day (c. 25 vehicles per site)
- Likely focused on major logistical operators in strategic locations where battery technology currently in use – up to c. 10 sites
- US deployments suggest focus is on largest sites initially, where economics are most favourable

2020-2025

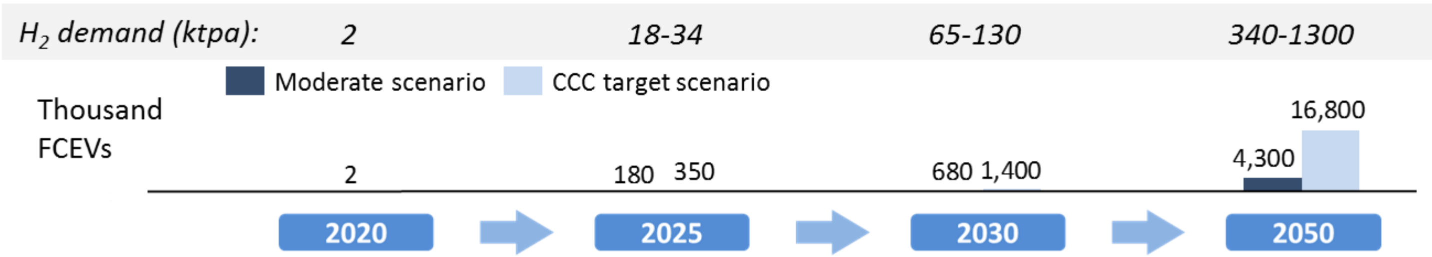
- Indoor refuelling with capacities up to c. 100-200kg/day (up to c. 100 vehicles per site)
- Focused on major logistical operations in strategic locations (e.g. ports, large retailer distribution centres, airports, etc.) – likely starting with expanded fleets at initial trial sites, with 10's of additional deployments beyond that

2025-2030

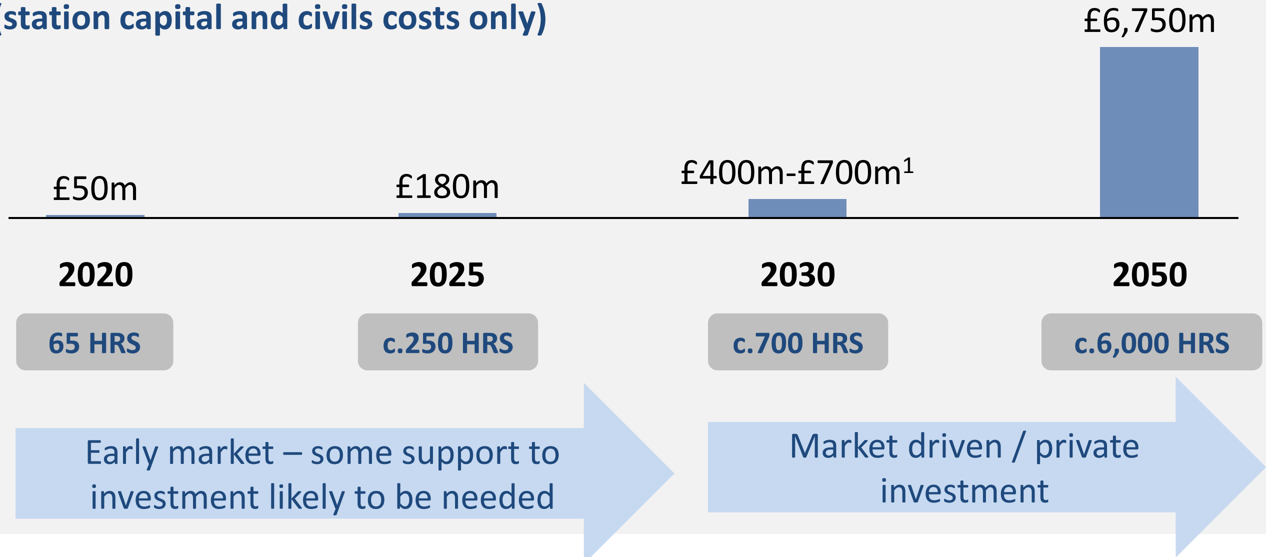
- Likely low 100's of sites suitable in the UK with similar specs (i.e. 100-200kg/day) by 2030
- Beyond 2030, as costs start to compete with incumbent technologies, e.g. gas or diesel, customers in locations with lower operating hours and fewer vehicles – may be indoors or outdoors and cover range of capacities

Investment needs in hydrogen stations are expected to be up to £700m by 2030, rising significantly to 2050 to serve a large UK vehicle fleet

Total FCEVs in the UK vehicle parc



Approximate cumulative public infrastructure investment required (station capital and civils costs only)



Production and distribution capacity has not been considered when estimating overall station numbers.

[1]Lower bound based on UK H_2Mobility Phase 1 report, assuming 1,150 stations by 2030. Upper bound based on HRS cost data from H_2TINA

Source: H_2TINA (2015). Costs = HRS costs 80kg/day: £0.8m (2012), £0.4m (2025). 500kg/day: £1.4m (2012), £0.7m (2025). 1000kg/day: £2.4m (2012), £1.3m (2025). No cost reduction for 2030 & 2050.

