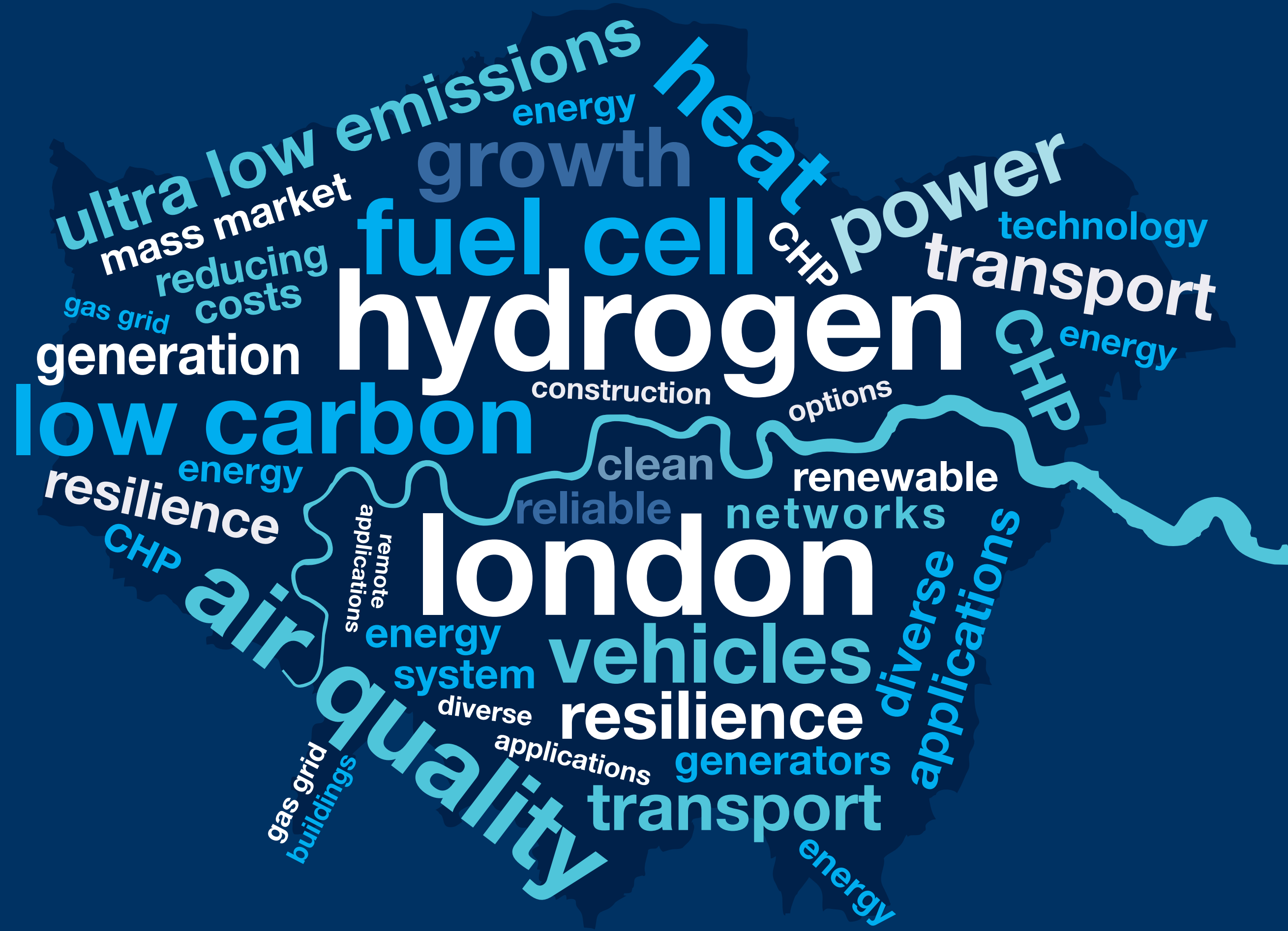
LONDON: a capital for hydrogen and fuel cell technologies

April 2016



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MAYOR OF LONDON

HYDROGEN LONDON

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Hydrogen and fuel cell technology has the potential to provide **solutions to London's most critical energy challenges** – enabling growth while improving quality of life and minimising environmental impacts.

Since being established by the Mayor's Office in 2002, Hydrogen London has been at the heart of London's hydrogen and fuel cell industry.

This group has played a central role in facilitating knowledge sharing, raising the profile of the sector, and initiating projects to demonstrate the potential for hydrogen and fuel cell technologies in London. The members of Hydrogen London include experts from government, the private sector and academia.

This document was prepared for Hydrogen London by Element Energy Ltd.

Foreword

London is already an acknowledged leader in deploying zero emission hydrogen and fuel cell technologies in urban operation – having pioneered fleet operation of hydrogen powered buses and taxis; installed the largest total capacity of stationary fuel cells in any European city; and established a commercial market for transportable fuel cell applications. However, there is still much to be done and London needs to build on this initial platform to reap the environmental and economic benefits from deploying these applications.

For any major urban area the benefits are quite clear, and particularly so for London. On the environment side the uptake of hydrogen powered vehicles, fuel cell units in buildings and portable applications will all help meet energy and transport requirements with ultra-low emissions – offering a pathway to delivering cleaner air and significantly enhanced health benefits. At the same time hydrogen can be produced from a range of low carbon sources and be stored to help support a more resilient energy network in London.

The economic benefits are also significant and Hydrogen London members are investing to ensure London remains a leader in innovation. Being ahead of the game ensures the development of a specialised and skilled industry, which in turn attracts further investment and demonstrates London's ambitions to drive positive change.

This is an exciting time for London – the report highlights that the transition to a hydrogen economy is already underway and that we now need to pick up the pace and work together to achieve the benefits of being ahead of the curve.

I hope you find this report informative and valuable but, more importantly, that you will work with us to ensure London remains a global capital for hydrogen and fuel cell technologies.

Dennis Hayter,

Vice Chair of Hydrogen London

Contents

London's challenges: growth, access and liveability

GROWTH

Space-constrained growth

Emissions need to be cut dramatically despite London's population growth

Many low emission technologies are not space efficient

Energy network upgrades (gas, electricity) are expensive and can cause congestion

Stronger, resilient energy networks

Increased energy security needed to support London's growing economy

Commercial buildings need secure electricity and heat: decentralised energy needed to avoid costly upgrades to the electricity grid

ENVIRONMENT

Cleaner air for London

Limited options for eliminating vehicle airborne emissions, particularly for large vehicles

Traditional options for decentralised generation produce local pollution – particularly energy from biomass/waste

Avoiding climate change

Emissions reductions needed in all sectors – heating and transport particularly hard to address

Electrifying transport, heat and power in order to decarbonise increases pressure on the electricity grid, which is already strained

Hydrogen and fuel cells offer holistic solutions

Space-constrained growth

Fuel cells are one of the the most space-efficient ways to provide low carbon decentralised energy (easily integrated into buildings, vs solar & wind)

Zero-emission transport infrastructure with minimal land use

Cleaner air for London

Hydrogen fuel cell technology: zero emissions at point of use

Hydrogen combustion: ultra low emissions

GROWTH

ENVIRONMENT

Stronger, resilient energy networks

Hydrogen can be produced affordably from a range of low carbon sources outside London and transported into the capital as a new clean way to import energy

Electrolysers producing hydrogen in London could help support an electricity system with increased renewable generation

Avoiding climate change

Low carbon hydrogen can be produced from local renewable sources and used to fuel heat, transport and power

Hydrogen can be used in the gas grid to progressively convert to zero carbon heat

Mass uptake will unlock increasing benefits for London

Broad energy system benefits unlocked when hydrogen is integrated throughout the energy economy

- Hydrogen supplied for heat & power through diverse supply routes (gas pipelines, onsite generation, freight delivery).
- Opportunity to meet London's growing energy demands without over-reliance on electricity networks.
- Low emission transport with minimal land use impacts.
- Inherently flexible generation from electricity and other low carbon sources.

Significant impacts for London

Full range of commercial applications

As costs fall, emissions savings will accrue from hydrogen in transport and fuel cells for heat and power

- Vehicle commercialisation brings greater demand for hydrogen.
- Business models for hydrogen production and trading become established.
- Gas fuel cells for heat and power drive fuel cell cost savings.
- Reduced construction emissions through adoption of fuel cell generators.

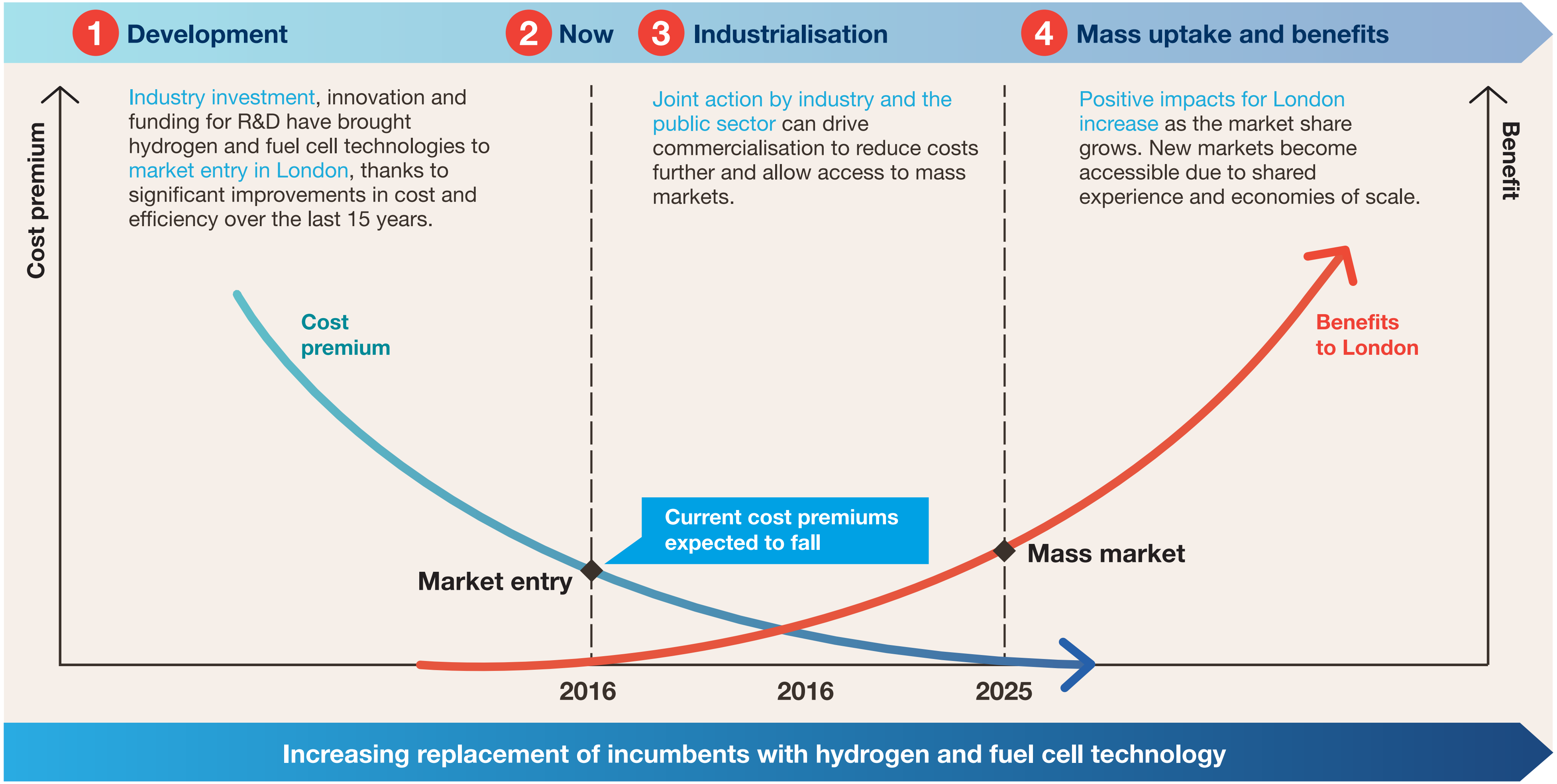
Local benefits are already being achieved in applications across London

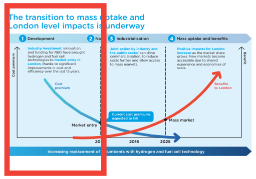
Local level impacts

Early commercial opportunities

Increasing scale of impacts

The transition to mass uptake and London level impacts is underway





1 London has helped mature the technology

The private sector has invested many tens of millions in hydrogen and fuel cells in London to date, resulting in a wide range of proven applications, demonstrating the market readiness of the technology

On a global level in 2014, **fuel cell sales exceeded $2.2 billion** (up from $1.3 billion in 2013)[1] and **over 100,000 fuel cells were shipped worldwide.**[2]

Construction & specialised applications

- Unsubsidised, low power fuel cell units are in use in lighting towers, CCTV and road signs across London.
- Efficient, low emission heat & power for remote site cabins has been demonstrated using a fuel cell.

