Road transport – pre-read in advance of workshop on 11th April

E4tech elementenergy

This project aims to drive sustainable economic growth in the UK hydrogen and fuel cell industry in the period to 2025 and beyond

- **Public-private project** steered by Innovate UK, the Department of Energy and Climate Change (DECC), Transport Scotland, Scottish Government, Scottish Enterprise, Scottish Hydrogen and Fuel Cell Association (SHFCA), UK Hydrogen and Fuel Cell Association (UKHFCA), and the Knowledge Transfer Network (KTN)
- **Delivered by E4tech and Element Energy**, in consultation with the Steering Board and wider stakeholders
- Launched in January, due to be completed in early June
- Consists of **11 mini roadmaps**, on different sectors of hydrogen and fuel cell use, which will be brought together with an overall national case

WP 1 – kick-off workshop

Aligning on scope, timescale, governance

↓

WP 2 –Analysis of individual roadmaps

↓

WP 3 – Consultation

Workshops + bilateral discussions

↓

WP 4 – Revision of individual roadmaps

- Based on feedback and evidence received from consultation, revise individual roadmaps and benefits assessments

↓

WP 5 – Understanding the overall national case

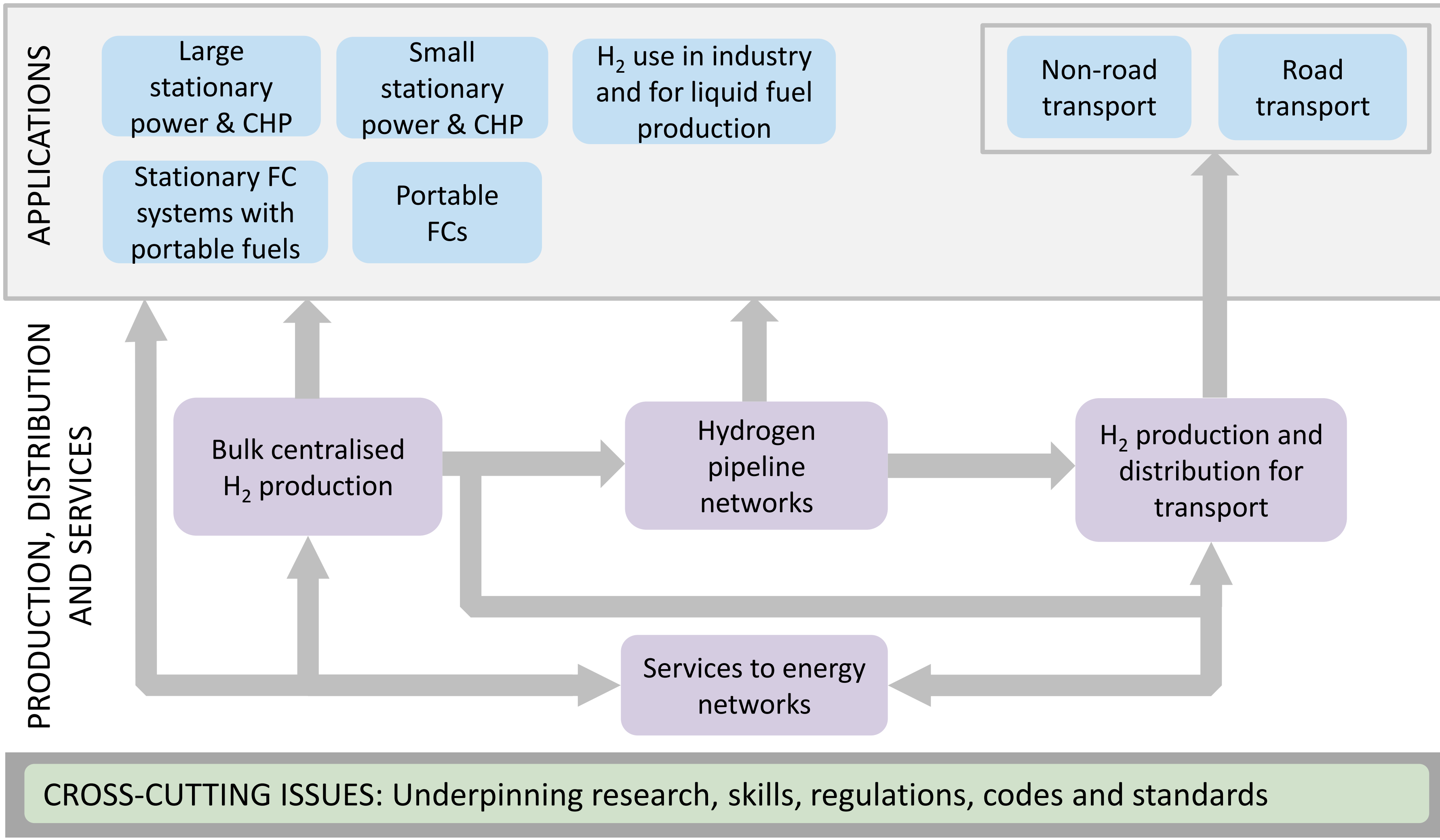
- Understand interdependencies between roadmaps and critical decisions on each roadmap
- Agree on a prioritisation
- Assess required support
- Calculate national benefits

↓

WP 6 - Draft and final reports

E4tech elementenergy

The 11 mini roadmaps cover uses of hydrogen and fuel cells, and production and distribution of hydrogen



End-use roadmap

Supply chain roadmap

This workshop is to get your feedback on the draft mini-roadmap on road transport

- This draft mini-roadmap has been issued as a straw man document to provide a basis for discussion. All aspects are up for discussion and we welcome all input
- The roadmap shows **aims** for each application for 2025, **barriers** to achieving those aims, **actions** that need to be taken to overcome the barriers, and **benefits** of doing so
- During the workshop on 11th April, we will discuss **your views on**:
  - Accuracy (30 mins) - Have the main issues and barriers been captured in the draft roadmaps?
  - Ambition (30 mins) - Are the aims for 2025 appropriate? What level of ambition is reasonable?
  - Action (60 mins) - Will the actions proposed be enough to overcome the barriers? If not, what else is needed? How reasonable is it to expect these actions? What might they cost, how long will they take and who might pay?
- Note that we are focusing on **actions to 2025**, not the long term vision for the hydrogen and fuel cell sector. The longer term vision will be articulated in the overall national roadmap
- We also want your views on cross cutting issues that could affect more than one mini-roadmap

Road transport – draft roadmap

This roadmap focusses on three main areas

- This roadmap focusses on three main applications – these were selected as those with the greatest potential to add value to the UK:
  - **Passenger vehicles and light commercial vehicles** –manufactured by global vehicle manufacturers such as Toyota and Hyundai – these vehicles typically require >50kW fuel cell propulsion systems:
  - **Range extended electric vehicles** (FC RE-EV) **and fuel cell minicars** (which require <20kW propulsion systems): there is a potentially attractive early market for FC RE-Evs, which is currently being exploited by e.g. Symbio FCell in France and could be addressed by a number of UK players. Fuel cell micro-cars face stronger competition from battery electric vehicles, but the UK has established a number of SMEs with innovative products in this segment.
  - **Heavy-duty vehicles such as buses and trucks**: the larger vehicle segment has very few options for complete zero emission propulsion, which makes the fuel cell option attractive. In the short term, buses, delivery trucks and refuse trucks appear to have potential. Longer term, larger HGV's could also be targeted. The UK has a large OEM base in this segment and potential to create globally attractive products.
  - Note that all of the above may include **hydrogen combustion** vehicles as well as fuel cells, though the man focus for hydrogen combustion is on the heavier duty vehicles
- Other applications (not included here, as they were considered to have less overall potential to add value for the UK compared to the segments above), but which also have the potential for hydrogen/fuel cell applications include: Auxiliary power units for trucks and two wheeler vehicles (which have much in common with the microcars described above)

The UK can take an active role in supporting automotive applications and generate value from developing dedicated H_2 vehicle solutions

- The road transport sector is a trillion-pound market with over 60 million sales per annum for passenger cars alone. The sector is facing the twin challenge of needing to cut air pollutant and carbon dioxide emissions from exhausts. Only hydrogen vehicles and battery electric vehicles offer completely emission free driving. Relative to battery electric vehicles, hydrogen offers long range and shorter refuel times. However the hydrogen option is currently less commercially mature, with battery electric vehicle starting to gain market traction (over 20,000 battery electric vehicles have ben sold in the UK between Jan 2011 and March 2016).
- Because of the size of the automotive market, this is inevitably one of the most promising applications for hydrogen technologies as even a small penetration of hydrogen vehicles could constitute a significant market. Furthermore, any meaningful conversion to hydrogen fuel can deliver very large Greenhouse Gas (GHG) and Air Quality benefits for the UK.
- The UK is already has suppliers well placed to take a leading position in the nascent technology for vehicles which require small fuel cell stacks (range extended electric vehicles, minicars, scooters) and heavy-duty applications involving combustion of hydrogen. There is also potential for fuel cell powered heavy duty applications, given the number of UK OEMs in this sector (though currently UK fuel cell system suppliers are not focussed on this sector).
- A UK vehicle rollout and technology development programme aimed at these segments can create an attractive market for these solutions and drive UK innovation. UK companies can in principle secure a competitive market position as early as by 2020 if supported today in low volume deployments to prove out the technology.
- The scope for a direct UK intervention in passenger car technology is somewhat less clear, as this market segment requires very large volume and multi-billion R&D investments which are currently led by the major international passenger car manufacturers. The deployment of hydrogen infrastructure in the country can nevertheless catalyse domestic deployment of vehicles and – in turn – support UK-based companies actively working in the FCEV and hydrogen supply chains, as well as promoting inward investment in UK production facilities.