Contents

The H_2 infrastructure roadmap reflects the diverse refuelling needs of different vehicle types and the uncertainty about the speed of the rollout

Infrastructure roadmap

2015 | 2020 | 2025 | 2030 | 2050

Public access

- **HRS #'s**: First 65 'small' HRS (c.£40m) → Next c. 250 'medium' and 'large HRS (c.£180m) → Next c. 700 'medium' and 'large' HRS (£400-700m) → Continued growth based on demand (c.£6,800m)
  - **Basic national coverage**
  - **Full national coverage**
- **Pressure**: 700 bar SAE-compliant fuelling for cars. HRS investors encouraged to make 350 bar H_2 available to support other vehicle types where needed
- **Location**: Increasing forecourt integration/decreasing stand-alone HRS

Legend: Cost; Stations; Technical

Provide base load to underutilised network in early years

Van/small truck depots: Limited use of depot-based refuelling where cost-effective/convenient

HDV depots – **350 bar**: Up to 5 additional c. 1t/day depot-based HRS → Emergence of multi-tonne/day depots in major urban areas, covering multiple routes each → Nationwide deployment of large bus depots

Indoor forklifts – **350 bar**: Gradual growth in indoor HRS as market develops, moving from small (<50kg/day) to large (>100kg/day) → Conversion of multiple large logistics centres from batteries to fuel cells with indoor large HRS

H_2 supply and logistics

- **Production capacity**: Production capacity largely for industry application → Provision of new centralised capacity to support on-site deployments
- **Transport demand**: c. 3 ktpa (2020) → c. 190 ktpa (2030) → *2015 production capacity exceeded* → c. 2.3 Mtpa (2050)

Hydrogen vehicle stock

Projections are based on policy-led uptake scenarios presented on page 22

Data supported quantification of infrastructure requirements

Thousand vehicles	2020	2025	2030	2050
Cars	2	180-350	680-1,400	4,200-16,800
Vans	<1	30-60	100-200	750-3,000
HDVs	<1	3	8	130

Dashed lines represent high uncertainty | **Major milestone /enabler**

HRS: hydrogen refuelling station

Industry and government will need to work closely to secure the deployment of the early public HRS network and hydrogen vehicles

1 Securing deployment of the early public HRS network

- A certain number of HRS (e.g. 65 set out by the H_2Mobility strategy) is likely to be needed to meet the needs of the earliest customers and to continue to attract OEMs to the UK
- Low utilisation means that these early HRS will need public funding to attract private investment
- HRS investors will also require confidence from vehicle suppliers on the timing and ambition of vehicle deployments
- Customer incentives are likely to be needed to encourage early vehicle sales as OEMs transition to lower cost second generation vehicles
- The network will also need to offer a consistent and high quality customer experience, in terms of the station 'look and feel', ease of use, payment methods etc.

Recommendations

Central Government: Provide financial support to early HRS, using funding conditions to ensure high quality user experience and coherent geographic strategy. Provide support to vehicles through existing ULEV incentives

Local Government: Help provide 'base load' demand to public HRS (e.g. FCEV procurement for public fleets) and make sites available for refuelling stations where possible

OEMs: Provide transparency on numbers and locations of vehicle deployments (as far as possible) to maximise confidence of HRS investors

HRS operators/suppliers: Work closely with vehicle suppliers and their customers to ensure that HRS siting and specifications meet their needs

Source: Element Energy

Ensuring infrastructure is compatible with all vehicle types and publicly accessible will maximise station utilisation

2 Maximising utilisation of early stations

- Early network is likely to use 700 bar refuelling, based on requirements of OEM passenger cars
- Other vehicle types (e.g. vans, small trucks) currently use 350 bar tanks which are not compatible with higher pressure dispensers
- The use of dual-pressure stations (700/350bar) allows public HRS to meet refuelling demands of these vehicles, increasing early usage where demand exists
- Fleet vehicle users should also be encouraged to use public HRS rather than depot solutions where feasible to further increase utilisation

Recommendations

HRS investors: Work with vehicle suppliers to identify needs for dual-pressure HRS sites

Local government: Encourage fleet stations to be publicly accessible for private customers where feasible (e.g. through planning system)

3 Coordination

- As the network grows, coordination of HRS siting is likely to be needed to optimise coverage and customer convenience
- Coordination is also likely to be needed on cross-cutting topics e.g. securing deployments of 'green hydrogen' production capacity, metering and billing, progress towards fully forecourt-integrated stations
- If use of standalone HRS continues, HRS operators should work closely to define a consistent approach to siting and 'look and feel' to allow drivers to find and use the infrastructure

Recommendations

All H_2 stakeholders: Identify an appropriate forum to allow discussion of these coordination activities, and to present an aligned UK strategy in outreach to international OEMs to maximise appetite to bring vehicles to the UK

Source: Element Energy

Existing regulations should be amended to harmonise the planning approval process, thereby streamlining infrastructure installation

4 Siting and planning process

- Lack of guidance on HRS safety requirements can lead to planning delays and inconsistent user experience
- Transition from standalone to forecourt-integrated sites likely towards 2020
- Work to include hydrogen in the Blue Book[1] is underway to represent hydrogen, in particular addressing electrical hazardous zones and safety distances, giving clear guidance for use by developers and petroleum officers in designing and approving HRS on forecourts

Recommendations

Local Authority planning teams and regulatory authorities: Support the approval of integrating hydrogen infrastructure into existing forecourts; produce guidance documents for standalone HRS