Lighting towers e.g. for construction

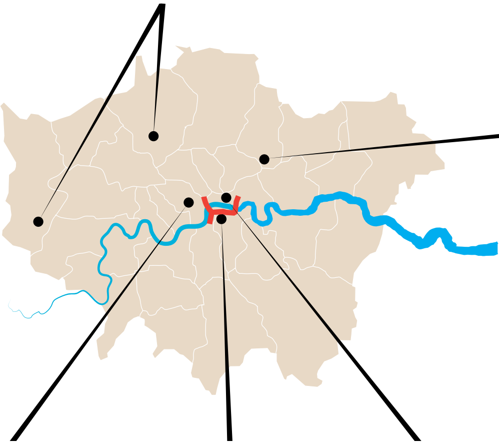
Remote site heat & power

Fuel cell & solar powered lighting for construction at the Olympic park

Transport

- Hydrogen cars, buses and delivery vans are now on the roads in London.
- Fuel cell cars can be commercially purchased or leased via OEM showrooms.

Public stations at Hendon and Heathrow; three more due to be installed in 2016



Quadrant 3, Regent Street

TfL's Palestra Building

20 Fenchurch Street

Fuel cell cars in operation with a range of public and private sector fleets

Fleet of hydrogen-diesel delivery vans (eligible for 100% congestion charge discount)

Fuel cell taxis introduced during 2012 Olympics and operated to late 2015

Fuel cell buses on a dedicated hydrogen route

Heat & power

- London is the European capital for fuel cell combined heat and power (CHP), with the largest installed capacity of any European city.
- Gas fuel cell CHP has been installed without subsidy to meet new build planning guidelines.
- In other cities such as Seoul, hydrogen and hydrogen-ready fuel cells are starting to be used for megawatt-scale CHP, showing the potential for London.

References: 1- Fuel cell technologies market report 2014, Fuel Cell and Hydrogen Energy Association, DoE 2015
2 - 4th Energy Wave Fuel Cell 2015 annual review

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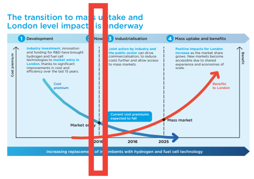


2 Londoners are enjoying using the technology today

◀ Fuel cell buses

Fuel cell buses in London have covered over **1.1 million kilometres**

"I think this is a great bus, very quiet, very comfortable to drive, people are loving it" (TfL Bus driver)

Fuel cell taxis ▶

Fuel cell taxis have covered **101,000 zero emission kilometres** in central London

"This is the quietest and most responsive vehicle I've driven since I started driving a taxi nearly 40 years ago. After a day's driving you do not feel fatigued by the constant drone that you normally get from a diesel taxi"
(Taxi driver)

Hydrogen-diesel vans ▼

"The hydrogen technology powering Commercial's vans currently offers best-in-class carbon emissions without significantly affecting range or payload requirements. Being able to offer a hydrogen-powered delivery service …is a key differentiator in the stationery market place."
(Simone Hindmarch-Bye, Director of Commercial Group)

Fuel cell cars ▶

Toyota Mirai

"Passenger feedback is always positive because it's so quiet, it's really comfortable. My son calls it the muscle car because of the way it just takes off. It's really fantastic to drive"
(Theo Etrue-Ellis, Mirai driver for Green Tomato Cars)

Fuel cell combined heat & power ▼

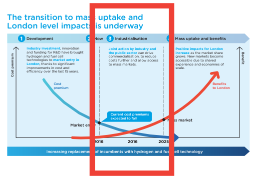
"Installing the UK's biggest in-house hydrogen fuel cell and signing up to the 10:10 commitment reinforces TfL's commitment to cutting carbon and improving our energy efficiency."
(Andrew Stanton, TfL's Head of Sustainable Buildings)

▼ Ecolite-TH2 fuel cell lighting tower

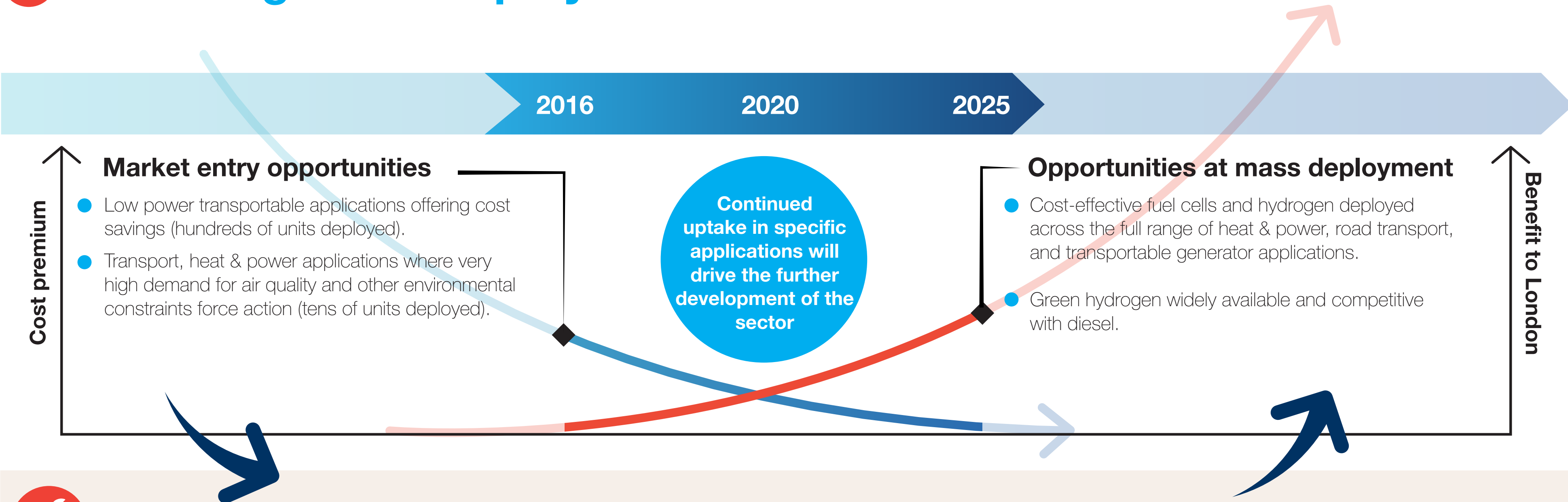
"The use of the Ecolite-TH2 lighting unit on our project has significantly enhanced our mission to protect the environment by reducing our carbon emissions and noise impact of work on Network Rail's lineside neighbours." (Geraldine Simak, Environmental Manager for Costain)

◀ Hydrogen stations

"Refuelling with Hydrogen is as easy and as quick as a petrol or diesel car… topping up with Hydrogen gives you another 220 miles in less than 5 minutes."
(Luke Tan, FCEV driver)



3 Achieving mass deployment in London

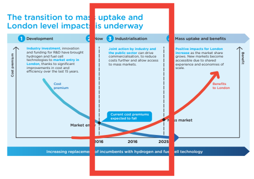


London's toolkit to drive commercialisation

Develop a 4 year action plan, including:

- Help facilitate early product deployment projects.
- Use the London Plan to ensure that policy is inclusive and references the potential of hydrogen and fuel cells to help meet London's targets.
- Support Greater London Authority family organisations in adopting more hydrogen and fuel cell technologies.
- Encourage other public and private users to be early adopters, using London's influence and networks.

Heat & Power	• Enforce air quality regulations for distributed generation via the planning system. • Promote the reliability and air quality benefits of fuel cells for power (and heat).
Road transport	• Use the Ultra Low Emission Zone to stimulate zero-emission vehicle uptake. • Conduct high profile trials for new segments (e.g. heavy vehicles); joint procurement to reduce costs (e.g. fuel cell buses). • Increase demand around existing stations and work with industry on strategic deployment of new stations.
Transportable generators	• Use the Low Emission Zone for non-road mobile machinery to introduce new regulations for generators e.g. mandate zero emissions for remote, low power applications; incentivise zero emission options for larger generators.



3 Hydrogen and fuel cells in other world-leading cities

Achievements to date (early 2016)

Future plans

Tokyo

Achievements to date:

- Tens of hydrogen stations, hundreds of fuel cell vehicles
- Local subsidies for microCHP have led to many tens of thousands of units deployed, driving cost reductions

Future plans:

- Target: 6,000 fuel cell vehicles and 35 hydrogen stations by 2020
- 10,000 fuel cell vehicles and 80 hydrogen stations by 2025
- 2.5 million microCHP units in Japan by 2030

California (Los Angeles, San Francisco, San Jose)

Achievements to date:

- Ten hydrogen stations, hundreds of fuel cell vehicles, trials of hydrogen hybrid trucks
- Fuel cells have access to state combined heat & power incentive scheme; over 100 MW of stationary fuel cells installed

Future plans:

- Zero Emission Vehicle Program – sales targets for battery electric vehicles and fuel cell vehicles signed into law: >50,000 fuel cell vehicles expected by 2020
- Up to 100 hydrogen stations to be built by 2024

London

- 3 hydrogen stations, with more planned for 2016
- 8 fuel cell buses, 15 fuel cell vehicles from global OEMs, 10 hydrogen-diesel vans
- 3 large-scale fuel cell combined heat & power plants (largest number in one European city – combined total of c.1MW)
- Hundreds of unsubsidised portable power units sold

NOW:
opportunity for London to define clear goals and remain a leading world city for these technologies

New York

Achievements to date:

- 15 MW of fuel cells for heat & power
- State grant and loan programmes; tax incentives and renewable portfolio standards

Future plans:

- Targeted 543–724 MW of fuel cells for heat and power by 2025
- State incentive programmes are planned for fuel cell transport as well as heat & power

Copenhagen

Achievements to date:

- Tens of fuel cell vehicles, 3 hydrogen stations (9 in total in Denmark)
- 50–100 fuel cell microCHP in homes across Denmark

Future plans:

- The city aims to be carbon neutral by 2025
- Targeted 185 hydrogen stations in Denmark by 2025

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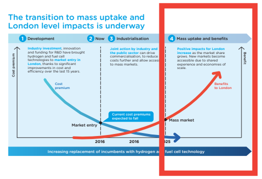


4 Delivering major positive impacts across London

Benefits to London will accrue over time as the market share of hydrogen and fuel cell technologies increases

2025

Growth
Strong hydrogen skill-base and increased employment in London

Environment
Hydrogen and fuel cells bring local air quality improvements by displacing diesel in thousands of cars, hundreds of buses, and thousands of transportable generators, and displacing gas combustion in hundreds of fuel cell CHP installations

Resilience
Locally produced hydrogen widely available and competitive with diesel, bringing energy resilience

Benefits accrue

2050

Environment
Hydrogen vehicles deliver 15–50% reduction in transport CO_2 (vs 1990)

Zero carbon from heat and power, including hydrogen supplied via gas grids, and hydrogen fuel cell CHP taking a significant market share

Clean air across London; fuel cells a key contributor (e.g. construction emissions vastly reduced through use of fuel cell generators)