Source:: International Energy Agency (IEA), Technology Roadmap, Hydrogen and Fuel Cells (2015), www.eafo.eu

The roadmap includes targets for both development of UK products and deployment in the UK to justify infrastructure deployment

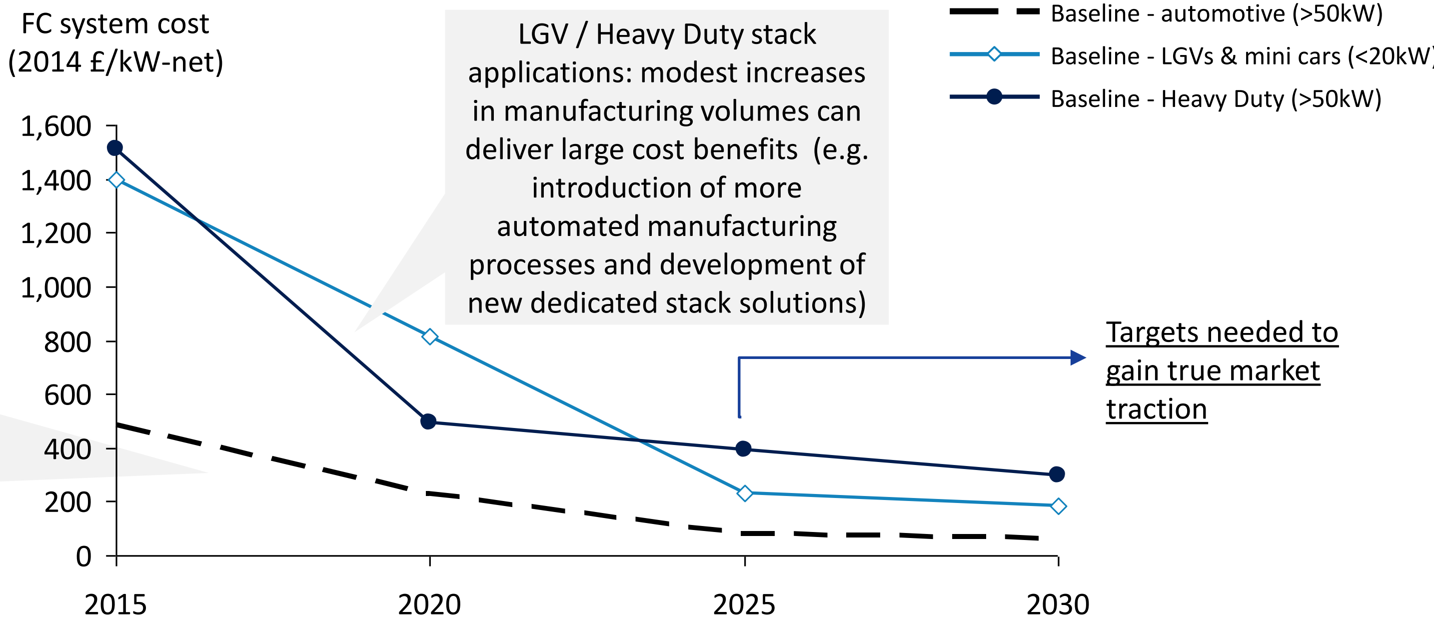
- **Targets** - this roadmap considers a pathway for two aspects of hydrogen vehicles, including:
  - the development of hydrogen vehicles and components in the UK – **with the aim of catalysing development of small fuel cell vehicles and larger heavy duty vehicles from UK companies ready for deployment by 2020**
  - the deployment of sufficient hydrogen vehicles of all types which help to underpin a hydrogen infrastructure – **with the aim of 10,000's of vehicles on the roads by 2025 and sufficient vehicles before 2020 to allow commercial deployment of fuelling stations (implies many 100's of vehicles with a preference for larger/well used vehicle types)**

1: International Energy Agency (IEA), Technology Roadmap, Hydrogen and Fuel Cells (2015)

Cost reductions in automotive FC stacks are required to achieve a commercial breakthrough – these will be mainly driven by volume

Automotive stacks: moving from current volumes (<10k units / annum) to 100k or more can significantly reduce costs due to better economies of scale and improvements in manufacturing technology

LGV / Heavy Duty stack applications: modest increases in manufacturing volumes can deliver large cost benefits (e.g. introduction of more automated manufacturing processes and development of new dedicated stack solutions)



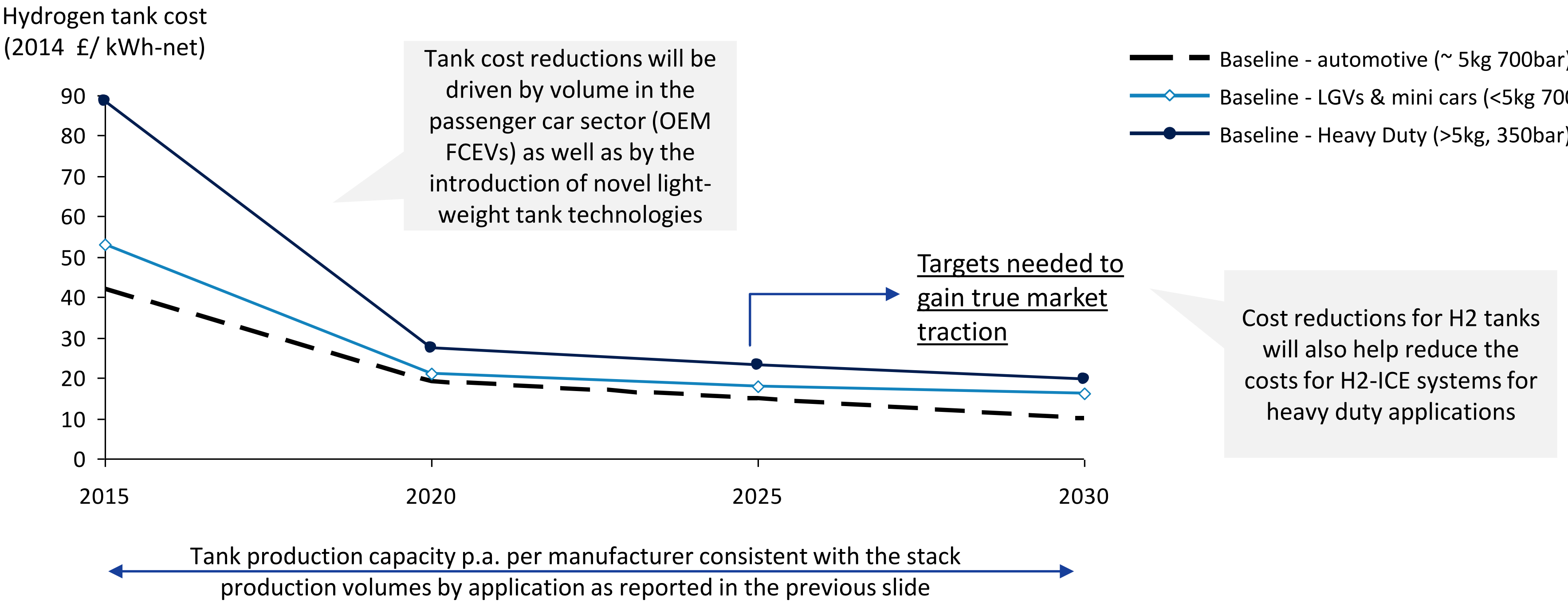
FC systems production capacity p.a. per manufacturer

	2015	2020	2025	2030
Automotive	~1k	~10k	~100k	~200k
FC RE-EV / minicars	~200	~500	~10k	~20k
Heavy Duty	~ 10/30	~ 100/200	~ 500	~ 1k

- Fuel cell stacks (and related BoP components) for range-extended applications, minicars or heavy-duty vehicles (buses/trucks) are currently based on dedicated, small-volume (<<1k per annum) solutions
- These applications have the greatest cost reduction / optimisation potential even for modest increases in global deployment volumes →**UK domestic deployments can drive innovation and cost reductions**

Data sources: Strategic Analysis, Mass Production Cost Estimation of Direct H2 PEM Fuel Cell Systems for Transportation Applications (2013); DOE Fuel Cell Technologies Office Record, Fuel Cell System Cost – 2014; International Energy Agency, Technology Roadmap – Hydrogen and Fuel Cells (2015) ; FCH JU, A portfolio of power-trains for Europe (2011); Element Energy for the European Climate Foundation (2015) and industry consultations (2015)

Larger production volumes and novel light-weight composite materials will also drive cost reductions in the H_2 storage technology



- Hydrogen tanks for range-extended applications and minicars will be based on the same technology as for passenger OEM FCEVs (700bar as per the international refuelling standard) and thereby follow the same cost reduction trends as per passenger vehicle applications. Range-extended applications and minicars have lower on-board hydrogen storage requirements and thereby use smaller tanks (currently typically up to 3kg of hydrogen). This is the main reason why the tank costs per stored kWh are expected to remain higher than for passenger FCEVs . 350bar tanks for fuel cell bus and truck applications have a lower capital cost per tank but costs per kWh stored are higher than 700bar technology due to lower specific volumetric density
- **UK domestic deployments** are unlikely to influence global dynamics (these are driven by automotive volumes) but if well taregtted **can support UK innovation in on-board H2 storage technology** (e.g. type V tanks)

E4tech elementenergy

Data sources: Strategic Analysis, Mass Production Cost Estimation of Direct H2 PEM Fuel Cell Systems for Transportation Applications (2013); DOE Fuel Cell Technologies Office Record, Fuel Cell System Cost – 2014; International Energy Agency, Technology Roadmap – Hydrogen and Fuel Cells (2015) ; FCH JU, A portfolio of power-trains for Europe (2011); Element Energy for the European Climate Foundation (2015) and industry consultations (2015)

There are several latent UK players which can benefit from targeted national interventions

UK Companies active in the sector

- Intelligent Energy (stacks), Millbrook (vehicle engineering), Revolve/ULEMOC (hydrogen engine conversions), Riversimple (microcars), MicroCab (microcars), Arcola Energy (integration), Frost EV (power electronics), Johnson Matthey (component supply), Luxfer (tanks), SGL (carbon fibre for tanks). ACAL (new stack technology) among others are already active in the hydrogen vehicle supply chain