5 Innovation opportunities

- Reducing the cost of HRS, H_2 production and distribution and vehicles will be required to allow mass-market deployments
- Quality assurance of H_2 (lower cost analysis, continuous monitoring etc.) needs to be further developed and standardised
- Engineering solutions are required for large scale depot refuelling beyond current fleet sizes (e.g. c.100 bus depot requiring c.2 tonnes/day)
- Full integration of water electrolysers into the grid will require further trials of technical and commercial arrangements

Recommendations

Innovation funding bodies: Work with industry to define clear innovation needs that can be delivered through R&D funding and trials

[1]National Guidance document jointly published by the Energy Institute and Association for Petroleum and Explosives (APEA) used to assess and sign off the safety of new forecourt installations and upgrades

New policy may be required in the medium term to ensure that the future hydrogen production mix delivers CO_2 emissions savings

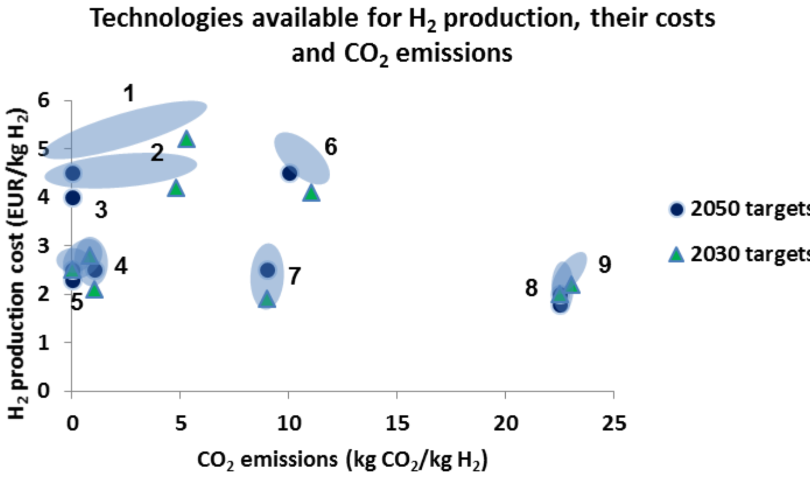
6 Hydrogen production pathways

- Current UK hydrogen production capacity is insufficient to meet transport demand from the mid 2030s
- Therefore new production capacity will need to be introduced concurrently with vehicle demand growth, taking into account GHG emission reduction targets
- A strategy will be needed on how this capacity will be delivered (based on the expected volumes of hydrogen vehicles) while ensuring that the overall production mix delivers very low well-to-wheel emissions

Recommendations

Central Government: Consider policy mechanisms to ensure sufficient volumes of low carbon hydrogen sources

R&D bodies: Investigate low cost green hydrogen production technologies



Technology type

1. Distributed water electrolysis
2. Conventional water electrolysis
3. Coal gasification + carbon capture and storage
4. Centralised SMR + carbon capture and storage
5. IGCC + carbon capture and storage
6. Distributed steam methane reforming
7. Conventional steam methane reforming
8. Internal gasification combined cycle
9. Coal gasification

Source: A portfolio of power-trains for Europe: a fact-based analysis, McKinsey & Co, 2011
Targets: technical targets to reduce carbon footprint of hydrogen as a transport fuel

Contents

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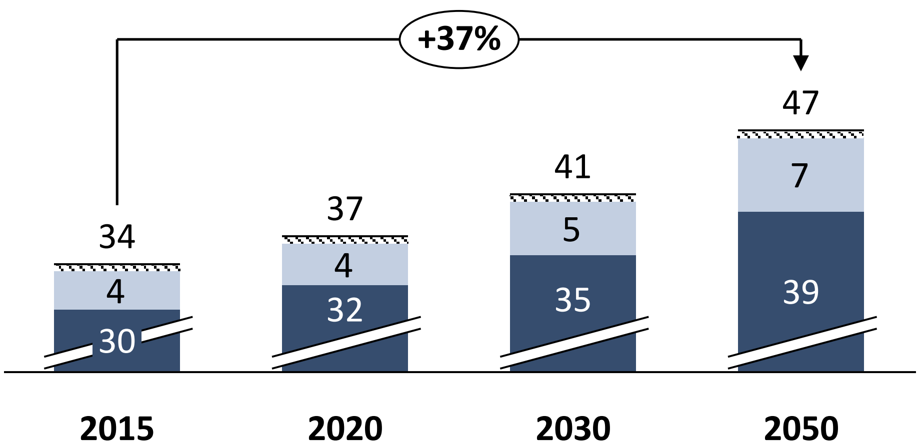
Acronyms