Growth
Jobs and economic growth for London as a result of local fuel production and specialised maintenance skills

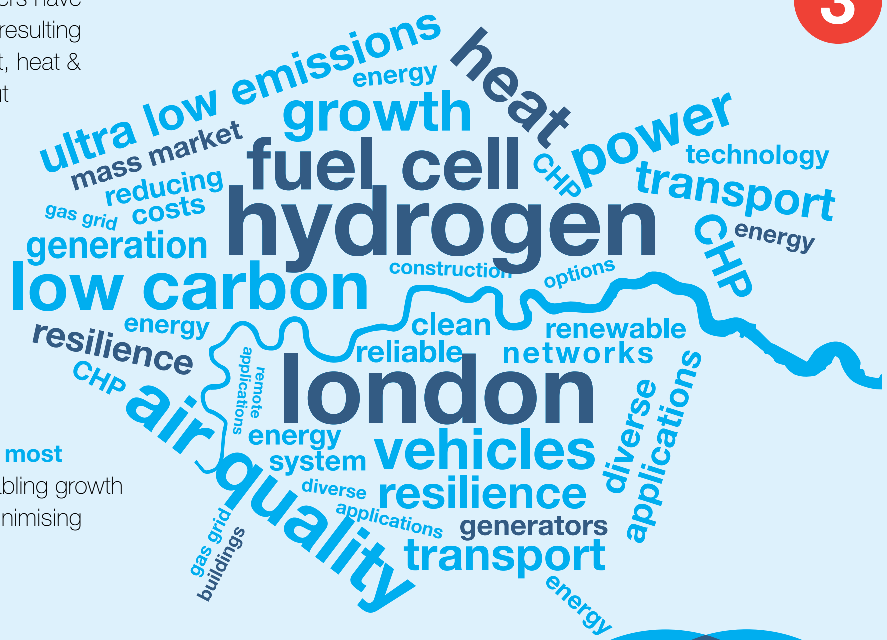
Resilience
Hydrogen as a competitively priced, locally produced, low carbon fuel

Increasing replacement of incumbents with hydrogen and fuel cell technology

A call for leadership to address London's challenges

1 **London is already recognised as a major global platform** implementing and showcasing the capabilities of hydrogen and fuel cells. Hydrogen London members have used London as a proving ground, resulting in sustainable solutions for transport, heat & power that are ready to be rolled out across the city.

2 The technology has the potential to provide **solutions to London's most critical energy challenges** – enabling growth while improving quality of life and minimising environmental impacts.



3 To realise this vision, the Hydrogen London industry partners invite the Mayor of London and the Greater London Authority to work alongside them to take the **decisive strategic actions needed to deliver successful technology outcomes for London** into the next decade and beyond.

- **Develop** an updated hydrogen action plan for London with Hydrogen London partners.
- **Support the inclusion** of hydrogen and fuel cells within the London Plan and other strategic documents, recognising their potential impact on London's challenges.
- **Make London a leading city** by encouraging early adoption of hydrogen and fuel cell vehicles across the GLA family fleets.
- **Encourage** others in London to engage with the technology, using the GLA's influence, networks and ability to organise partners within London.

Glossary

Hydrogen

- Hydrogen is a very common element. It does not occur naturally as a gas on Earth and is generally combined with other elements (e.g. carbon (as in hydrocarbons) or oxygen (to form water)).
- While it is not a primary source of energy, hydrogen is an energy carrier and can therefore be used as a fuel. Transporting hydrogen (e.g. via gas networks) in order to move energy to its point of use provides an alternative to using electricity networks.
- Pure hydrogen can be obtained from hydrocarbons via the application of heat (reforming), by passing electrical current through water (electrolysis), and from a number of other processes.
- There are a number of low carbon routes to produce hydrogen, including electrolysis using renewable electricity and reformation of biogas.
- Hydrogen has been used as an industrial gas for decades, which means methods to safely and efficiently produce, distribute, store and use hydrogen are mature.
- The versatility of hydrogen as a fuel makes it a good candidate to replace fossil fuels in a range of applications – it can be combusted in an engine or used in an electrochemical device (fuel cell) to generate electricity.
- Whether burnt or used to produce electricity, hydrogen fuel provides ultra low emissions (carbon and other) at the point of use.

Hydrogen storage (compressed gas)

Fuel cells

- Fuel cells are electrochemical devices that generate electricity (and water) from oxygen and hydrogen. Being based on a chemical process instead of combustion, fuel cells can operate at high efficiency and have ultra low / zero harmful emissions such as NOx and particulates.
- Various types of fuel cells exist, each with their own characteristics (power density, fuel flexibility, cost, lifetime, etc.).
- Fuel cells can therefore be used in applications with a wide range of energy and power requirements, from consumer electronics charging, to powering vehicles, to providing heat, cooling and electricity for buildings.

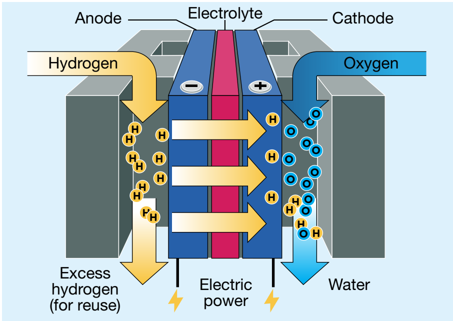


Diagram of a typical fuel cell

Introduction

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Overview

This report shows how hydrogen and fuel cell technologies can help solve some of London's major environmental and energy issues

- This report was commissioned by Hydrogen London to:
  - Illustrate the ways in which hydrogen and fuel cell technologies can help solve some of London's most pressing challenges.
  - Provide evidence to support the case for continued investment in HFC technology in London by public and private sector organisations.
  - Communicate the benefits of these technologies to a wide audience, including those not familiar with the sector.
- The report has benefited from input and evidence provided by Hydrogen London members, alongside further evidence from literature and the wider industry experience.

Some of Hydrogen London's major projects

CCHP = combined cooling, heat and power; CHP = combined heat and power; FCEV = fuel cell electric vehicle; HRS = hydrogen refuelling station; ICE = internal combustion engine; MCFC = molten carbonate fuel cell; OEM = original equipment manufacturer; PAFC = phosphoric acid fuel cell

Report scope and structure

This project considers applications for hydrogen and fuel cell technologies in three main areas:

Transport	Transportable	Stationary
Passenger cars, vans, taxis, buses, other vehicles and vessels	Remote monitoring (CCTV, environmental sensors etc.), remote lighting, leisure applications	Combined heat and power (large scale and domestic), prime power, UPS and standby power











Report structure

- The following section gives an overview of the policy context in London and describes some of the cross-sector benefits associated with the hydrogen economy that could accrue in the medium to long term as the technology gains access to mass markets.
- The subsequent sections present the arguments and evidence for continued deployment of hydrogen and fuel cell technologies in each of these three main application areas.

CCTV: closed-circuit television, UPS: uninterruptable power supplies.

Policy context and cross-sector benefits of hydrogen and fuel cells

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London's policy challenges: growth, access, and liveability

Most available technologies lead to tensions between growth and achieving environmental goals

London Infrastructure Plan 2050

SPACE-CONSTRAINED GROWTH

Emissions need to be cut dramatically despite accelerated population growth

Growth demands ***investment and optimal land use across health, housing, education and energy services***

Many low emission technologies are not space efficient

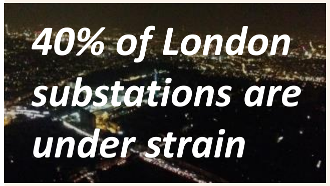
Total energy demand will increase by up to 20% by 2050

STRONGER, RESILIENT ENERGY NETWORKS

Energy network upgrades (gas, electricity) are expensive and can cause congestion and delays to developments

25% of heat and power demand to be met from local generation by 2025

Increased energy security needed to support London's growing economy



Commercial buildings need secure electricity and heat: decentralised energy needed to avoid costly upgrades to the electricity grid

GROWTH

ENVIRONMENT

Air Quality Strategy

CLEANER AIR FOR LONDON

National Air Quality Objectives *will not be met until 2025 under current measures*

Delivering the ULEZ *& the* ***LEZ for NRMM*** *will require a range of ultra-low emission technologies across transport & construction*

Traditional options for decentralised electricity generation produce local pollution – particularly energy from biomass/waste

Climate Change Mitigation and Energy Strategy

AVOIDING CLIMATE CHANGE

Converting the fleet of ***2.6 million cars registered in London*** *to low carbon fuels will be essential to achieve London's climate goals*

Emissions reductions urgently needed in all sectors *– heating and transport particularly hard to address*

Electrifying transport, heat and power in order to decarbonise increases pressure on strained electricity networks

NRMM: non-road mobile machinery, ULEZ: ultra low emission zone

Hydrogen and fuel cells offer holistic solutions

Hydrogen: **an energy carrier which can be made from a range of low carbon sources; easily stored and transported**
Fuel cells: **efficiently produce power and heat from a range of fuels including hydrogen; low to zero emissions**

GROWTH

SPACE-CONSTRAINED GROWTH

*Fuel cells are one of the the most space-efficient ways to provide low carbon decentralised energy (**easily integrated into buildings**, vs solar & wind)*

*Zero-emission transport infrastructure with minimal traffic disruption during installation, minimal land use, and **no behavioural change needed** for car owners and other drivers*

ENVIRONMENT

CLEANER AIR FOR LONDON

*Fuel cell technology is already **reducing local emissions from NRMM** in some applications*

Fuel cell CHP: significant NO_x and PM reductions compared to combustion engines

*Hydrogen transport already offers multiple ultra low emission options, including **solutions for larger vehicles and longer journey distances**, e.g. longer bus routes*

STRONGER, RESILIENT ENERGY NETWORKS

*Hydrogen can be **produced affordably from a range of low carbon sources** outside London and transported into the capital as a new clean way to import energy*

*Fuel cells are a highly efficient decentralised generation technology and can **alleviate grid constraints***

*Hydrogen can be stored for long periods to **meet peak demand** (e.g. for heat supply)*

AVOIDING CLIMATE CHANGE

*Low carbon hydrogen can be produced from a variety of **local renewable sources** and used to fuel heat, transport and power*

*Electrolysers producing hydrogen in London could help support an electricity system with **increased renewable generation***

*Hydrogen can be used in the gas grid to progressively convert to **zero carbon heat***

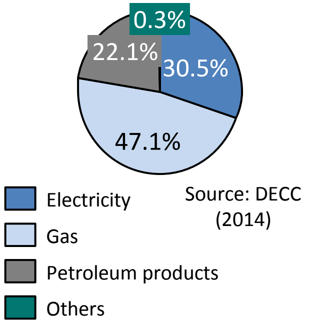
NRMM: non-road mobile machinery, CHP: combined heat and power, PM: particulate matter.

In the long term hydrogen could play a role in supporting the decarbonisation of electricity and gas supplies

London's growing population will put increasing pressure on energy infrastructure

- Population growth forecasts for London suggest that the total number of people living in the capital could grow to over 10m by the late 2020s (a 20% increase on 2012 levels).*
- This will put increasing pressure on London's electricity networks, particularly in the context of a focus on electrifying demands such as heating and transport as part of the UK's decarbonisation strategy.**
- The majority of London's energy needs are currently met via the gas network (see chart). Finding ways of continuing to use this asset in a low carbon future will be an important element of providing affordable, secure energy supplies while meeting decarbonisation targets.

Energy consumption in London by fuel (2012)



Others = coal, manufactured fuels, bioenergy and waste

Hydrogen and fuel cell technologies can help address these issues

Short term

- Fuel cells are an efficient means of generating electricity (and heat) locally and can provide meaningful reductions in greenhouse gas emissions even when fuelled by natural gas.
- Natural gas-fuelled stationary fuel cells currently available can be used at a range of scales and in various building types (see following sections).

Long term

- Hydrogen can be used as a low carbon fuel and is therefore a viable option for decarbonising heat supplies.
- Hydrogen could be transported using existing gas distribution systems, ensuring longevity of this infrastructure (see following slide).
- Fuel cells running on pure hydrogen offer even higher efficiency (compared to methane-fuelled systems).