UK Latent potential

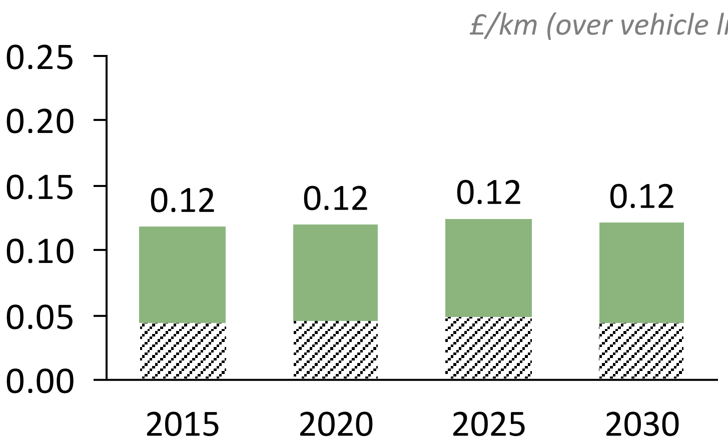
There is substantial scope for UK firms to become more active across the FC technology value chain (note, company examples are for illustration):

- **Cars and light commercial vehicles (e.g. vans)** – the UK is one of the leading countries in ICE engine manufacturing and innovation (including for hybrid electric powertrains). Much of this is based on supply for factories owned by non-UK OEMs, many of whom have an active fuel cell program, such as Honda, Toyota and Nissan**.** In addition, the UK automotive supply chain has already adapted to electrification and has the engineering expertise to support hydrogen (Ricardo, JLR, university skills base etc.). The UK is therefore well placed to take a more active role on FC system manufacturing and electric drivetrain integration
- **Light vehicles** – The UK's automotive engineering and particularly motorsport sector has the potential to respond o the opportunity for small light, fuel cell cars.
- **Buses and trucks** – several UK bus manufacturers and integrators are actively working on diesel electric and pure electric bus solutions and can potentially take an active role in developing fuel cell buses (such as **Wrightbus**, **ADL**, **Optare**) Note that Wrightbus has already worked on fuel cell bus solutions before (provided chassis and homologation support for London's 8 FC buses). In addition, a number of integrators are evolving with either active hydrogen programs (**Magtec**) or appropriate programs (Vantage Power). There currently are very few low-carbon truck powertrains available in the market[1]. The UK is one of the leading EU countries testing alternative truck powertrains (e.g. via the Government Low Carbon Truck programme) and can create a domestic platform for UK-based companies / integrators to develop and demonstrate novel zero-emission FC powertrain solutions for HGVs. For the truck segment, companies such as **Dennis** as an OEM, or **Smith Electric** and **Tevva Motors** could become involved in fuel cell/hydrogen engine integration.

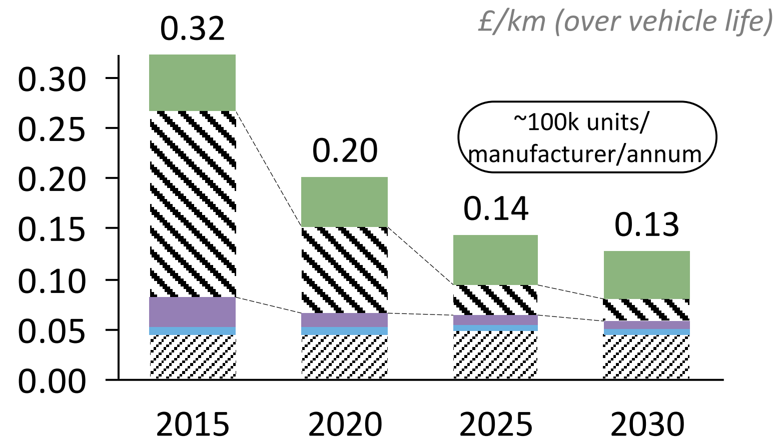
1- Most alternative solutions rely on CNG or LNG fuels but their environmental performance has been challenged on a well-to-wheel basis due to gas leaks or boil-offs (source: Natural Gas Conference, Birmingham, October 2015)

FC system costs dominate the economics for passenger cars and need substantially larger production volumes to reduce (e.g. ~100k units/ manufacturer / annum)

Example: Diesel ICE - Segment D



Example: FCEVs - Segment D



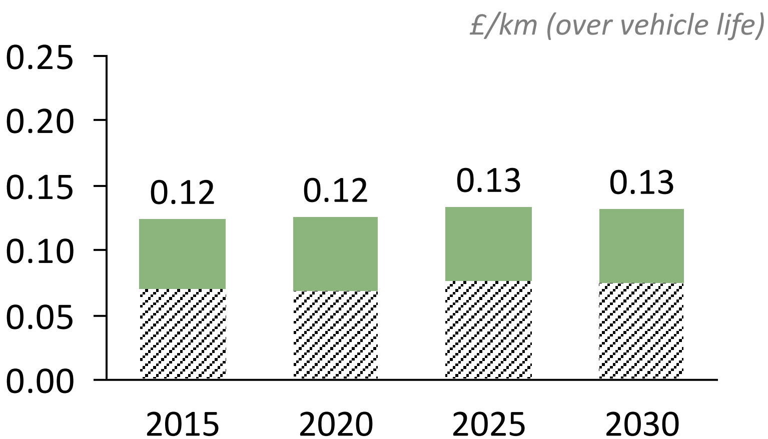
All figures exclude margins and VAT (unless stated)	Diesel 2015	Diesel 2025	ICE 2015	ICE 2025
Base costs (Chassis, engine/motor etc.)	~£17.5k	~£18.5k	~£13k	~£12k
Fuel Cell system cost (90kW)			~£43k	~£7k
H2 tank cost (5kg at 700bar)			~£7k	~£2.5k
Additional powertrain cost (incl. battery)			~£2k	~£1.5k
FC Replacement cost			FC warranted to cover vehicle life	
Fuel cost	£0.93/l (excl. VAT)	£1.19/l (excl. VAT)	*H_2 price to match Diesel fuel-only cost:* ***~£5.8/kg***	***~£8.4/kg***
Vehicle efficiency	~ 4.7l/100km	~ 4.0l/100km	~0.8kg/100km	~0.6kg/100km

E4tech elementenergy

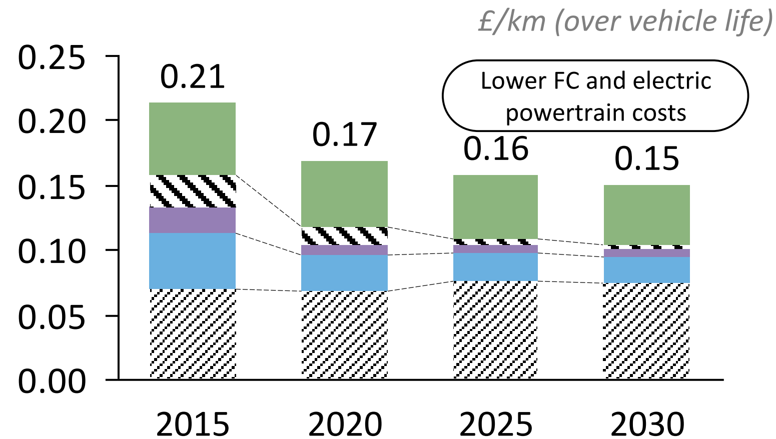
Other assumptions: vehicle life = 15 years; annual mileage: ~15,000 p.a.
Data source: DECC energy projections, Element Energy for the European Climate Foundation (2015) and existing supplier NEDC data (2015)

<20kW FC applications (e.g. FC RE-EV and FC minicar) are more competitive at low production volumes but require optimisation to reduce stack and powertrain costs

Example: Diesel ICE van – standard panel



Example: FC RE-EV van – standard panel



All figures exclude margins and VAT (unless stated)	Diesel 2015	Diesel 2025	ICE 2015	ICE 2025
Base costs (Chassis, engine/motor etc.)	~£15k	~£16k	~£15k	~£13.5k
Fuel Cell system cost (5kW)			~£7k	~£1.2k
H2 tank cost (3kg at 700bar)			~£5k	~£2k
Additional powertrain cost (incl. battery)			~£12k	~£6k
FC Replacement cost			FC warranted to cover vehicle life	
Fuel cost	£0.93/l (excl. VAT)	£1.19/l (excl. VAT)	*H_2 price to match Diesel fuel-only cost:* ***~£10.1/kg***	***~£16.3/kg***
Vehicle efficiency	~ 7l/100km	~ 6l/100km	~1.3kg/100km ~ 21kWh/100	~1kg/100km ~17.5kg/100km

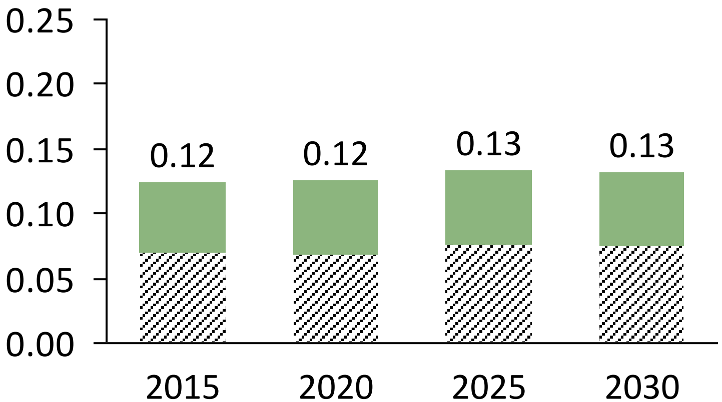
E4tech elementenergy

Other assumptions: vehicle life = 12 years; annual mileage: ~23,000 p.a.; electricity price: £15p/kWh. **Data source:** Element Energy for the European Climate Foundation (2015) and industry consultations (2015)

H2-ICE applications have a low capital cost premium from the outset but hydrogen fuel and tank cost can challenge the overall economics