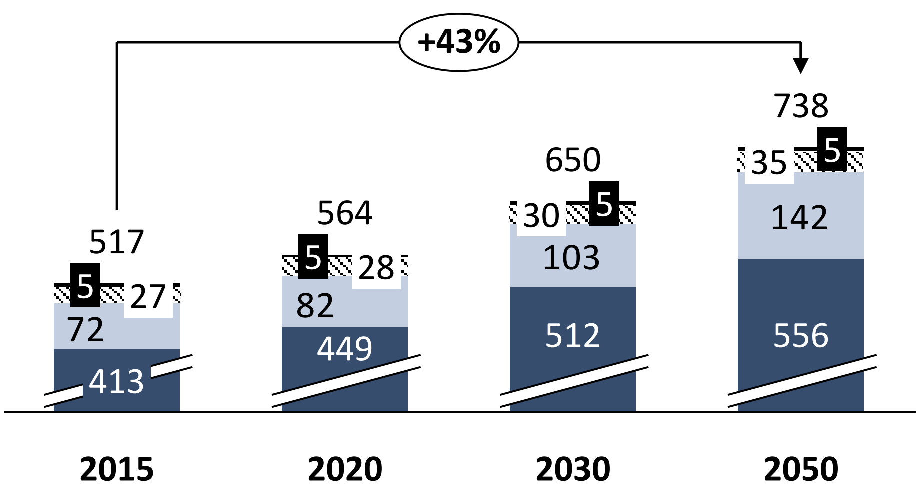
AFV	Alternative Fuel Vehicle
CCC	Committee on Climate Change
CCS	Carbon Capture and Storage
CHP	Combined Heat and Power
COMAH	Control of Major Accident Hazard
DECC	Department of Energy & Climate Change
DfT	Department for Transport
DUKES	Digest of United Kingdom Energy Statistics
EC	European Commission
EE	Element Energy
ETI	Energy Technologies Institute
EU	European Union
FC	Fuel Cell
FCEV	Fuel Cell Electric Vehicle
FCH JU	Fuel Cell Hydrogen Joint Undertaking
FLT	Fork Lift Truck
H_2	Hydrogen
HDV	Heavy Duty vehicle
HGV	Heavy Goods Vehicle
HRS	Hydrogen Refuelling Station
HSE	Health and Safety Executive
ICE	Internal Combustion Engine
ktpa	thousands tonnes per annum
LCN	Low Carbon Network
Mt	Million tonnes
NG	National Grid
NPPF	National Planning Policy Framework
OEM	Original Equipment Manufacturer
OLEV	Office for Low Emission Vehicles
PM	Particulate Matter
R&D	Research and Development
RED	Renewable Energy Directive
SMR	Steam Methane Reforming
TEN-T	Trans-European Transport Networks
TSB	Technology Strategy Board
TTW	Tank-to-Wheel
ULEV	Ultra-Low Emissions Vehicle
WE	Water Electrolysis
WTT	Well-to-Tank
WTW	Well-to-Wheel

The modelling of the future UK fleet is based on DfT traffic and park size projections

Total UK vehicle stock (million vehicles)



Total vehicle km travelled (billion km)



- Future vehicle projections use figures provided by DfT:
  - Cars stock to increase from c. 30 million to 39 million and c. 550 billion vehicle km travelled by 2050
  - Vans stock to increase from c. 3.5million to 7 million by 2050
  - HGVs stock to increase from c. 500 thousands today to c. 630 thousand by 2050
  - Buses stock and vehicle km travelled to stay broadly constant at around 170 thousand units and 5 billion vehicle km travelled
- Overall fleet and km increase of c. 40% between 2015 and 2050

Buses HGVs Vans Cars

The powertrain/fuel uptake scenarios underpinning the Infrastructure Roadmap are policy led

Uptake scenarios focus on alternative fuels

- **The scenarios used are not intended to cover all possible outcomes but instead focus on cases with ambitious uptake of alternative fuels**
- Scenarios are **policy led,** typically based on targets set by the Committee on Climate Change (sources shown next); they are illustrative rather than based on detailed of new modelling technology costs and customer decision making behaviour
- Therefore the uptake scenarios represent possible futures where low and ultra low emission powertrains are successfully deployed
- Focus is intended to provide the most interesting inputs for the analysis of the Infrastructure Roadmap – e.g. a ‘business as usual’ case where petrol and diesel continue to provide over 98% of road transport energy would not require new refuelling/recharging infrastructure
- In accordance with the Fuel Roadmap, blends higher than B7 are not considered for the mainstream fuels and E20 is considered only from the 2030s
- Scenarios have enabled future infrastructure requirements to be quantified and upfront costs capital costs for public infrastructure have been estimated. Cost of setting new fuel production assets, distribution/logistics costs and general infrastructure operating costs have not been considered. Costs of other incentives that might be required to achieve the uptake scenarios (e.g. vehicle grants) haven not been estimated in this study

Overview of the powertrain options considered and key sources

	Cars and vans	Buses	HGVs	NRMM
RELEVANT POWERTRAINS /FUELS	▪ ICE: petrol, diesel, LPG, (gas), (H_2 in early years) ▪ EVs: Battery EVs, plug-in hybrid EVs, fuel cell (FCEVs)	▪ ICE: diesel, (bio)methane ▪ EVs: BEV, PH/RE, FCEV ▪ (Liquid air for cooling/hybrid power)	▪ ICE: diesel, (bio)methane, (methanol) ▪ EVs - in lighter segments only	▪ ICE: diesel, LPG, (gas), Liquid air for refrigeration units ▪ (Batteries and Fuel Cells – in some applications)
KEY SOURCES / INDICATORS	▪ The Carbon Plan and the Committee on Climate Change's recommendations ▪ H_2Mobility Phase 1 report, 2013 ▪ Historic trends for petrol/diesel split	▪ Current and announced commercial availability, policy drivers ▪ *Alternative Powertrain for Urban buses*, 2012 ▪ CCC – 4^{th} Carbon Budget Review	▪ Current and announced commercial availability ▪ DfT HGV Task Force ▪ TSB-DfT Low Carbon Truck Trial ▪ CCC – 4th Carbon Budget Review	▪ *Data on fuel usage of NRMM is sparse* ▪ *More qualitative approach suggested*