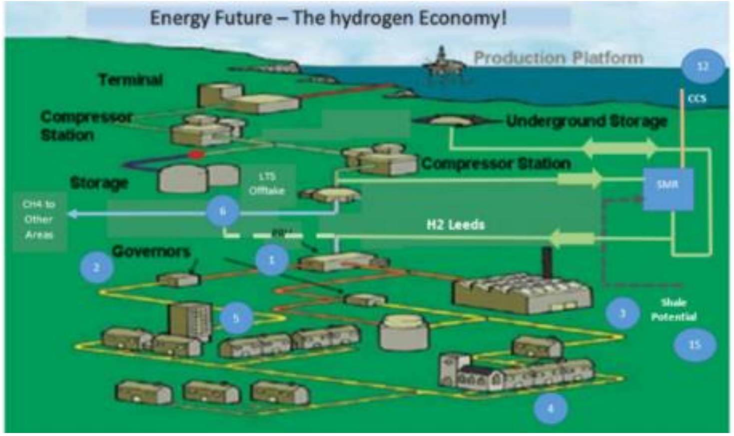
Time

* Source (ONS). ** The existing pressure on London's electricity distribution system manifests itself through very high charges for new connections. These types of issues are being studies in detail as part of on-going work on developing London's Energy Plan.

There are two main concepts for using low carbon hydrogen to decarbonise gas grids

1. Low carbon hydrogen from conventional fuels

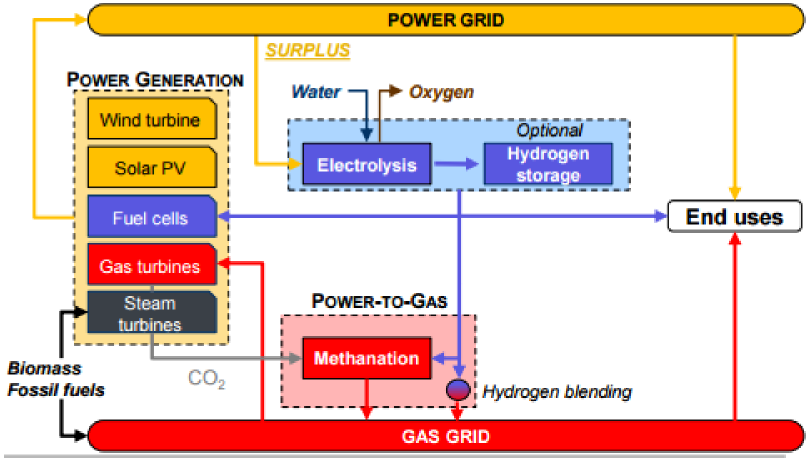
- Longer term, low carbon H2 can be used in 100% hydrogen pipelines bringing a new fuel to London.
- This hydrogen can be sourced from a number of large scale low carbon production technologies (e.g. using nuclear power or fossil fuels with carbon capture & storage).
- There is growing interest in this concept as a way of prolonging the life of the gas network in a low carbon future. E.g. the **H21 Leeds City Gate** project being led by Northern Gas Networks, which is investigating the feasibility of redesigning existing gas networks to accommodate injection of hydrogen.*



Source: *D Sadler, Northern Gas Networks*
www.praseg.org.uk/docs/PRASEG%20EVENT%20NGN%20SLIDES%20dan%20sadler.pdf

2. Low carbon hydrogen from power-to-gas

- Power-to-gas (P2G) involves converting excess renewable electricity into hydrogen and injecting it into gas networks.
- P2G offers promise as the link between the two main existing energy carrying systems (natural gas and electricity grids).
- A positive economic case for P2G will require a number of factors: very low (possibly negative) electricity prices at times of high generation and low demand, technology cost reductions and efficiency improvements, etc.



Source: *Hydrogen-based energy conversion*, SBC Energy Institute, Figure 110, p.103 (2014)

This study (for London) considers the period to 2025, hence the focus (in terms of the stationary sector) is on natural gas-fuelled fuel cells as part of a broader process of transitioning to this type of longer term hydrogen vision.

* See www.smarternetworks.org/Project.aspx?ProjectID=1630.

Mass uptake of hydrogen and fuel cell technologies will unlock increasing benefits for London

Broad energy system benefits unlocked when hydrogen is integrated throughout the energy economy

- Hydrogen supplied for heat & power through diverse supply routes (gas pipelines, onsite generation, freight delivery)
- Opportunity to meet London's growing energy demands without over-reliance on electricity networks
- Low emission transport with minimal land use impacts
- Inherently flexible generation from electricity and other low carbon sources

Significant impacts at London level

Full range of commercial applications

As costs fall, emissions savings will accrue from hydrogen in transport and fuel cells for heat and power

- Vehicle commercialisation brings greater demand for hydrogen
- Business models for hydrogen production and trading become established
- Gas fuel cells for heat and power drive fuel cell cost savings
- Reduced construction emissions through adoption of fuel cell generators

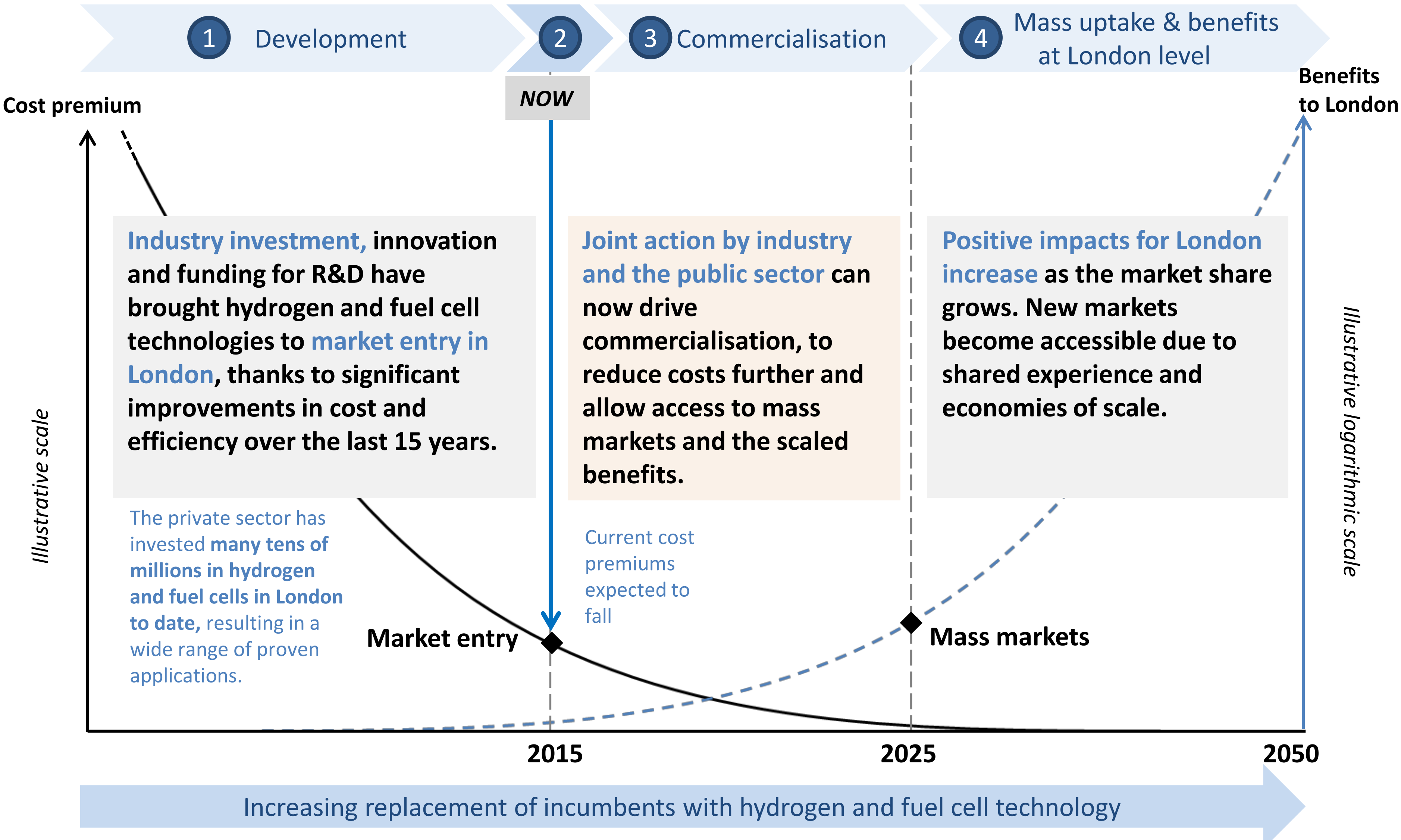
Early commercial opportunities

Local level impacts

Local benefits are already being achieved in applications across London

INCREASING SCALE OF IMPACTS

To ensure that the benefits for London are delivered at scale, joint action to accelerate uptake is needed today



Solving transport sector problems with hydrogen and fuel cell technologies

Focus on transport applications

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Overview: how hydrogen and fuel cells can address the major transport policy challenges

The key challenges:

DECARBONISATION

- **Road transport** contributes c.15% of overall CO_2 emissions in London (LAEI 2010).
- To achieve London's targets, transport CO_2 must be reduced by at least 4.6 Mt by 2025 (from 1990 levels). **Projections based on existing measures predict only a 1 Mt reduction by 2025**.

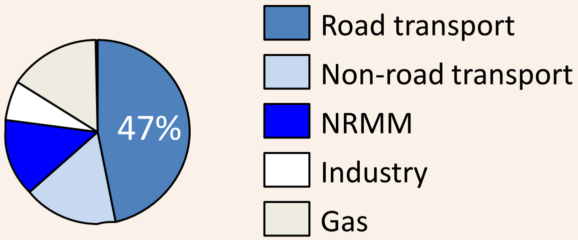
Sources of CO_2 emissions in London (LAEI 2010)

- Cars alone account for 49% of transport CO_2 emissions in London, and the transition to a low carbon fleet presents a significant challenge.

AIR QUALITY IMPROVEMENT

- Around 47% of overall NO_x and PM_{10} emissions in Greater London come from **road transport** (LAEI 2010).
- Projections based on existing measures indicate that **national air quality objectives will not be met until at least 2025**.

Sources of NO_x emissions in London (LAEI 2010)



- Heavy goods vehicles and buses are key contributors in the worst affected areas, so ultra low emission options are needed to drive improvements.

Overview: how hydrogen and fuel cells can address the major transport policy challenges

The solution:

- Hydrogen vehicles have **ultra low emissions,** can refuel quickly and can drive long distances, making them suitable for a wide range of applications; **hydrogen cars, vans, taxis, private hire vehicles and buses** have already been used successfully in London and will be an important part of a future ultra-low emission fleet.
- Fuel cell mobility: **zero harmful emissions** at point of use; hydrogen combustion mobility: ultra low emissions.
- If 50% of miles driven by light vehicles in the ultra-low emission zone (ULEZ) were from zero-emission capable vehicles (including hydrogen vehicles) this **could reduce overall NO_x emissions in central London by 10–15%.**
- **Zero tailpipe CO_2 emissions and very low CO_2 emissions on a well-to-wheel basis** are possible when using hydrogen produced from renewable energy sources.
- With a range comparable to diesel/petrol cars, fuel cell electric cars (FCEVs) are the **ideal ultra low emission option for London car owners**, many of which buy cars to enable travel outside of London.