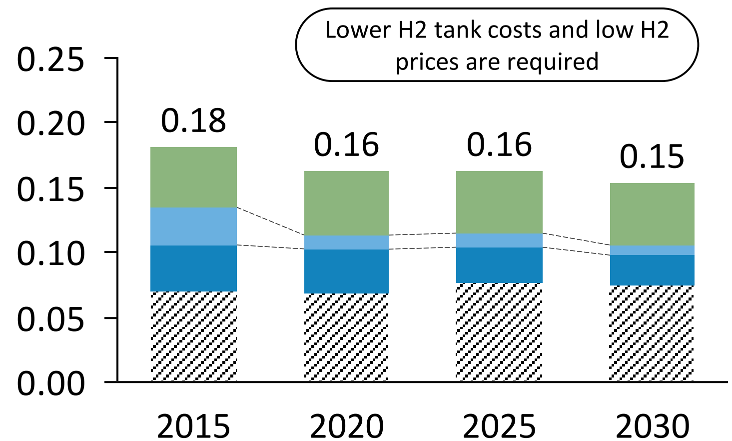
Example: Diesel ICE van – standard panel

£/km (over vehicle life)



Example: H2-ICE van – standard panel

£/km (over vehicle life)



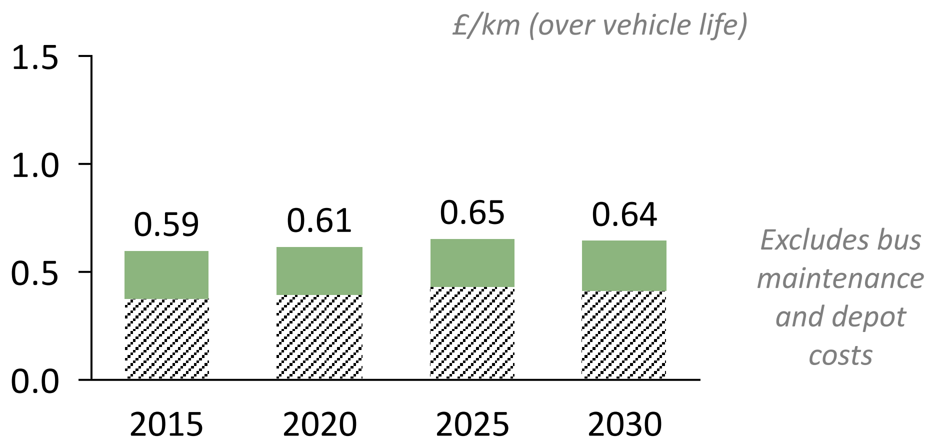
All figures exclude margins and VAT (unless stated)	Diesel 2015	Diesel 2025	ICE 2015	ICE 2025
Base costs (Chassis,engine etc.)	~£15k	~£16k	~£12k	~£13k
H2 tank cost (4.5 kg at 350bar)			~£8k	~£3k
H2-ICE engine engineering and conversion costs			~£10k	~£7k
Fuel cost	£0.93/l (excl. VAT)	£1.19/l (excl. VAT)	*H_2 price to match Diesel fuel-only cost:* ***~£4.1/kg***	***~£5.2/kg***
Vehicle efficiency	~ 7l/100km	~ 6l/100km	~1.7kg/100km	~1.5kg/100km

E4tech elementenergy

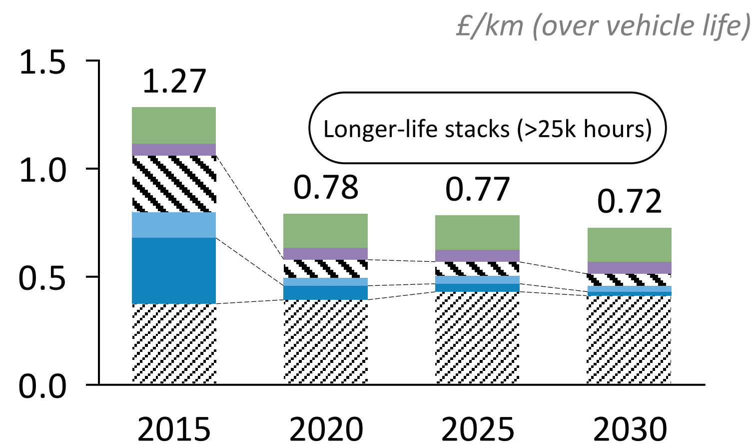
Other assumptions: vehicle life = 12 years; annual mileage: ~23,000 p.a.
Data source for ICEs: H2FC working Paper 2, Review of the prospects for using hydrogen as a fuel source in internal combustion engines, Samuel L. Weeks, UCL Energy Institute (2015)

Heavy-duty FC applications require long-lasting, affordable FC stacks to reduce replacement costs and improve overall economic performance

Example: Diesel ICE bus – 12m urban bus



Example: FC bus – 12m urban bus



All figures exclude margins and VAT (unless stated)	Diesel 2015	Diesel 2025	FCEV 2015	FCEV 2025
Base vehicle	~£150k	~£160k	~£115k	~£110k
Electric Integration and other powertrain costs			~£45k	~£40k
Fuel Cell system cost (120kW)			~£180k	~£50k
H2 tank cost (30kg in total 350bar)			~£90k	~£25k
FC Replacement cost (@ 40% of FC cost)			FC life: ~15k hours	FC life: ~35k hours
Fuel cost	£0.93/l (excl. VAT)	£1.19/l (excl. VAT)	*H_2 price to match Diesel fuel-only cost:* ***~£3.9/kg***	***~£5.1/kg***
Vehicle efficiency	~ 40l/100km	~ 36l/100km	~10kg/100km	~8kg/100km

E4tech elementenergy

Other assumptions: vehicle life = 12 years; annual mileage: ~60,000 p.a.
Data source: FCH JU, Urban buses: alternative powertrains for Europe (2012); Element Energy industry consultations (2015)

Economic conclusions (1/2): small FC-stack applications can enter the UK market faster and in larger volumes than OEM FC passenger cars in the near term

OEM Passenger car (FCEVs)

- Today the FC passenger cars (FCEVs) offer the largest TCO gap of all of the applications. The technology requires a far larger economy of scale (deployment volume) than other segments to reach a more competitive case versus incumbents
- The key issue is reduction in the cost of the fuel cell system and hydrogen tank via increased volume of production (and the associated learning about reduction in processing costs)
- Significant volumes around 100,000 units per year will be needed for the segment to be competitive. Even at this point, it is likely that there will be a small premium over conventional diesel vehicles up to 2030

Vehicles with smaller stacks (FC RE-EV and minicars)

- FC stacks for these applications are relatively small and have a limited impact on the overall TCO. The main focus for these applications is on complete system cost reduction (which need to be achieved in spite of the relatively low volumes envisaged for this segment) as well as on FC stack and tank cost reductions
- Given the small stacks (either due to lightweight car or complementary use with electricity), their H2 consumption is low.
- Accordingly, the technology benefits from a smaller TCO gap versus incumbents in the early years, which makes their market entry easier. FC vehicles using smaller (<20kW) FC stacks can therefore become competitive at smaller volumes but will still have a small cost premium up to 2030
- These markets may also be easier to access in the near term for large fleet users having corporate environmental goals and long driving range requirements (e.g. incompatible with EV options)

Economic conclusions (2/2): heavy-duty and H2-ICE applications require very low hydrogen prices at the pump

Vehicles with heavy duty stacks (e.g. buses and trucks)

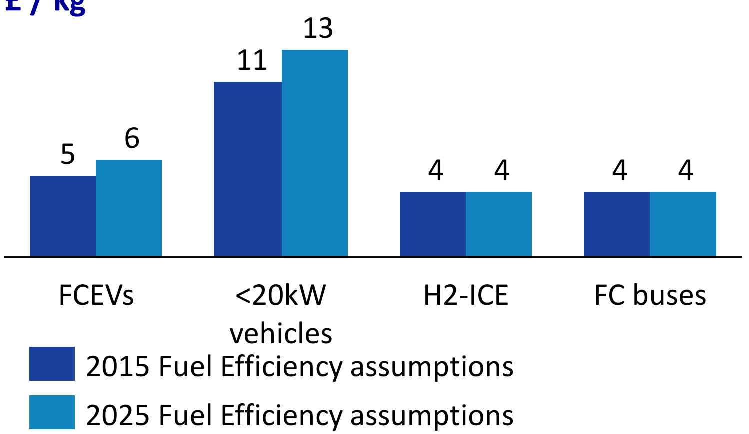
- The priority for these applications are:
  I. Demonstrating high reliability of vehicles
  II. Developing longer-lived FC stacks (to avoid frequent stack replacements)
  III. Improving fuel efficiency
  IV. Reducing overall system and integration costs via volume
- These applications require the lowest volume to achieve economies of scale (low 100's-1,000's of units per year per manufacturers) and still allow competitive costs (again with a small premium versus other applications)

Note on hydrogen fuel costs

- FCEV current and projected high fuel efficiency implies that hydrogen can be sold at £5 to £6 / kg at the pump to deliver the same cost per km as conventional Diesel vehicles (excluding other vehicle costs)
- <20kW (FC RE-EV and minicar) applications can deliver the same fuel costs as for equivalent Diesel vehicles for much higher hydrogen prices (even at today's marker prices – e.g. £10-£12/kg)
- H2-ICE and heavy-duty FCEV applications require extremely low hydrogen prices in order not to impose an additional TCO penalty to drivers

Maximum H2 selling price at the pump to match Diesel fuel cost on a km-driven basis (excluding vehicle costs)