Parentheses indicates the powertrain/fuel option is expected to stay niche in the 2050 horizon

HGV = Heavy Goods Vehicles, NRMM = Non Road Mobile Machinery

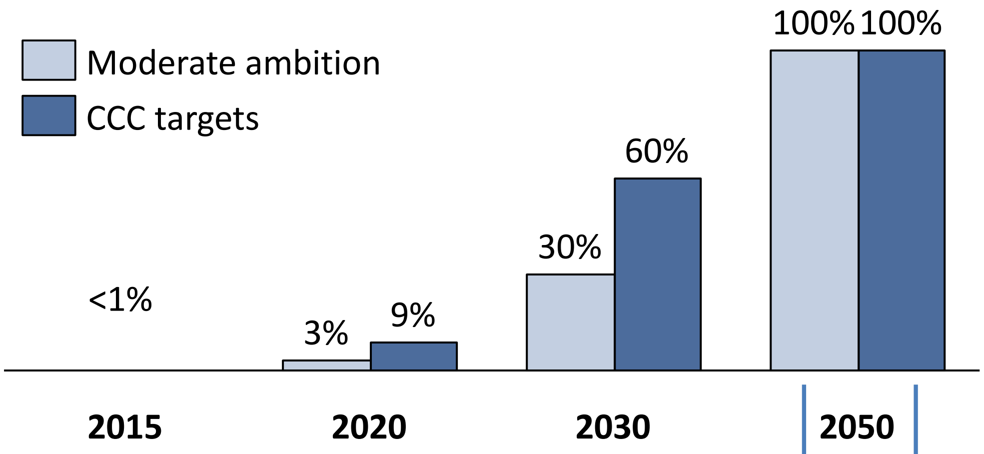
Cars and vans are expected to transition to zero emission powertrains for the UK to meet its GHG reduction targets

- Cars and light commercial vehicles (‘vans’) are treated together as they have the same technology options and fall under the same electrification targets in the Carbon Plan.
- Sales of vans running on **methane** are not considered in the modelling on the basis of the low commercial availability (only 2 models on the market), lack of policy drivers for growth and aforementioned electrification targets. Any gas demand resulting from vans would be small enough to be considered negligible, in comparison to the potential gas demand from trucks.
- **Dual fuel vans running on diesel and hydrogen and Range Extender Fuel Cell electric vans** (being deployed currently in the UK and in continental Europe) are not modelled explicitly. Instead, their hydrogen demand is accounted for in the ‘FCEV’ heading. The specific requirements for dual fuel and range-extender H_2 vans are however considered in the Infrastructure Roadmap (e.g. dispensing pressure).

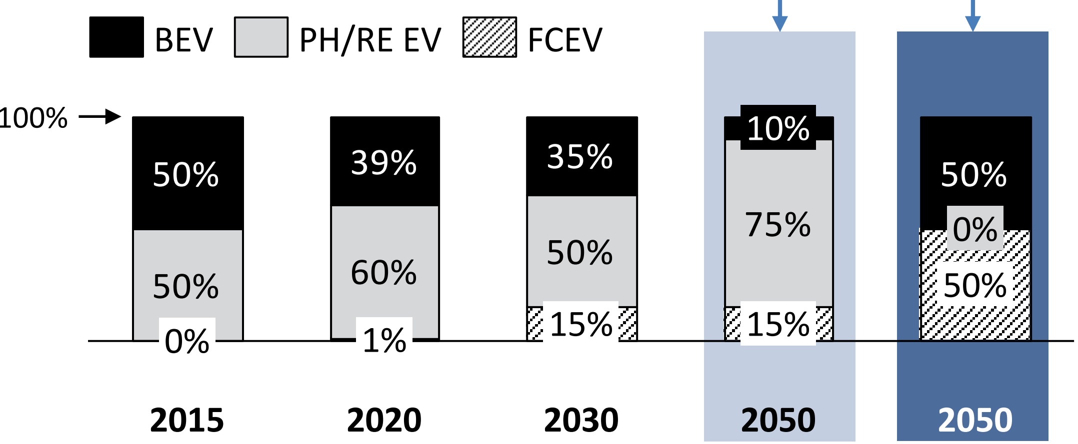
Source: Element Energy

We studied infrastructure requirements set by the Committee on Climate Change targets as well as a case with a slower EV uptake

Market share of EVs (new sales)