The following slides will show that the benefits of hydrogen transport can be achieved in London

Key arguments for hydrogen and fuel cells in transport

Hydrogen and fuel cells can address key challenges relating to transport in London

1. Hydrogen vehicles offer many benefits to London, including the potential to fully decarbonise transport, eliminate harmful local emissions, and link the renewable energy and transport sectors. These benefits will only accrue at scale following successful commercialisation of the technology. Evidence
2. London has positioned itself as a key early market for hydrogen vehicles, including passenger cars, buses, and commercial vehicles. A number of models are available now and more are coming to market. Evidence
3. Fuel cell electric vehicles (FCEVs) can directly replace diesel and petrol vehicles in London across a range of applications and vehicle types. Feedback from early adopters of FCEVs has been positive. Evidence
4. A compelling ownership cost case for hydrogen-fuelled vehicles is already available for some end users today and before 2030 hydrogen vehicles will be as affordable as other drivetrains. Evidence
5. Infrastructure will be affordable at scale and there is a clear strategy for rollout in London, which has already begun. Evidence
6. When made from electricity via water electrolysis, the production of hydrogen can act as a responsive source of demand and thus can support an electricity system with increasing levels of renewables. Evidence
7. Hydrogen refuelling facilities can be integrated with existing refuelling infrastructure, providing a non disruptive, space efficient infrastructure for ultra low emission transport and giving customers an equivalent user experience to existing fuels. Evidence

Presenting the evidence

1 *Hydrogen vehicles offer many benefits to London, including the potential to fully decarbonise transport, eliminate harmful local emissions, and link the renewable energy and transport sectors.*

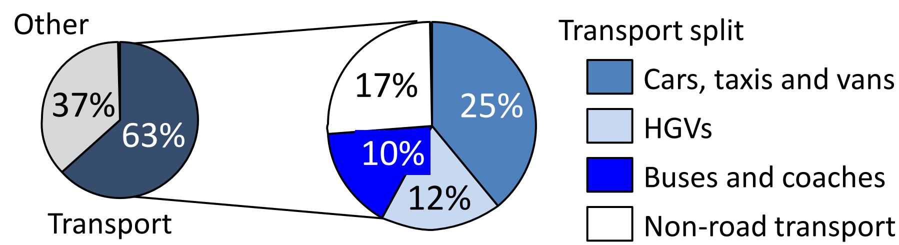
See all arguments

1 Transport NO_x and PM emissions in London must be cut across all vehicle segments to reduce air pollution to safe levels

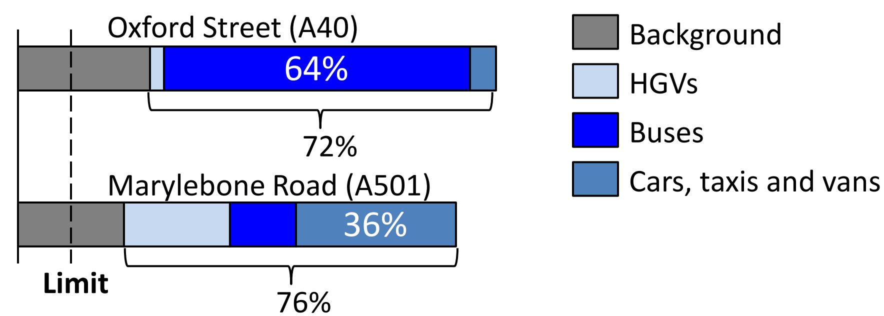
Emissions in London by source

- European legal limits for NO_2 are currently exceeded in Greater London and some sites across London continue to record high levels of particulate matter.[1]
- **Road transport contributes around 47% of NO_x** in London, of which NO_2 is a major constituent. The NO_x share from road transport can be >70% on roads with the most severe air quality problems (e.g. Marylebone Road and Oxford Street).[2]

Sources of NO_x emissions in London (LAEI 2010)[1]



Annual mean roadside NO_x by source as NO_2 (µg/m³) on roads in central London (2013)[2]



Limit value (40 µg/m³) is c.10% of current levels on these roads

Current projections suggest that London will only achieve compliance with NO_2 limits by 2025

- Emissions need to be cut across all vehicle segments to achieve compliance with NO_2 limits. Recent Defra modelling indicates will not be met by 2025, and only with significant additional intervention.[2]
- Due to variations in emissions at different speeds, the NO_2 contribution from diesel vehicles on urban roads may be even higher than current estimates suggest, making the required reductions even more challenging.

1 - Transport For London, Transport Emissions Roadmap, September 2014

2 – Defra AQ Plan for the achievement of EU AQ limit value for NO2 in Greater London, September 2015

1 Increased uptake of hydrogen vehicles in areas of poor air quality can accelerate emissions reductions

Hydrogen fuel cell vehicles have zero tailpipe emissions and will help alleviate air quality issues

The only emission from pure hydrogen vehicles (such as FCEVs) is water vapour, and therefore replacing diesel or petrol vehicles with FCEVs would deliver a 100% reduction in vehicle emissions.

Light vehicles

- If 50% of miles driven by light vehicles within the ultra-low emission zone (ULEZ) were from zero-emission capable vehicles (including hydrogen vehicles) this could **reduce overall NO_x emissions in central London by 10–15%.**

- In light of the failure of Euro standards to deliver the targeted emissions reductions for light vehicles, the uptake of zero emission capable vehicles will be important to help achieve the required emissions reductions.

1 Increased uptake of hydrogen vehicles in areas of poor air quality can accelerate emissions reductions

Hydrogen fuel cell vehicles have zero tailpipe emissions and will help alleviate air quality issues

Heavy vehicles

- Significant emissions reductions for heavy vehicles will come from uptake of Euro VI diesel vehicles, which offer significant reductions compared to the current fleet.
- However, uptake of hydrogen buses on routes with particularly bad air quality will accelerate the process of achieving compliance with air quality objectives.
- Freight makes a significant contribution to NO_x and PM, and the options for zero-emission trucks are currently restricted in terms of payload and capacity. Trials of hydrogen fuel cell trucks in the US and China suggest that this could be a viable way to reduce freight emissions in future.

Conversion to hydrogen-diesel dual fuel provides a low emission option for vans and trucks today

- ULEMCo’s Ford Transit conversion to hydrogen and diesel dual fuel is the only existing alternative fuel option in the 1.8–3t van category, and recently qualified for a 100% Congestion Change discount. The conversion is also an option for trucks, with a refuse truck trial ongoing in Scotland.

1 There is a diverse range of production routes for hydrogen which can produce a near zero CO_2 fuel for mobility

Hydrocarbon-based production

- The **most common form of industrial H_2 production** today.
- Involves reforming methane (SMR) 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 decarbonised 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.

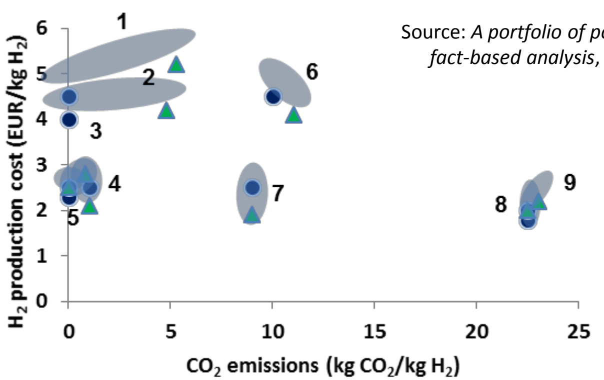
Several suppliers based in the UK

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[1]



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

(Technical targets to reduce carbon footprint of hydrogen as a transport fuel)

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 (combined cycle gasification)
9. Coal gasification

Other options at lab stage include direct generation from the sun and from nuclear heat

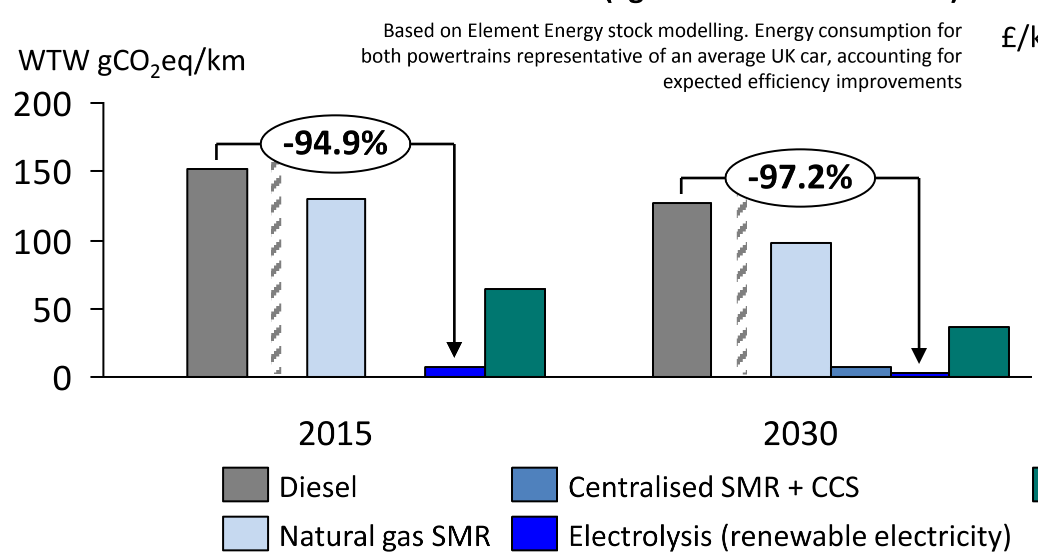
* Partial oxidation is another method of producing hydrogen from hydrocarbons. See http://energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming.
CCS = carbon capture and storage, SMR = steam methane reforming 1 Assumes access to green electricity for electrolysers

1 On a well-to-wheel basis, these low carbon pathways could deliver up to 97% reduction in CO_2 emissions compared to diesel vehicles

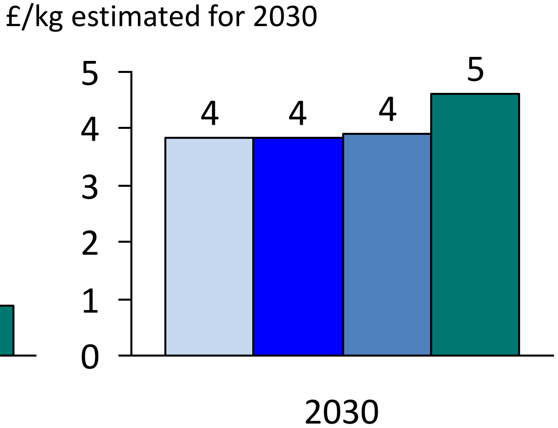
Hydrogen production routes will become "greener" and more affordable as demand increases

- Renewable pathways to hydrogen production are currently more expensive than other routes but costs are expected to fall as demand increases.
- Emissions associated with various hydrogen production pathways **(below left)** are expected to reduce in the future, as both electricity and heat required as part of these pathways are expected to be decarbonised.

Indicative GHG emissions for a fuel cell car (against diesel benchmark)



Estimated production costs for hydrogen in 2030



Based on:
FCH JU Green Hydrogen Study, McKinsey & Co Power-trains for Europe

Assumptions
1 EUR = 1.3 GBP

- The next wave of hydrogen refuelling stations to be opened in London will include on-site production using water electrolysis. When using electricity from renewable sources this production method can yield very low carbon hydrogen. Electrolysers are also modular, scalable, and remove the need for hydrogen logistics.

NB: electricity for hydrogen compression and dispensing (including pre-cooling) is assumed to be sourced from the grid average mix, hence there are some CO_2 emissions associated with the renewable electrolytic route.

1 The next wave of hydrogen stations in London will produce fuel locally using renewable electricity, in line with national production mix plans

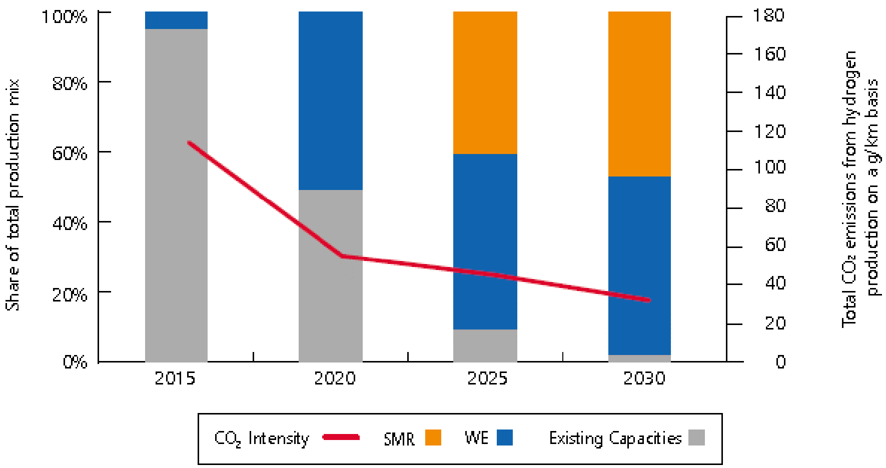
Hydrogen production plans in London / the UK – overview

HRS in London (operational / in build as of early 2016)

Funding is in place for a further five HRS in and around London (siting work is on-going), all of which will produce H_2 from renewable electricity.