£ / kg



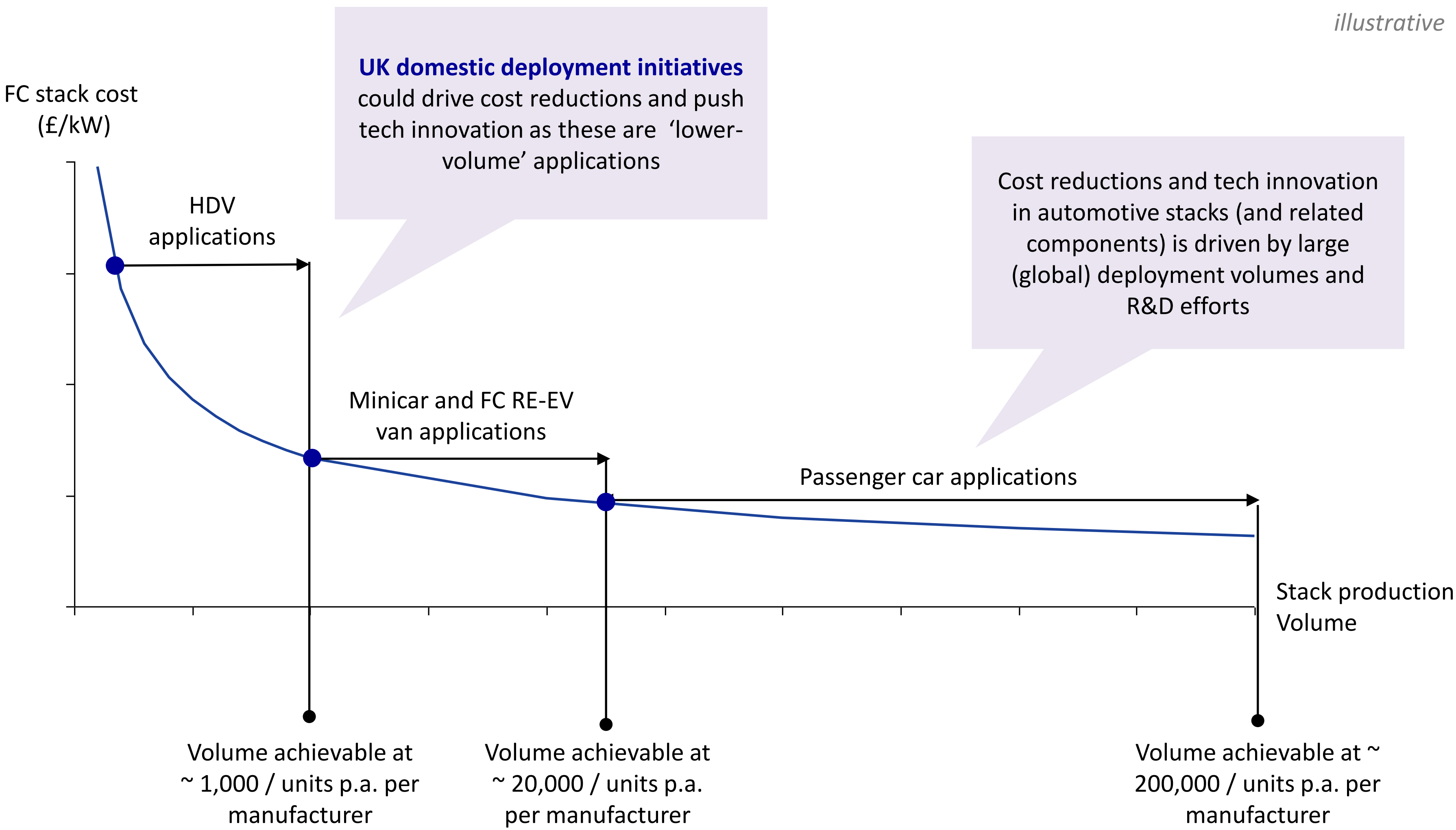
Early markets which place a premium on the advantages of hydrogen fuelled vehicles

- The economic calculations above suggest that until significant volumes are achieved, end users will be forced to accept a significant ownership cost premium to use a fuel cell vehicle.
- Whilst this inevitably leads to a request for subsidy to help support the technology as it matures, there are also opportunities to consider niches where other externalities help to shift the purchasing decision in favour of a hydrogen vehicle. These niches require the advantages of hydrogen vehicles to be combined with a requirement for a long range (which rules out the battery based options):
  - **An improved driving experience** – electric vehicles can have a very smooth, quiet and fast driving characteristic. Companies such as Tesla have made this improved driving experience central to their early offer – a similar approach could be adopted by hydrogen companies – see for example recent prototypes by BMW, Riversimple and Pinifarina.
  - **Air Quality** – vehicles which need to access low emission zones such as London's congestion charging zone and planned Ultra Low Emission Zone. Avoiding the congestion charge can be worth as much as £10,000 over the life of a van or car.
  - **Very strong CO_2 sensitivities –** firms with a strong corporate requirement to cut emissions from the vehicle fleet such corporate or public sector fleets – examples include public buses and corporate chauffeur fleets
  - **Noise** – this is particularly relevant for areas with night time curfews, where the fuel cell delivery vans and trucks could provide longer duties and make operational savings
  - **Health issues** – where the vehicle operator places a value on the health of the user through avoided vibrations, pollution etc. In some cases (e.g. La Poste in France), this has been valued as £1,000's per year
- Vehicles deployed in the UK should be encouraged to demonstrate an approach which maximises the use of these drivers of value, to support early sales

A UK vehicle rollout and technology development programme can contribute to advancing all sectors and create innovative products

Aspect	Technology development case for the UK	Deployment case for the UK
FC stacks / FC systems for automotive applications (e.g. >50kW) (e.g. OEM FCEVs)	• Innovation on automotive FC stacks / systems is largely driven by OEM-led international R&D programmes. • Selected UK companies have a role along the supply chain where technical innovation can have large impacts (such as **Intelligent Energy**, developing stacks with OEM partners, **Johnson Matthey**, who actively develops Membrane Electrode Assemblies (MEA) and catalyst solutions)	UK domestic deployment volumes are unlikely to influence global dynamics (these are driven by large (global) deployment volumes).
<20kW FC stacks / FC systems (for minicar and FC RE-EV applications)	• There are several UK companies developing <20kW FC stack / system solutions for FC RE-EV applications (such as **Intelligent Energy**) and minicars (such as **Riversimple, MicroCab**), or are actively working on FC system integration and electric component optimisation for FC applications (such as **Millbrook, Frost EV**). • The UK is therefore well placed to drive innovation in these applications and develop competitive UK-made products	Low-volume deployments of FC RE-EV or minicar solutions can drive large cost reduction and push technology innovation.
FC stacks / FC systems or hydrogen combustion for heave-duty vehicles (HDV) (e.g. buses and trucks)	• Innovation on HDV FC stacks / systems is largely driven by non-European OEMs (most notably Ballard, Hydrogenics) UK companies (such as **Johnson Matthey**) can nevertheless have a role along the supply chain. Intelligent Energy could in principle serve this market but as yet have not produced a dedicated HDV stack • Selected UK companies are working on hydrogen combustion (ULEMCO, Revolve), FC system integration (such as **Magtec**) or electric component optimisation which can be applied to FC HDV applications. The UK is well placed to drive innovation in these applications and develop UK-made products	Low-volume deployments can drive large cost reduction and push technology innovation. UK deployment initiatives can thereby create an attractive market and drive UK innovation.
On-board hydrogen storage (gaseous)	• Innovation on automotive tanks is driven by international (often OEM-led) efforts. However, the UK could promote next generation, lower cost cylinder development via e.g. **Luxfer Gas Cylinders** (based in Salford, UK) who are among the world's largest manufacturer of aluminium and composite gas cylinders, or smaller companies such as **Haydale** and partners in the HOST project	UK domestic deployment volumes are unlikely to influence global dynamics (these are driven by automotive volumes) but can support UK innovation

Progress in automotive stacks (and related H_2/FC components) require larger production volume but different applications have considerably different volume requirements



UK specific actions which can progress the sector (1/5)

Barrier	UK-specific actions
Very low sales volume are holding up progress across the industry	• Continued support for global OEM passenger car deployment helps create an early market for hydrogen in the UK helps ensure the UK's position as a leading early market for FCEVs, with associated benefits for attracting global auto players to the UK, improving the visibility of the hydrogen sector and making the case for investment in hydrogen infrastructure scale-up. However, volumes from passenger car OEMs are likely to be low before 2020. • The UK is unlikely to drive global deployment volumes for passenger cars. Instead **UK programmes for rolling out FC RE-EV commercial vans** (e.g. several hundred per annum by 2020), **minicars** (e.g. several hundred per annum by 2020) , **hydrogen fuelled buses or trucks** (e.g. several tens per annum by 2020) can secure sufficient volume to support UK industry in developing novel products targeting these markets and drive substantial cost reductions. • Deployments of hydrogen fuelled buses and trucks can generate substantial demand for hydrogen fuel and thus support the investment case for constructing more hydrogen refuelling stations across the country. In turn, this will directly support the rollout of FC passenger cars. As discussed in the "H2 production and distribution" roadmap, deployment should be clustered in order to secure a high utilisation of refuelling assets and thus support reductions in the hydrogen fuel price. This can be achieved by supporting the conversion to H_2 of captive fleets and link refuelling assets and vehicle deployments together.

1 - For example, Intelligent Energy is currently developing their next generation of FC systems for fuel cell range extended electric van applications via a £12.7 million project supported by UK Advanced Propulsion Centre (ZERE project)

UK specific actions which can progress the sector (2/5)

Barrier	UK-specific actions
Willingness to supply - OEMs are often reluctant to produce and market fuel cell models	• There is often a reluctance within OEM's of all vehicle classes to develop and commercialise fuel cell vehicles for the market. This is apparent in the bus sector, where despite considerable effort (e.g. by the FCH JU) to create demand in the 100's of vehicles per year, the number of OEM's coming forwards Is limited. It is also apparent in the passenger car segment, where only a relatively limited number of OEM's have committed to series production and even then this has occurred in low volume and with high prices. For any hydrogen transport strategy to work, OEM's will need to enthusiastically commit to the technology and associated aggressive sales strategies. This reluctance is obviously driven in part by concerns over the high cost of the technology, but in smaller niche companies can be caused by simple issues such as not having the engineering resources available for an additional model development. • This calls for **an entrepreneurial approach to vehicle deployment**, where companies are encouraged to see business opportunities from developing the new technology, as opposed to a reluctant response to a regulatory push. The electric car sector is a good example of this, where the actions of two companies seeking to gain market share (Tesla and Nissan) have helped transform the sector. • This should affect policy making in the field. There is a danger that regulations create "compliance cars" designed only for the specific regulation and that deployment subsidises lead to opportunistic niche vehicle deployment with high margins for existing players, rather than true investment in commercialisation (this is at risk of occurring in the bus segment). • Therefore in addition to regulations and subsidy for early deployment, policy makers might consider **results based competitions** (e.g. the X-Prizes in the US) to encourage the release of vehicles with a given price/performance target, or perhaps **more direct intervention to fund prototyping and scale-up of manufacturing in the UK**, as opposed to generic deployment. Furthermore any funding should be directed to companies who can demonstrate a clear and credible path to un-subsidised sales of vehicles, to avoid the risk of creating grant-reliant companies. • The proposed use of debt based support as opposed to direct grants may be beneficial here, provided sufficiently large sums are made available to support manufacturing scale-up.