Breakdown of market share of EVs

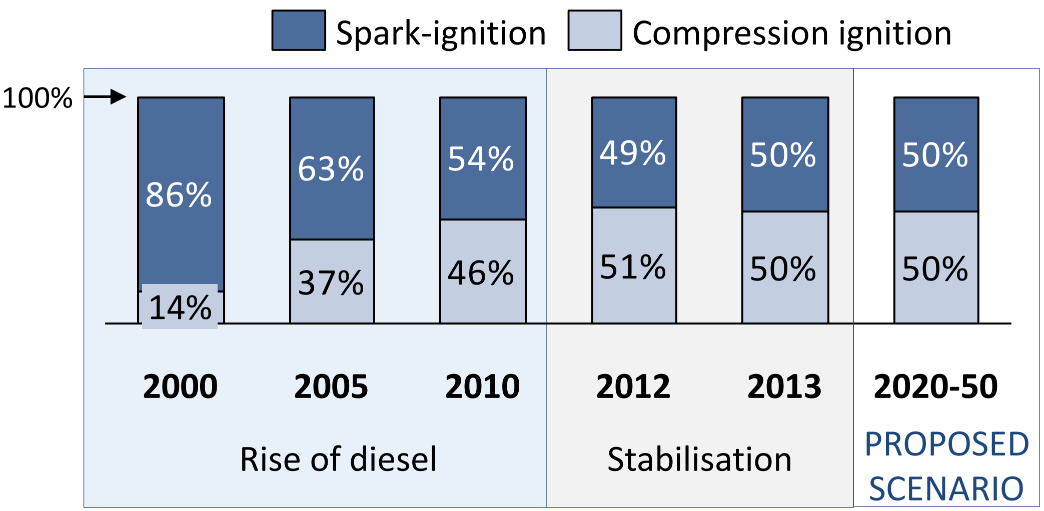


Scenarios

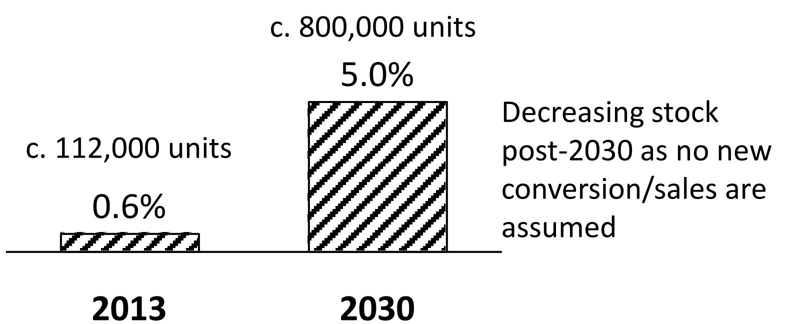
- Two EV uptake scenarios have been used:
  - '**CCC targets**': EVs reach 60% market share by 2030 and Zero Emission vehicles reach 100% of market share before 2050
  - '**Moderate ambition**': the 2030 CCC targets are not met but EV uptake is nonetheless high (30% new sales); by 2050 EVs represent 100% of sales but are mainly PHEVs or RE-EVs, i.e. still reliant on liquid fuels

We assumed continuation of the observed petrol /diesel share for cars and modelled an ambitious LPG uptake

Sales of new cars with Internal Combustion Engine vehicles - split between spark-ignition ('petrol' type) and compression ignition engines ('diesel' type)



Share of spark-ignition cars (ICE and HEV) stock that run on LPG



Scenarios

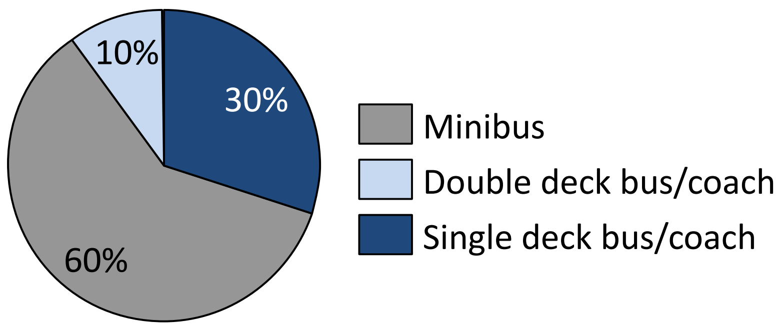
- We assumed that the current split of petrol/diesel engines for new cars (50/50) is maintained going forward
- In line with the Fuels Roadmap, diesel will be B7 (EN590) with an increasing amount of drop-in renewable diesel – i.e. no compatibility issue to be considered for the distribution infrastructure
- For petrol engines, we will evaluate the amount of:
  - Ethanol needed if the E10 becomes the main grade by 2020 and E20 by 2032
  - LPG needed for a case where the rate of conversion (or sales if OEM supply is put in place) accelerates to reach 5% of the petrol car stock (equivalent to c. 40,000 conversions per year until 2030)
- All new vans are assumed to run on diesel

Sources: Element Energy, SMMT data for 2000-2013 sales, UKLPG for LPG 2013 figures

Buses have many powertrain options but overall small fuel use so we used only one scenario, where all technologies see high sales

Current UK bus market

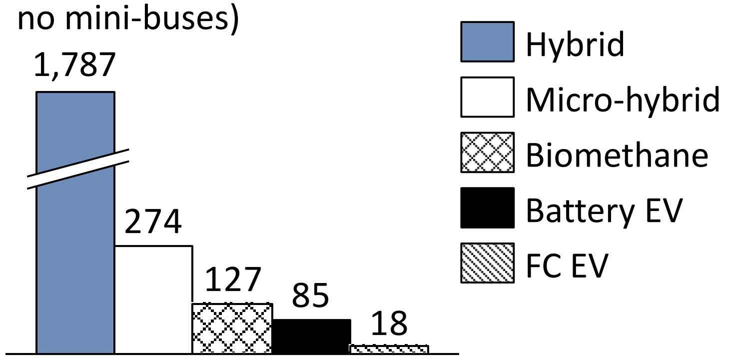
UK bus fleet, c. 165,000 vehicles:



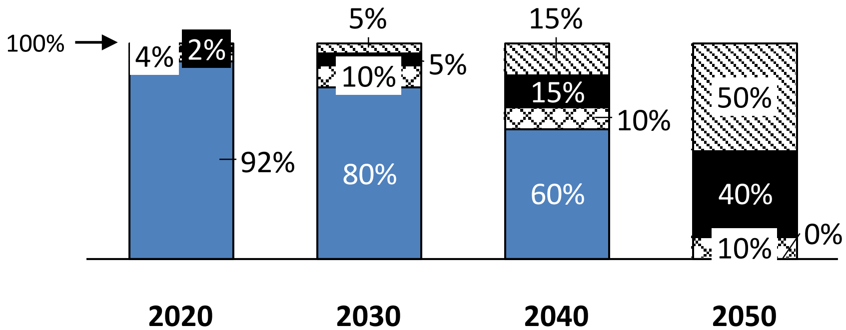
Scenario

- We ramped up the alternative fuel market share from 2030, in line with the European study[1] that suggests that the TCO of battery and FC e-city buses will become comparable and competitive with diesel and CNG buses by 2030[1]
- We assume 90% uptake for Zero Emission Vehicles by 2050
- This is lower that the 100% FCEVs assumed in the CCC projections, to reflect the fact that double decker buses (and buses in highly rural areas) might require gas

UK low emission buses (all single or double deck, no mini-buses)



New buses sales scenario:



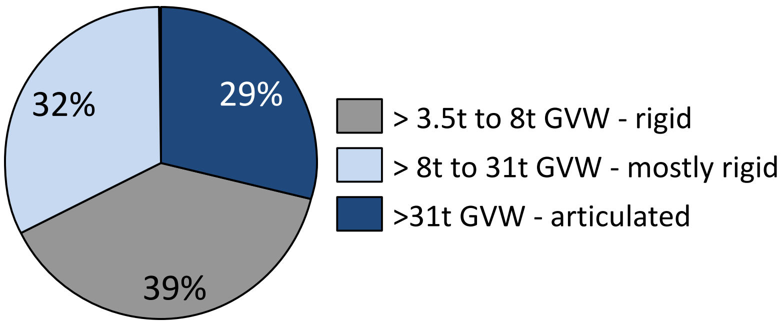
'Diesel' refers to a blend of B7 and drop-in renewable diesel, as per the Fuels Roadmap

Source: Element Energy, DfT Statistics Table VEH0601, LowCVP Low Carbon Emission Bus Market Monitoring (Jan 2015), CCC, 4th *Carbon budget*, 2013   1 - Alternative Powertrain for Urban buses study (2012)

For Heavy Goods Vehicles, we tested a high uptake of both electric (battery and fuel cell) and gas trucks

Current UK Heavy Goods Vehicle market

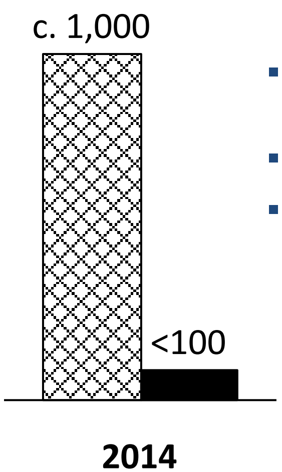
UK HGV fleet, c. 460,000 vehicles:



Scenario

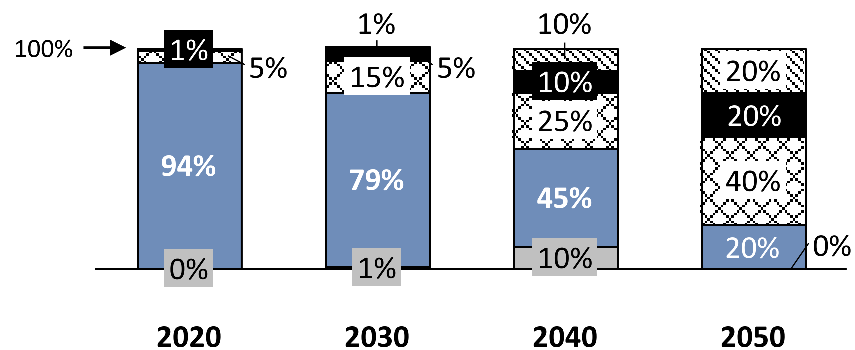
- We to modelled a High Alternative Fuel Uptake case where both pure electric and gas trucks reach a significant sales levels in their respective markets (light and heavy trucks)
- FCEVs also capture a large share of the market, as per the CCC's vision of the role of hydrogen

UK low emission trucks - estimates

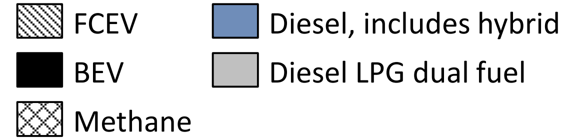


- *Gas trucks all over 18t GVW, mostly dual fuel (diesel and methane)*
- *Electric trucks all under 18t GVW*
- *FCEV light trucks at early demo stage*

New truck sales scenario:



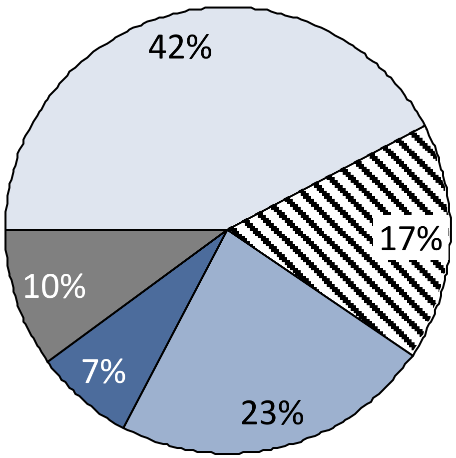
'Diesel' refers to a blend of B7 and drop-in renewable diesel, as per the Fuels Roadmap