Delivered H_2 (sourced from steam methane reformation)

On-site H_2 production using renewable electricity



Hydrogen production mix in UK H_2Mobility roadmap over time and resulting CO_2 emissions (g/km).

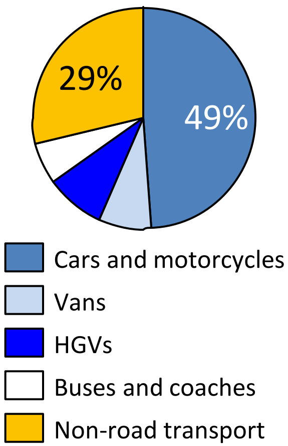
Source: UK H_2Mobility Phase 1 Results (2013), Figure 14, p.20.

- London's hydrogen refuelling station (HRS) network is expanding, and all of the new stations currently being planned (i.e. with funding in place) will produce low carbon hydrogen from renewable electricity.
- This is consistent with the vision of the hydrogen production mix at the national level developed in the UK H_2Mobility project, which would lead to FCEV emissions below around 50gCO_2/km from 2020, compared to a fleet average for conventional cars in excess of 100gCO_2/km at that point.

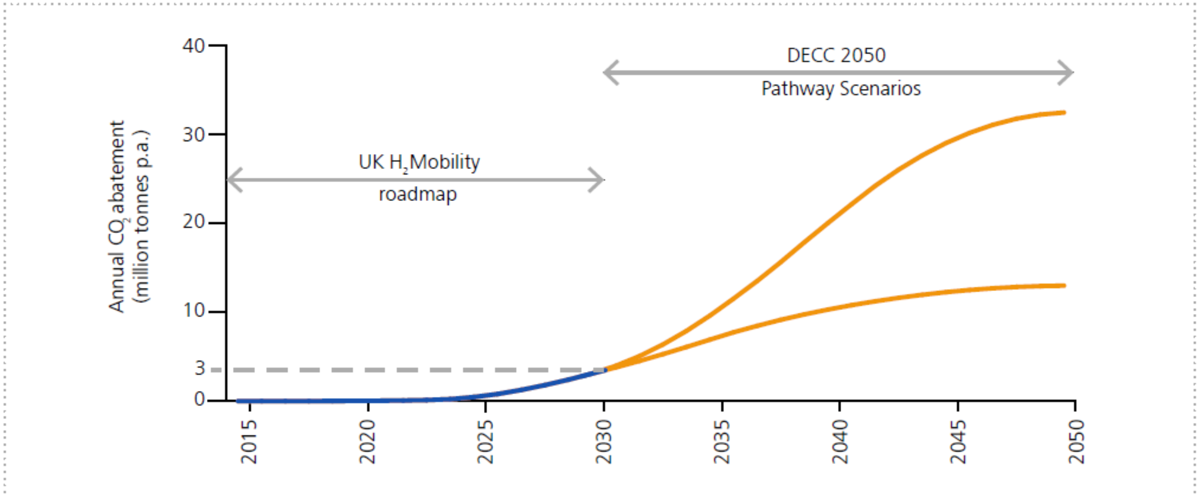
With a full infrastructure network by 2050, between 9% and 23% transport CO_2 savings could be achieved through uptake of fuel cell cars

Overall emissions savings will be largely dependent on the level of uptake of fuel cell electric cars

Although carbon emissions need to be reduced across all vehicle types, cars account for 49% of transport CO_2 emissions in London (with only 22% from other road transport segments) and therefore overall emissions reductions are strongly linked to the level of uptake of fuel cell cars.



Sources of CO_2 emissions in London (LAEI 2010)



Annual CO_2 savings to 2030 delivered by the UK H_2Mobility roadmap would put the UK on the right trajectory to meet DECC's CO_2 targets for 2050. Source: UK H_2Mobility Phase 1 Results (2013), Figure 15, p.23.

By 2030

- If c.110,000 diesel cars are displaced by fuel cell cars in London, this would deliver 2% annual CO_2 savings to the London transport sector, compared to a 1990 baseline.

By 2050

- Annual CO_2 savings to the London transport sector from fuel cell cars could range between 9% and 23% from a 1990 baseline (for 0.5 million – 1.2 million displaced diesel cars).

Calculations based on projections in UK H_2Mobility phase 1 report (2013).
Emissions data: Transport For London, Transport Emissions Roadmap, September 2014.

2 *London has positioned itself as a key early market for hydrogen vehicles, including passenger cars, buses, and commercial vehicles. A number of models are available now and more are coming to market.*

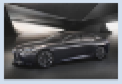
See all arguments

Fuel cell vehicles (FCEVs) from Hyundai (2014) and Toyota (2015) have been available in London for over a year, Honda's will arrive in 2016

2

Fuel cell electric vehicle availability from global OEMs – overview

- London is one of the launch markets for FCEVs from **Hyundai**, **Toyota**, and **Honda**.
- Vehicles from these OEMs will be available in low numbers initially while the market develops.
- Other car companies developing FCEVs include **Daimler** (Mercedes), **BMW**, **Nissan** (working in a collaborative partnership with Daimler and Ford), **General Motors** (collaborating with Honda), and **Volkswagen** / **Audi**.

Company	Target launch markets	Commercialisation dates (based on public announcements)			
		Pre-2015	2015–2016	2017–2018	2019–2021
Hyundai	South Korea, California (selected dealerships), Denmark, Sweden, Norway (Oslo), Italy (Bolzano), Germany, Austria, UK, Canada (Vancouver)				
Toyota	Japan, California (at 8 dealerships from autumn 2015), UK, Germany, Denmark				
Honda	Japan (from March 2016), followed by the US (California), and Europe within the following 12 months				
Daimler	Germany, California (others tbc)				
BMW	TBC				

Toyota recently announced its intention to release a fuel cell car under its Lexus brand in around 2020. See http://uk.reuters.com/article/us-autoshow-detroit-toyota-idUKKCN0UP22B20160111.

2 Fuel cell electric vehicle availability from global OEMs

- Vehicle OEM commercialisation plans involve producing low volumes of FCEVs initially while the refuelling infrastructure develops, followed by higher volume (lower cost) vehicles for a wider market in the medium term (post 2020). Therefore OEM FCEV uptake in London is likely to be low in the short term, but accelerate in the 2020s.

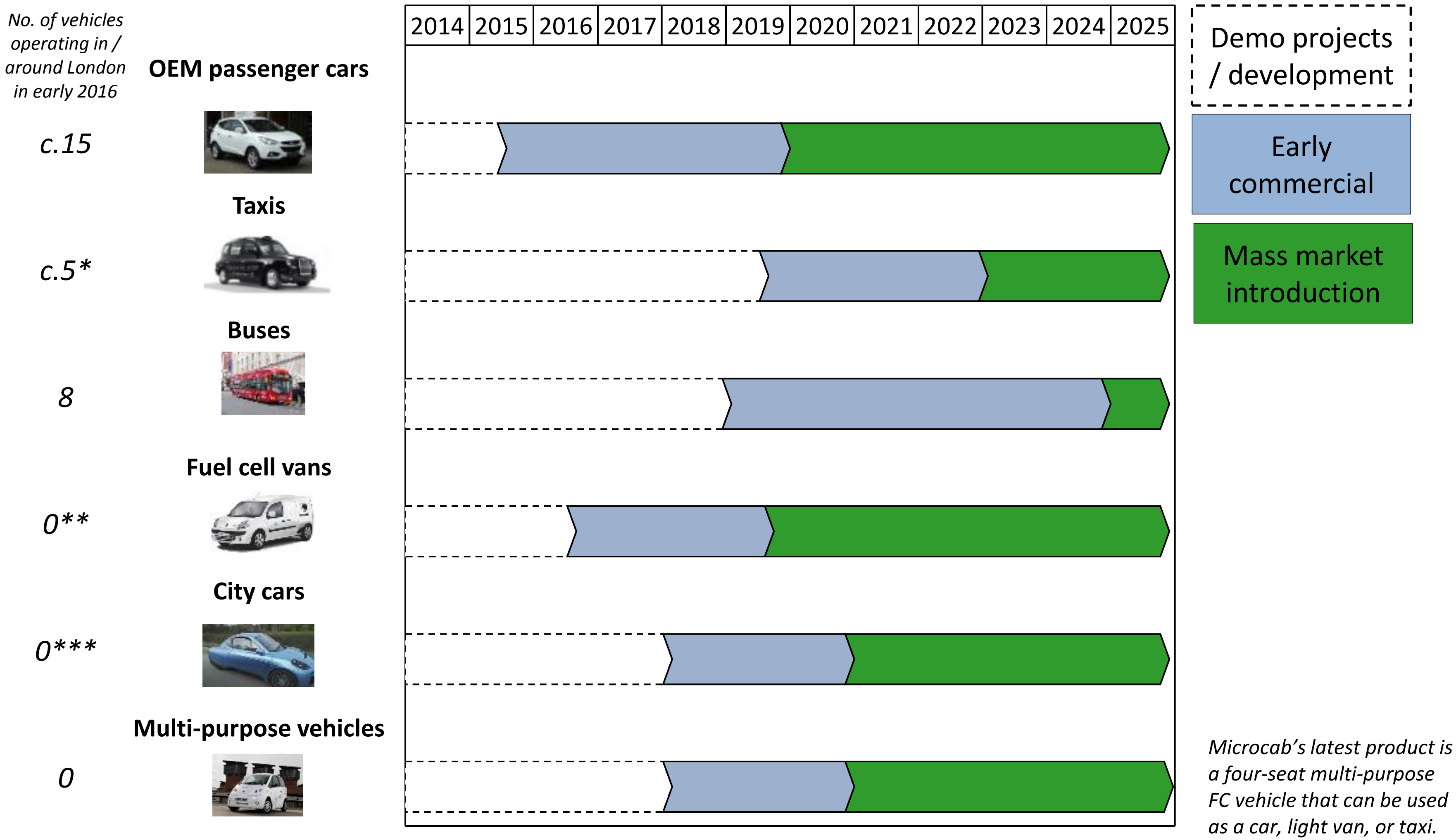
- The number of FCEVs deployed in London and the availability of vehicles from other OEMs will depend strongly on the success of UK stakeholders in **developing a fuelling network and policies that support uptake**. For FCEV deployment, OEMs will prioritise the cities that are the most successful in this respect, and London will face strong competition in Europe and worldwide.

- For this technology to be part of the solution to decarbonising transport and eliminating harmful emissions it is important to develop a refuelling network and implement the necessary support services.

Efforts to commercialise zero emission fuel cell electric vehicles in other segments are also underway

2

Fuel cell vehicle development – indicative commercialisation timelines



* No. of FC taxis that were demonstrated as part of the HyTEC project, which concluded in 2015. ** First wave of deployment of FC-RE vans in the UK planned for the coming years. *** Riversimple Rasa expected to be available from 2018.