UK specific actions which can progress the sector (3/5)

Barrier	UK-specific actions
Technology development for <20kW and heavy duty applications	• *FC Systems* – **funding programmes** aimed at accelerating technical and design improvements can have a impact by supporting UK companies in developing products optimised for this market[1] • *FC System/hydrogen combustion integration* - **funding programmes** aimed at streamlining the integration of fuel cell/hydrogen combustion systems in hybrid powertrains and designing dedicated lightweight chassis can support several UK companies in developing specialty expertise and products which can be marketed internationally
Technology development programs	• There is substantial on-going research on advanced stack technology including extremely reduced catalyst loading, novel membrane materials, non-precious catalysts, etc. which can further simplify stacking, improve life, reduce weight and costs • UK **R&D programmes** specifically targeting these needs can build on existing UK university research and develop innovative / ground-breaking products
Manufacturing equipment	• Stacking and manufacturing processes for FC stacks and hydrogen tanks are far from being fully optimised due to the very low volume nature of the existing market(s) • UK **R&D programmes** specifically designed to develop new techniques can create specialty equipment and concepts capable to generate substantial cost reductions

1- Let alone Renault Trucks who is developing a 4.7 tonne FC RE-EV truck with Symbio FCell

UK specific actions which can progress the sector (4/5)

Barrier	UK-specific actions
Lack of large truck solutions	• There are currently very few low-carbon truck powertrains and no major OEM is actively considering FC or hydrogen combustion trucks[2]. A UK **R&D programme** specifically designed to develop FC truck powertrains (e.g. for >4.5 t applications) can support the creation of a UK-made solution which can target the national and international demand for zero emission trucks
Lack of hydrogen refuelling infrastructure	• Any FC vehicle rollouts require an adequate hydrogen refuelling network. **HRS rollouts before 2020 require public funding** as technology costs and low H2 fuel demand make these assets not financeable by private investors alone
Hydrogen combustion option not currently considered as a mainstream hydrogen option	• Hydrogen combustion vehicles are currently the dominant hydrogen fuelled vehicle on the road. Whilst in the long term, their potential may be limited due to lower efficiency vs fuel cell vehicles, they do offer a near term option for hydrogen vehicle deployment, particularly for larger vehicles. They also have the advantage of crating considerable demand for hydrogen to justify infrastructure deployment. **Allowing hydrogen combustion** to make the case for support under existing and future funding schemes would seem beneficial and would support UK companies who are globally leading in this area. This implies action at both a national level (OLEV currently exclude combustion options) and at the FCH JU level (where fuel cell vehicles are favoured) • Furthermore, there are research questions associated with combustion – how clean can the emissions become, how can efficiency be optimised, improvements to reliability and maintenance regimes, which would benefit from further research work under UK R&D programs aimed at the hydrogen sector

1- Let alone Renault Trucks who is developing a 4.7 tonne FC RE-EV truck with Symbio FCell

UK specific actions which can progress the sector (5/5)

Barrier	UK-specific actions
High cost of fuel	• For low volume hydrogen station deployment, the high costs of hydrogen (>£7/kg) can harm the ownership case for fuel cell vehicles • Mechanisms capable of pricing in the benefits of using low carbon hydrogen fuel for road applications can support reduction in the hydrogen fuel price (such as the inclusion of hydrogen in the renewable transport fuels obligation (RTFO), fuel duty reduction/exemption for hydrogen in the early years of deployment, carbon pricing or other market based mechanisms to support low-carbon hydrogen use) • Vehicle rollout schemes designed to maximise the utilisation of refuelling assets can reduce the hydrogen fuel cost at the pump (**clustering of demand, captive fleet approaches**, etc. – see roadmap on H2 production for transport)
Variable pressures and refuelling standards	• OEM vehicles have standardised around 700 bar tanks and have required this standard from infrastructure providers. However, many of the smaller players are still looking for 350 bar systems, and buses have standardised around this pressure. Dual pressure systems are possible, but there are issues over the standards for 350 bar fuelling (essentially requiring costly pre-cooling if the OEM 700 bar vehicles are to be safely fuelled at these stations). Furthermore, there is currently no approved standard allowing fuelling of tanks below 2kg, this is a problem for small vehicles e.g. Suzuki bikes and Riversimple cars • These iisues can be addressed as a part of UK deployment programmes – e.g. by including dedicated work packages to support harmonisation of standards and test novel refuelling protocols / solutions for low-volume / low-pressure applications

Non-technical barriers which can be addressed via targeted policy / regulatory interventions and stakeholders engagement (1/2)

- **Need for infrastructure to permit deployment** – without markets emerging with coverage of hydrogen fuelling infrastructure at an affordable price (somewhere in the world), it will not be possible to create a market for hydrogen vehicles. This is a particularly severe problem for passenger cars, as to appeal to the private customer, they will require a high cost nationwide network. By contrast many of the other vehicle types are "captive" to a given region and so the infrastructure can be more limited.
- **Customer willingness to pay/accept H_2** – the customer's willingness to adopt a hydrogen vehicle is not yet established and in particular, the willingness to pay premium for zero emission driving is not yet demonstrated. **Green benefits also need to be better articulated** as many market participants question the green benefits of hydrogen vehicles and this harms the political and consumer case
- **Constrained spaces** (tunnels, indoor car parks, ferries, Eurostar) – regulations around hydrogen use in constrained locations need to be better defined and harmonised
- **Coping with an absence of policy certainty** – Governments inevitably struggle to provide long term certainty (10 year+) on issues which affect the market for new vehicles. Hydrogen vehicle deployment strategies need to focus as far as possible on approaches which avoid the need for intervention as rapidly as possible.
- **Certification processes** – are currently onerous, particularly for SME's without the resources for full crash testing etc. This delays introduction of new cars – an approach whereby already homologated vehicles are the basis for trials helps speed market introduction
- **Training and skills** – there is a lack of knowledge in maintenance, support of hydrogen fuelled vehicles in the field. There will also be a lack of trained engineers and operators in the production of hydrogen and fuel cells if major expansions in production capacity are to occur in the UK

Non-technical barriers which can be addressed via targeted policy / regulatory interventions and stakeholders engagement (2/2)

- **Training and skills** – there is a lack of knowledge in maintenance, support of hydrogen fuelled vehicles in the field. There will also be a lack of trained engineers and operators in the production of hydrogen and fuel cells if major expansions in production capacity are to occur in the UK
- **Need for coordination of actors** - there is a need for many aspects of the roll-out of hydrogen vehicles to be coordinated. These include the resolution of practical issues (e.g. fuelling protocols, billing approaches, strategies on fuelling pressure), as well as planning the roll-out of hydrogen networks and synchronising with vehicle deployments in the early years. The work of the new SMMT hydrogen task force, as well as the continued work of the UKH_2Mobility consortium will be valuable here.
- **Clearer role for hydrogen in wider automotive sector plans -** In addition, hydrogen's role in the future plans of different UK groups considering the wider automotive sector (e.g. LowCVP, Automotive Council etc.) needs to be better defined and accepted – this will require action by leading industry participants to ensure the case for hydrogen is made in these fora.

Overview of the deployment timeline, technology progress and possible actions for supporting this sector (1/2)

	2016-2020	2020-2025	2025 onwards
Global activities and deployment	First commercial gen. of FCEVs in their 100s/year	Reduction in FCEV premium pricing, 1,000s/year; Continued deployment of 10,000s/year	Commercial gen. FCEVs, no / minimum premium pricing, 100,000/year
	Global cumulative deployment of few 100s FC buses and 1,000s FC RE-EVs by 2020	Global deployment of few 100s FC buses and 1,000s FC RE-EVs per annum	Global deployment of several 100s FC buses and 10,000s FC RE-EVs per annum
Global Technology progress	Optimisation of stack manufacturing process and core technology	Optimisation of stack manufacturing process and core technology	Further optimisation of manufacturing process and advanced low-cost catalyst / MEA solutions (all applications)
	Optimisation of FC bus technology; Development of novel <20kW FC vehicles; Development of novel FC truck solutions	Optimisation of manufacturing process and technology – specific to <20kW and HDV stack applications	
	Development of cost effective H2 tanks	Further improvements in FC stack technology thanks to volume	Further improvements in FC stack technology thanks to volume
	Increased availability of FC vehicle types (all applications)	Increased availability of FC vehicle types (all applications)	Increased availability of FC vehicle types (all applications)

- Secure a minimum/basic deployment volume for all vehicle applications to guarantee continuity in industry efforts

FC stack:
- FCEV stacks: < £300/kW
- <20kW stacks: <£1,000/kW
- HGV stacks: < £500/kW and >20k hours life

H2 tank:
- 700bar tank ~ £20/kWh
- 350 bar tank ~ £30/kWh or lower

FC stack:
- FCEV stacks: < £100/kW
- <20kW stacks: <£300/kW
- HGV stacks: < £400/kW and >25k hours life

H2 tank:
- 700bar tank << £20/kWh or lower
- 350 bar tank ~ £20/kWh or lower

Overview of the deployment timeline, technology progress and possible actions for supporting this sector (2/2)