Source: Element Energy, DfT Statistics, *Birmingham City Blueprint for low carbon fuels refuelling infrastructure*, EE for Birmingham City Council (2015), Low Emission HGV Task Force (2014), HMRC (2014), CCC, *4th Carbon budget*, 2013

Non-Road Mobile Machinery typically refuels in private depots/premises but the case of LPG, liquid air and hydrogen were considered

UK NRMM fleet for industry, construction and agriculture, c. 700,000 units in 2014:



Scenario

- We to considered (qualitatively, considering the lack of disaggregated data on fuel use) the infrastructure impacts of:
  - A transition to Liquid Air for HGV refrigeration units
  - An increase in LPG, battery and hydrogen use for forklifts

Beyond the blending of renewable drop-in diesel in diesel, options for cleaner fuels are:

- Agricultural tractors → (Limited options, possibly (bio)methane or high blend biodiesel)
- Portable generator sets → (Could transition to LPG, Battery and Fuel Cell packs for some uses)
- Other off-roads → (LPG, limited alternative fuel options)
- Refrigeration units on HGVs → LPG, could transition to Liquid Air
- Forklifts → Use of LPG (already used by c. 30% of forklifts) and batteries could increase, could transition to hydrogen

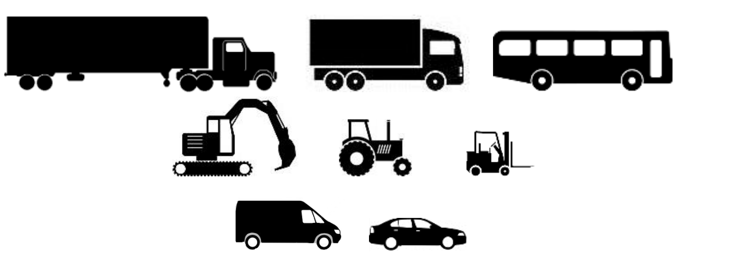
Other off-roads: Telescopic Handlers, Backhoe Loaders, Excavators, Cranes, Bulldozers, Compressors etc.

Source: Element Energy analysis based, on DfT statistics requested in Jan 2015 and *Non-Road Mobile Machinery Usage, Life and Correction Factors* AEA for Dt (2004) , industry input for LPG use in forklift

Appendix – There are broadly two types of refuelling infrastructure for liquid fuels in the UK

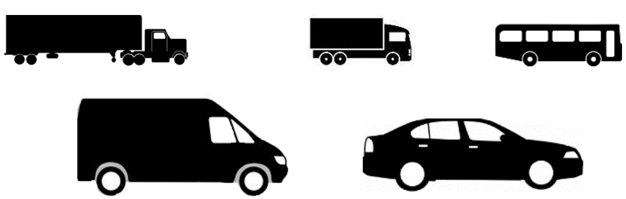
Refuelling at private depots: c.25% fuel sales

- Large fleet operators including public transport operators, hauliers, logistics companies, forklift operators tend to operate designated refuelling depots suited to their ‘return to base’ operations
- Such facilities tend to be private and exclusively service a single vehicle type
- **Most buses and heavy good vehicles refuel in depots** – share of diesel supplied through depot:
  - 90% for buses, 40% for coaches
  - 80% articulated trucks, 45% rigid trucks



Refuelling at public forecourts: c.75% fuel sales

- Generally, public vehicle refuelling (passenger cars, vans, motorbikes, scooters) is facilitated by one of the UK’s c.8,600 forecourts
- Refuelling forecourts are publicly accessible and are generally owned and operated by large oil companies (e.g. Shell, BP, Esso, etc.), independent retailers and supermarket chains



Source: Element Energy, DfT Modes 3 study (2011)

Appendix – National Grid "Future energy scenarios"

National Grid has developed four scenarios for future electricity generation and gas supply sources to 2050

Affordability
More money available

Low Carbon Life (LCL) is a world of high affordability and low sustainability. More money is available due to higher economic growth and society has more disposable income. There is short term volatility regarding energy policy and no additional targets are introduced. Government policy is focused on the long term with consensus around decarbonisation, which is delivered through purchasing power and macro policy.

Gone Green (GG) is a world of high affordability and high sustainability. The economy is growing, with strong policy and regulation and new environmental targets, all of which are met on time. Sustainability is not restrained by financial limitations as more money is available at both an investment level for energy infrastructure and at a domestic level via disposable income.

No Progression (NP) is a world of low affordability and low sustainability. There is slow economic recovery in this scenario, meaning less money is available at both a government and consumer level. There is less emphasis on policy and regulation which remains the same as today, and no new targets are introduced. Financial pressures result in political volatility, and government policy that is focused on short term affordability measures.

Slow Progression (SP) is a world of low affordability and high sustainability. Less money is available compared to Gone Green, but with similar strong focus on policy and regulation and new targets. Economic recovery is slower, resulting in some uncertainty, and financial constraints lead to difficult political decisions. Although there is political will and market intervention, slower economic recovery delays delivery against environmental targets.

Affordability
Less money available

Sustainability
Less emphasis

Sustainability
More emphasis

SOURCE: National Grid "Future Energy Scenarios" (2014)

Appendix – TEN-T Core Network