2

Hydrogen can also be used in larger internal combustion engine vehicles

Hydrogen internal combustion engine vehicles – overview

- While fuel cells use hydrogen to generate electricity which in turn drives electric motors, hydrogen can also be used as a fuel in internal combustion engines.
- For example, ULEMCo can convert standard diesel vehicles to run on a combination of diesel and hydrogen. Although these vehicles still have some tailpipe emissions, substantial savings are possible relative to standard diesel vehicles and with low carbon hydrogen, CO_2 emissions can be reduced by over two thirds.
- Other advantages of this technology include:
    - Relatively low capital cost for conversion.
    - Dual fuel permits range of operating modes – no range anxiety as diesel can be used if hydrogen is unavailable.
    - Lower purity hydrogen can be used (compared to FC quality H_2).
- Real world trials suggest that dual fuel configurations can lead to efficiency improvements (fuel needed per unit distance (kWh/km)) for vans.
- Hybrid hydrogen-diesel combustion vans can qualify as ultra low emission vehicles and be eligible for 100% discount on the London Congestion charge.*
- This technology can be applied to a range of vehicle types: panel vans, box vans, Luton vans, refuse vehicles, etc. There are currently no other low emission drivetrain options in many of these segments.

* Qualifying criteria for ultra low emission vans: light goods vehicles not exceeding 3.5 tonnes that emit 75gCO_2/km or less and meet the Euro 5 emissions standard.

3 *Fuel cell vehicles can directly replace diesel and petrol vehicles in London across a range of applications and vehicle types. Feedback from early adopters of FCEVs has been positive.*

See all arguments

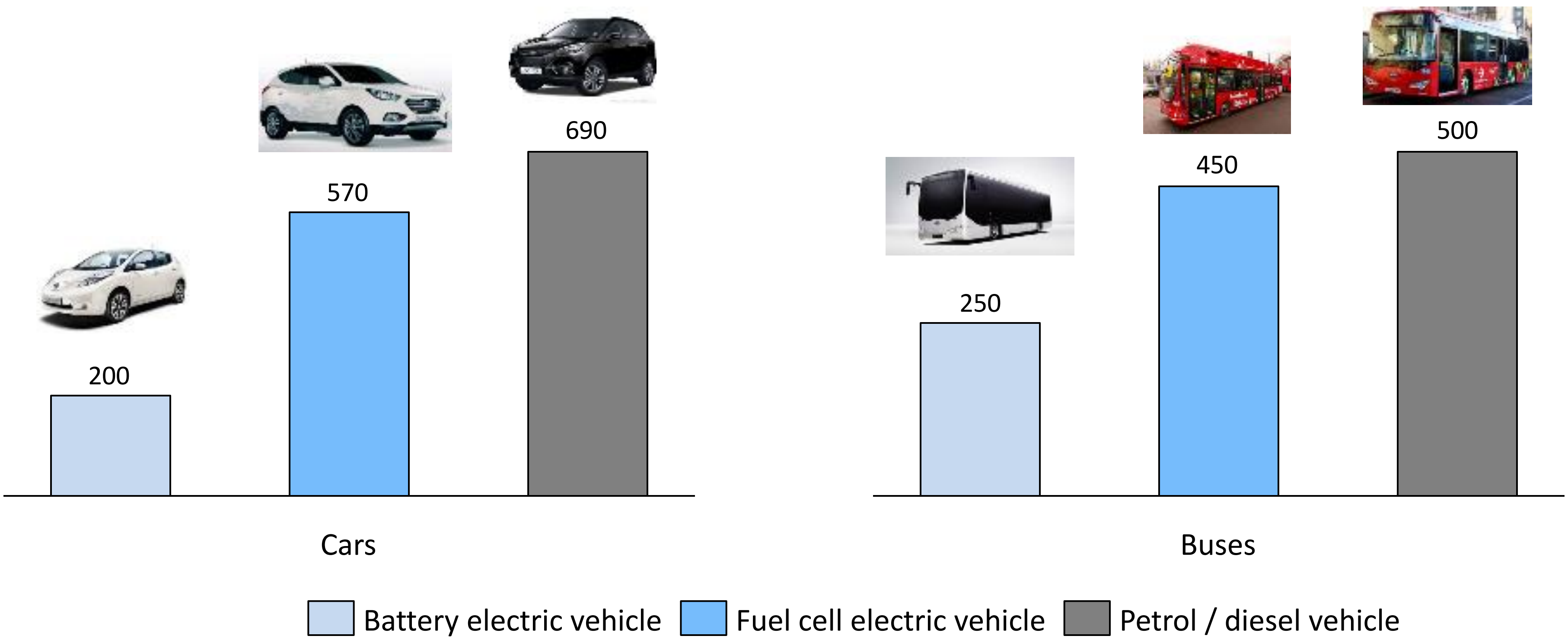
3

FCEVs offer ranges close to traditional petrol / diesel vehicles and are therefore a like for like replacement for existing vehicles

Driving range per tank of fuel – typical values for BEVs, FCEVs, and ICEVs

Typical maximum vehicle range (NEDC), km

Typical maximum vehicle range, km

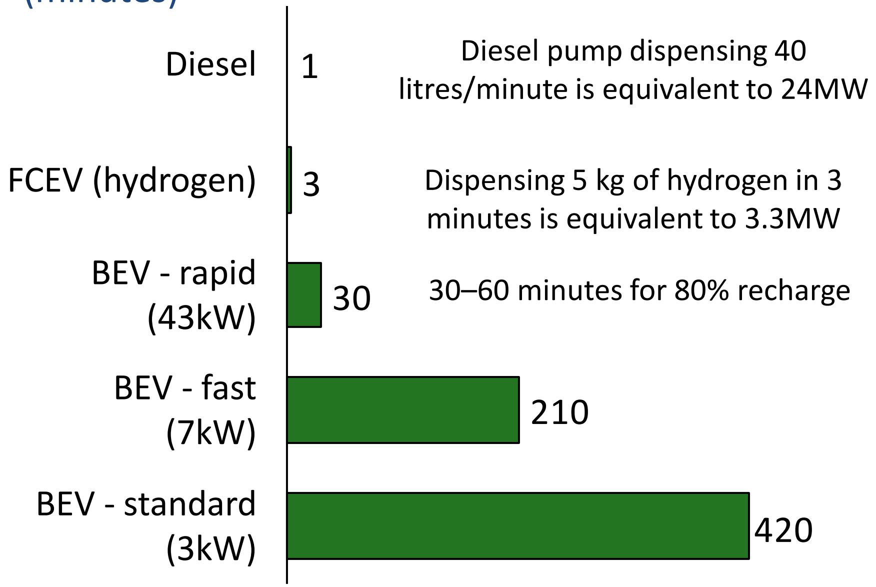


- Car ranges based on New European Drive Cycle test figures.
- Bus ranges based on manufacturer figures (e.g. the claimed range of the BYD e6 is 250+ km).

3 FCEVs can be refuelled in a matter of minutes, which is a major advantage over other zero emission transport options

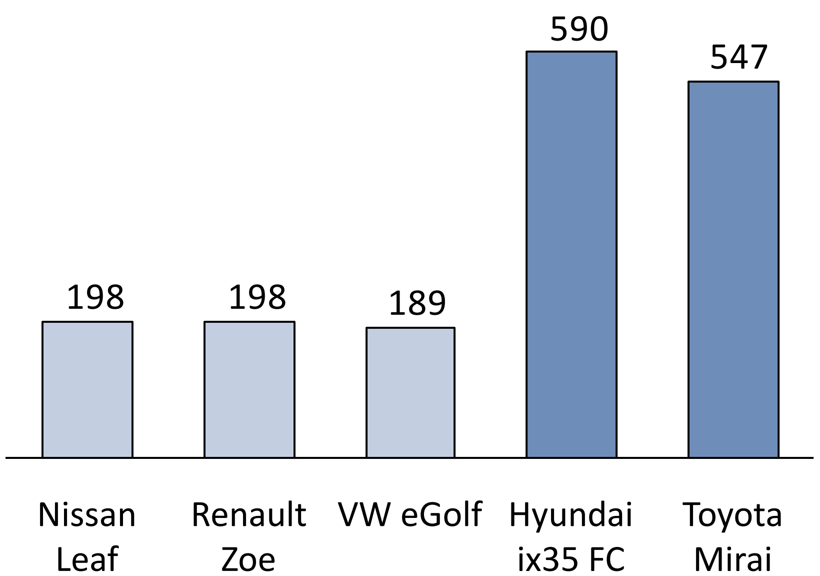
Typical refuelling times and passenger car ranges – summary

Time to refuel (minutes)



NEDC range of a selection of zero emission vehicles (km)

Source: OEM figures



- Refuelling times based on typical standards.
- Hydrogen-based transport systems offer very little compromise in terms of refuelling times compared to traditional fuels.

- Hydrogen-fuelled vehicles offer higher ranges than pure battery electric vehicles due to the relatively high gravimetric energy density of hydrogen (kWh/kg).

3

Hydrogen vehicles are already on the road in London and have been positively received by end users

Quotes from users of hydrogen vehicles in London

Fuel cell buses have been in operation on the RV1 route since 2011

"I think this is a great bus, very quiet, very comfortable to drive, people are loving it" (TfL Bus driver)

Fuel cell cars from Hyundai and Toyota are being used by Green Tomato Cars, Johnson Matthey and TfL

Toyota Mirai

- *"Passenger feedback is always positive because it's so quiet, it's really comfortable. My son calls it the muscle car because of the way it just takes off. It's really fantastic to drive"* (Theo Etrue-Ellis, Mirai driver for Green Tomato Cars)

Hyundai ix35 FC

- *"The Hyundai ix35 Fuel Cell car is a pleasure to drive, in cities and on motorways alike. It's quiet, smooth and responsive with the added bonus of being clean too."* (Luke Tan, FCEV driver)

Converted fuel cell taxis from Intelligent Energy were operated in London during the Olympics (London 2012)

- *"This is the quietest and most responsive vehicle I've driven since I started driving a taxi nearly 40 years ago. After a day's driving you do not feel fatigued by the constant drone that you normally get from a diesel taxi"* (Taxi driver)

Hydrogen-diesel vans are being used by Commercial Group for stationary deliveries

- *"The hydrogen technology powering Commercial's vans currently offers best-in-class carbon emissions without significantly affecting range or payload requirements."* (Simone Hindmarch-Bye, Director of Commercial Group)

4 *A compelling ownership cost case for hydrogen-fuelled vehicles is already available for some end users today and well before 2030 using hydrogen vehicles will be as affordable as other drivetrains.*

See all arguments

4 A model is emerging for the deployment of vehicles in captive fleets, which solves many of the early deployment problems

The captive fleet model could help solve some of the early deployment challenges

- In France a new model is emerging, which could also be useful in London. This has two components:
  1. An electric vehicle with a fuel cell range extender – this allows:
     - The use of a proven electric van (e.g. Renault Kangoo or Nissan ENV-200) as the platform for the development – this simplifies homologation, avoids new vehicle tooling costs etc.
     - The use of a relatively small fuel cell (5–10kW) and hydrogen tank, which reduces costs.
     - Two fuels (electricity and hydrogen) – which provides flexibility of fuel and helps optimise the ownership cost
  2. Deployment of these vehicles in large captive fleets based around a single new fuelling station:
     - An aggregated demand at a single station means some of the demand risk from constructing the station is removed, facilitating private investment in the station.
     - Early aggregated demand improves the economics of operating the station compared to station built with a very poor loading.

Intelligent Energy ENV-200 – available 2018

Symbio FCell – available now

Vehicles of this type are being developed by Intelligent Energy (UK) and are available for sale from Symbio (France), via Arcola Energy (UK).

This model is being actively pursued in France under the H_2Mobilité France project.