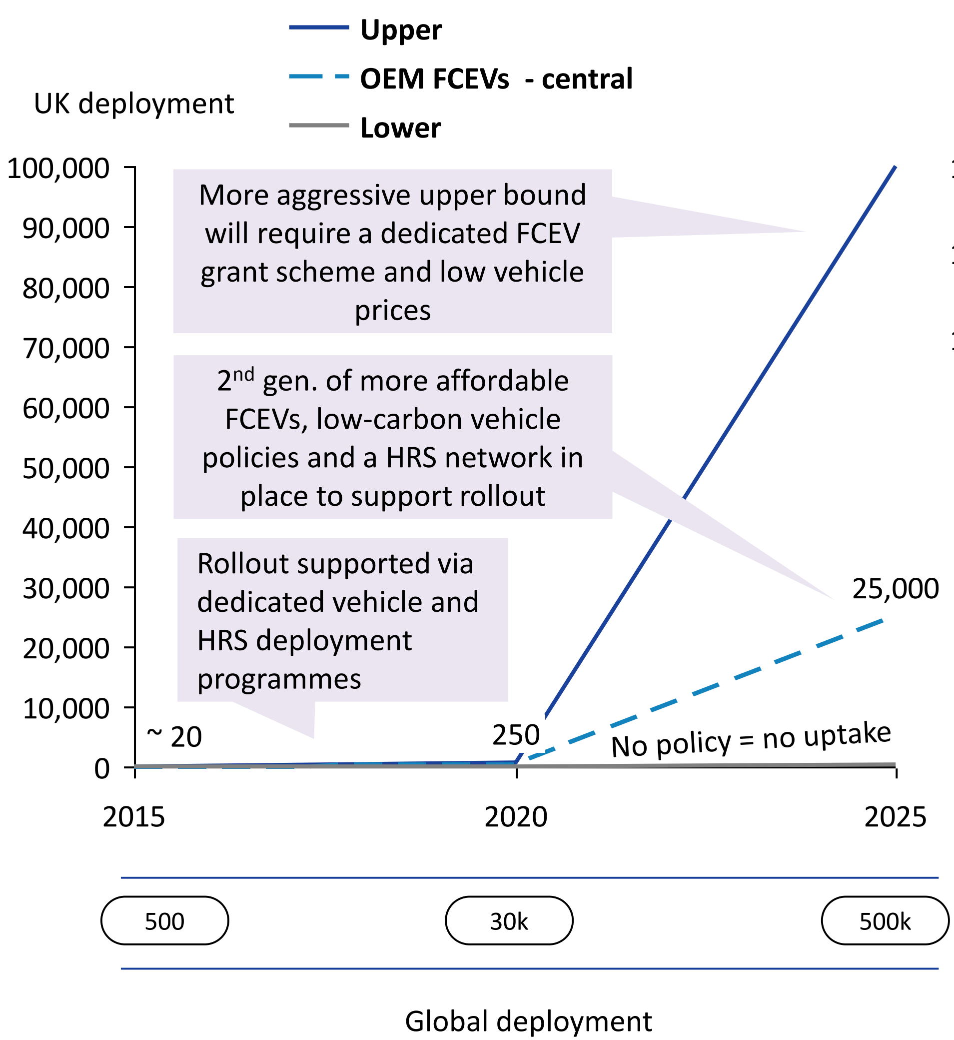
	2016-2020	2020-2025	2025 onwards
UK market development	~ 30-65 HRS deployed by 2020	> 150 HRS deployed by 2025	Several 10s to 100s stations per annum
	UK Fleet of 50-100 buses	UK Fleet of several 100s buses	> 100 FC buses per annum
	UK Fleet of ~500s FC REEV and microcars	UK Fleet of several 1,000s FC REEV and microcars	> 1,000 FC REEV and microcar per annum
	UK Fleet of ~ 100 OEM FCEVs	UK Fleet of several 10,000's OEM FCEVs	> 10,000 FCEVs per annum

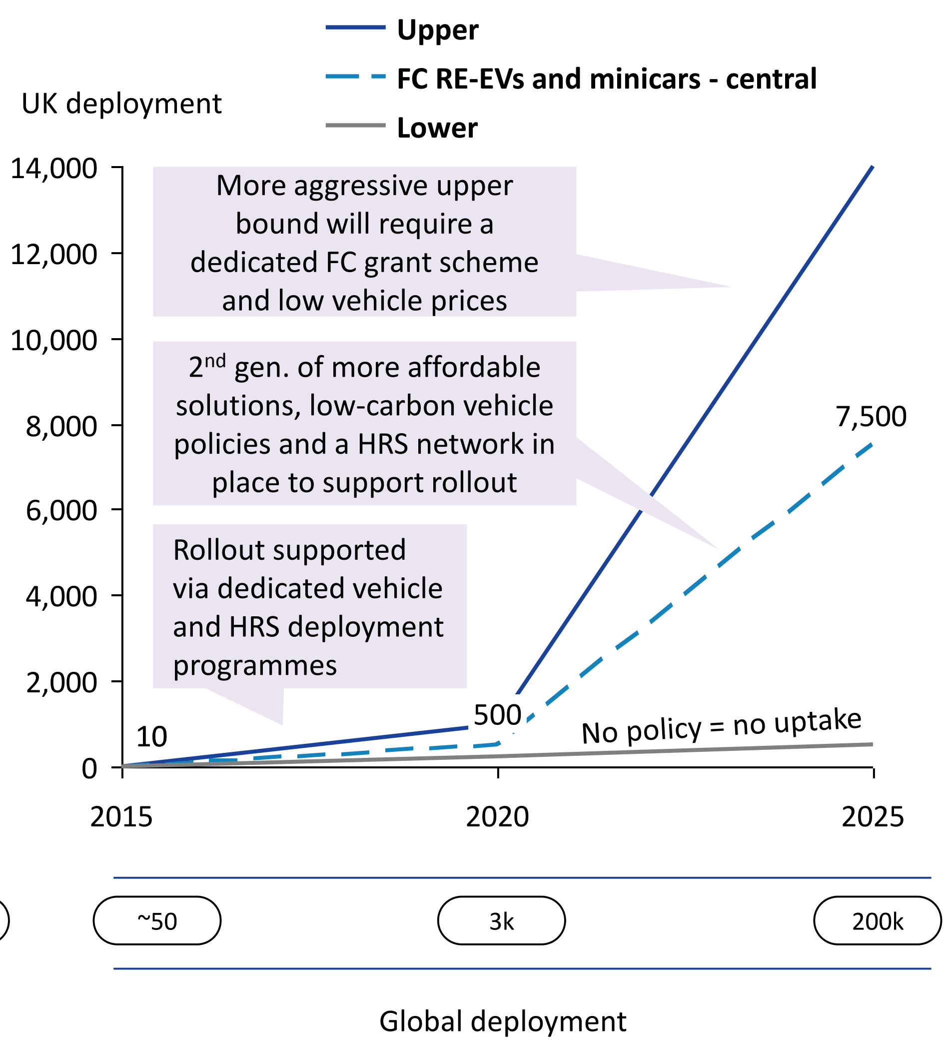
UK actions

- Programme to support the development of UK <20kW FC systems & vehicles
- Programme to support the development of hydrogen systems / powertrains for trucks
- Beginning of commercialisation of UK FC system and vehicle solutions for <20kW and heavy duty applications
- Dedicated rollout programme for UK produced vehicles FC RE-EVs, minicars, hydrogen buses and trucks
- Secure policy continuity for FC in transport applications (across national and local governments); coordination with EU efforts on clean mobility
- FC market reaches a critical size allowing unsubsidised deployments
- Resolve any outstanding HRS permitting, vehicle certification and other regulatory constraints to reduce barriers to larger-scale deployments

E4tech elementenergy

Deployment volumes to 2020 for FCEVs and <20kW applications will be moderate but supportive policies can secure an early market traction before 2025

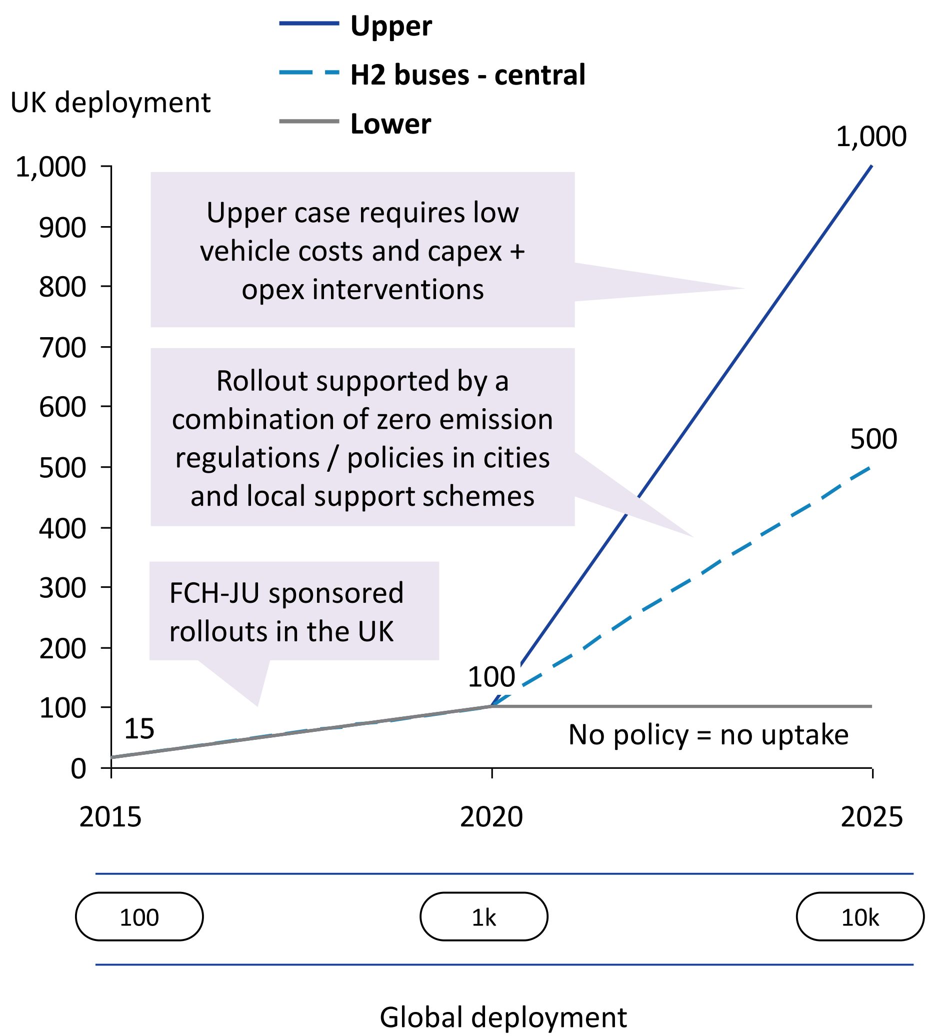


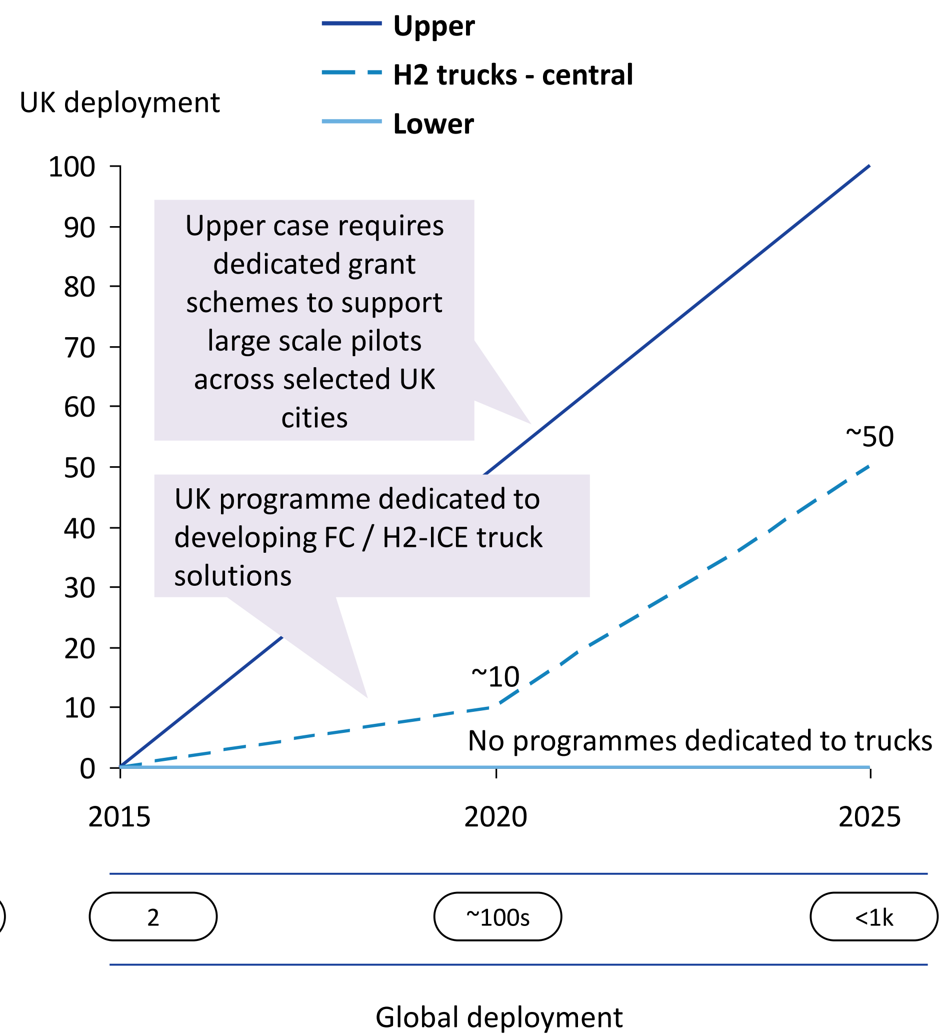


E4tech elementenergy

Data source: Element Energy analysis based on OEM statements, existing policies and insights from private consultations

FC buses can achieve meaningful volumes by 2025 if supported by zero-emissions policies in cities while trucks require a dedicated development programme





Data source: Element Energy analysis based on OEM statements, existing policies and insights from private consultations

UK deployment of FCEVs may be highly sensitive to the actions previously outlined

Scenario	Actions	Deployment numbers		
		2015	2020	2025
High	**Additional actions** • Enhanced R&D support leading to numerous competitive UK products in heavy duty and RE-EV space • All parties commit to bringing affordable vehicles to market rapidly (Govt support, OEMs etc.) • Enthusiastic and consistent rollout support from governments for HRS and FCEVs		1,000's	>100,000
Central	**Assumed actions** • Development programmes for fuel cell systems for FCEVs and larger hydrogen systems and powertrains • Rollout programmes for vans, FC RE-EVs, minicars, hydrogen buses and trucks, with a UK focus • Support for next wave of HRS deployment • Policy continuity for FC in transport • Resolution of HRS permitting and siting issues	10's	100's	>30,000
Low	**Conditions for achieving the low scenario** • No support for infrastructure deployment • Insufficient incentives forUK development of vehicles • No new rollout support for FCEVs		10's	100's of niche vehicles

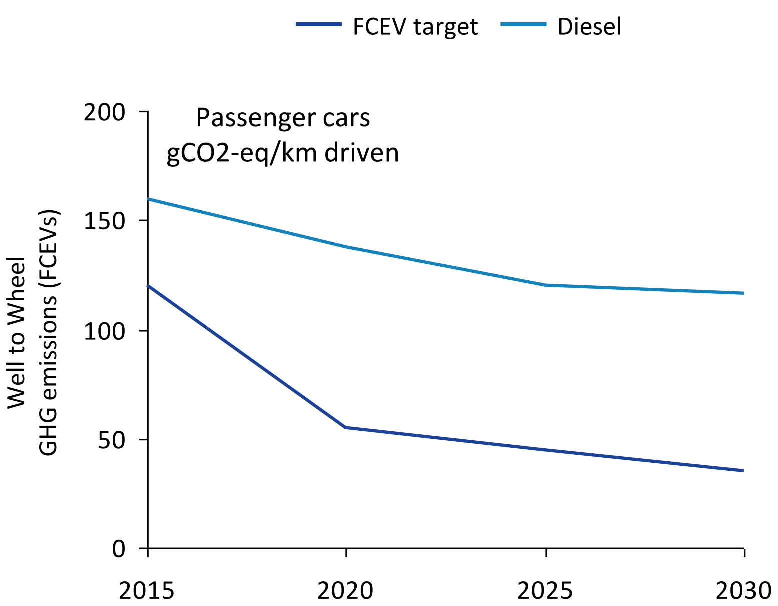
What is the UK benefit from reaching the aim in 2025?

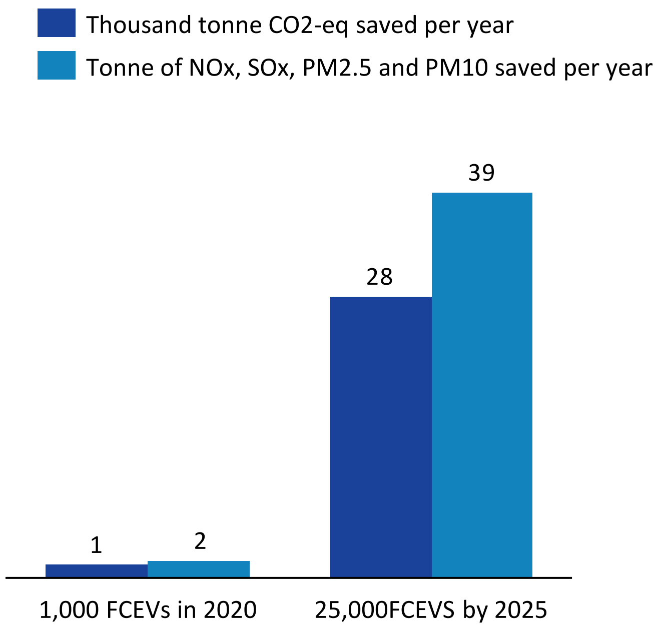
Market potential by 2025

<u>Cumulative by 2025</u>	FCEVs	FC RE-EV and minicars	Heavy-duty applications
Global addressable market	Up to 500,000 vehicles	Up to 150,000 vehicles	Up to 10,000 vehicles
Global addressable market value	Up to £12 billion	Up to £3 billion	Up to £2 billion
UK Share of Tradeable Global Market	Likely around 5%	Likely around 5%	Likely around 10%
Potential added value for UK economy (GVA)	~£0.2 billion (of which ~ 10% from UK market)	~£32 million (of which up to ~ 10% from UK market)	~£27 million (of which up to ~ 10% from UK market)
Potential UK new job creation	1,000's	100's	100's

Potential GHG and Air Quality (AQ) benefits for the UK

- Although environmental benefits are expected from all FC vehicle segments, the larger GHG and AQ benefits will be delivered by FC passenger cars (FCEVs) thanks to the large-volume nature of this segment (vans sales typically are ~10% of car sales, while truck and bus sales are even lower)
- The analysis reported below illustrates potential GHG and AQ benefits available from deploying ~ 250,000 FCEVs in the UK by 2030 based on the UK H2Mobility H_2 production pathways (capable to secure 60% to 70% GHG reduction per km driven on a well-to-wheel basis from after 2020 – also reported below)





Data source: UK H2Mobility, Phase 1 report

Assumptions: SOx, NOx, PM10 and PM2.5 emission figures per km driven by diesel ICE vehicles are as per the French General Committee of Sustainable Development (NOx:80mg/km; SO2: 0.99mg/km; PM2.5: 17mg/km; PM10: 5mg/km). Vehicle annual mileage: ~ 15,000km/year/ car. Diesel and FCEV gCO2-eq/km driven per km as per UK H2Mobility assumptions

Links to other roadmaps

Dependencies

- *Roadmap on H2 production and distribution* – any FC vehicle rollout requires an adequate network of refuelling stations and affordable hydrogen price at the pump

Beneficial effects

- Almost all roadmaps can benefit from large-volume deployments of FC vehicles as this will:
  - Drive down costs for FC stacks / systems
  - Generate substantial hydrogen demand and – in doing so – create the case for investments and thus cost reductions in hydrogen production, distribution and retailing value chain