4 Total cost of ownership calculations are based on a number of technology cost and performance assumptions

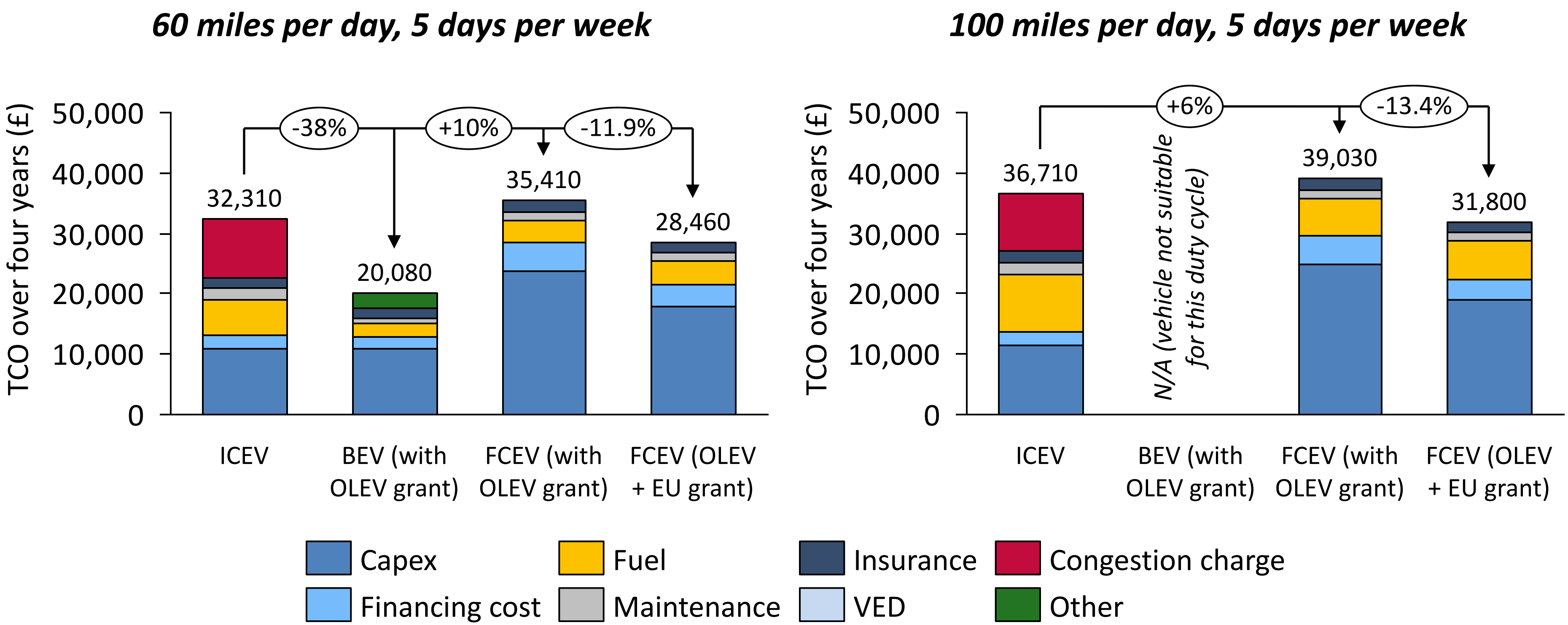
NB: Capex figures are for one-off vehicles. Volume orders could lead to significant discounts (even for modest volumes)	**Kangoo Diesel (ICEV)** 	**Kangoo ZE (BEV)** 	**Kangoo ZE Range Extender (FCEV)** 
Range (real world)	800 km	c. 100 km	c. 300 km
Capital cost (ex. VAT)	£14.9k	£17.1k	£37k
Capital cost after OLEV grant (ex. VAT)	£14.9k	£13k	£29.7k
Capex after OLEV + EU grant (ex. VAT)	£14.9k	£13k	£22.5k
Residual value after four years*	20% / 15%	5%	10% / 5%
Fuel consumption	7.5 litres/100km	25kWh/100km	15kWh/100km, 1kgH_2/100km
Fuel price (ex. VAT)	88 p/litre	10 p/kWh	10 p/kWh, £7/kgH_2
Maintenance	£550/yr	£180/yr	£400/yr
Insurance	£500/yr	£500/yr	£500/yr
VED	£30/yr	0	0
Other running costs	C-Charge: £2,730/yr	£60/month battery rental	0

Source: www.cdn.renault.com/content/dam/Renault/UK/brand-and-editorial/Brochures/Vehicles/kangoo-october.pdf .

* RV assumptions depend on mileage – higher mileage is assumed to lead to lower residual values.

For high mileage fleet applications in central London, the total costs for operating an FCEV are close to that of an ICEV (after grant funding)

Four year TCO for a van operating in the Congestion Charge zone on a daily basis



- For duty cycles involving daily mileages of over 100 miles per day and with users regularly operating in the Congestion Charge zone, the FCEV offers a compelling case, when grant funding is included.
- With higher capital and fuel costs, the FCEV is likely to come with a TCO premium over diesel vehicles, which can be closed in the short term with grant funding – longer term costs are expected to reduce by an amount which avoids the need for grant funding.

4

In addition to the direct emissions savings, delivering the zero emission captive fleet vision provides a range of wider benefits

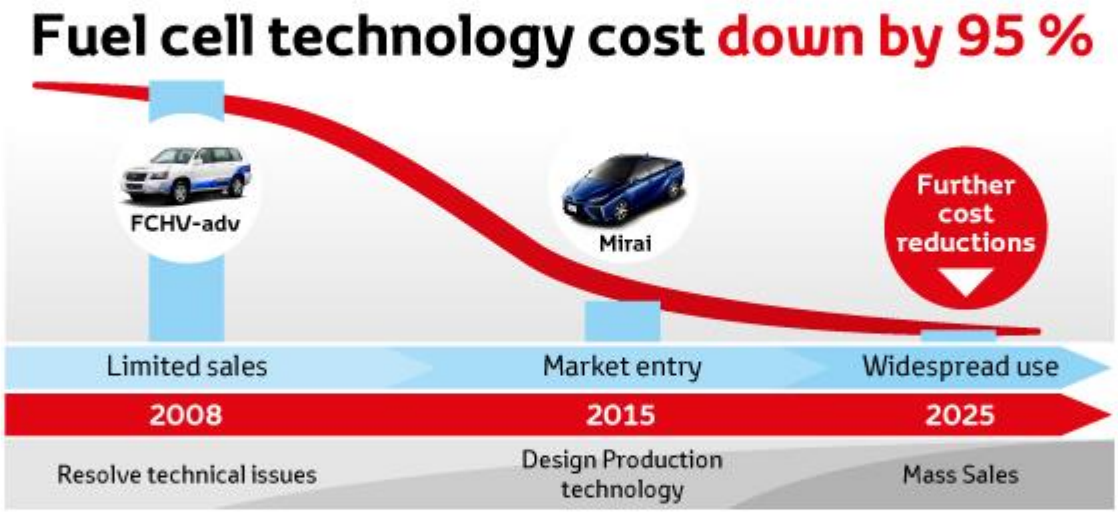
FCEVs in captive fleets – broader benefits

While the analysis above focuses on the total cost of ownership of individual vans, the broader vision for FCEVs in captive fleets involves deployment of multiple units in clusters that justify the installation of a hydrogen refuelling station. This offers a range of benefits, including:

- **Fuel security** – the ability to produce fuel on-site using renewable electricity gives a higher level of fuel security than relying on traditional liquid road fuels.
- **Greater control over fuel costs** – while vehicle operators have no ability to influence diesel prices, there is a more competitive market for electricity and supply contracts can be negotiated.
- **Driver health** – drivers of FCEVs and BEVs report a more comfortable ride, with less noise, vibration and emissions – this improves employee satisfaction and potentially health
- **Reputational benefits** – operating a zero emission fleet of vehicles may give companies a reputational / image benefit. In some cases this can have a quantifiable value, e.g. by allowing the organisation to win additional work on the basis of this differentiator.
- **Opportunity to supply fuel to other vehicles** – depending on the details of the site, HRS for captive fleets could supply other vehicles. This leads to additional revenue generating opportunities and is a useful contribution towards realising the vision of increased HRS coverage across London.

4 Once larger global volumes are achieved, vehicle costs will fall dramatically: a key example of this is the passenger car market

Component and hence vehicle costs are coming down with increasing production volumes



Current prices – Vehicle prices for the current range of vehicles from OEMs are in the range £50,000–£70,000 for a large passenger car. These prices can be reduced through the use of selective subsidies. However prices are set to decrease…

Toyota: "*We are confident that, as with hybrids, fuel cell vehicles will become increasingly affordable as sales grow. Our aim is to be selling around 30,000 fuel cell vehicles a year worldwide by 2020, 10 times our target figure for 2017*"

The price decreases will be driven mainly by increased volume production for fuel cell vehicles. The other effect will be new technological developments which reduce the cost of the key components – the fuel tanks and the fuel cell stack.

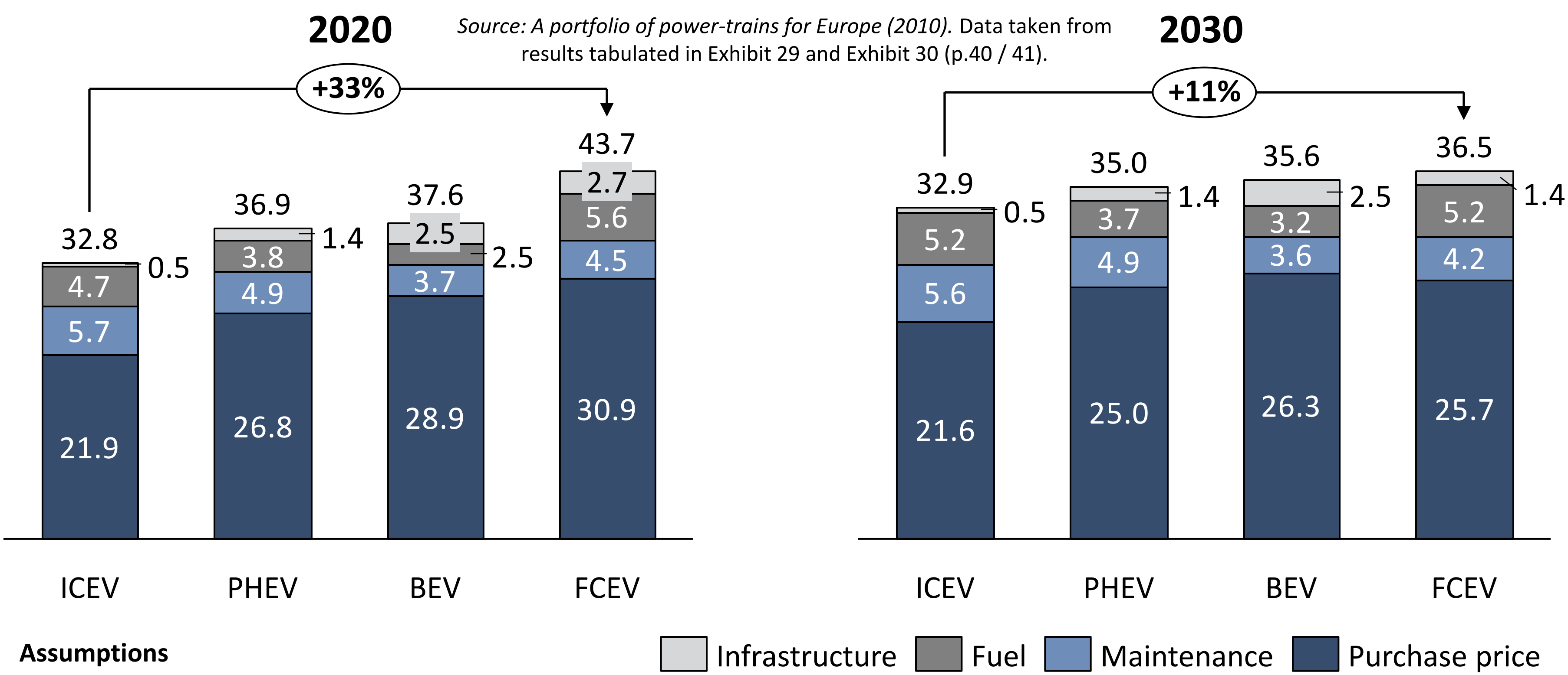
4

FCEVs are expected to become increasingly competitive on an ownership cost basis through the 2020s and beyond

Forecast total cost of ownership for typical passenger cars

Total cost of ownership for a C/D segment car (EUR '000s) Excluding taxes (fuel duty, VAT)

Source: A portfolio of power-trains for Europe (2010). Data taken from results tabulated in Exhibit 29 and Exhibit 30 (p.40 / 41).



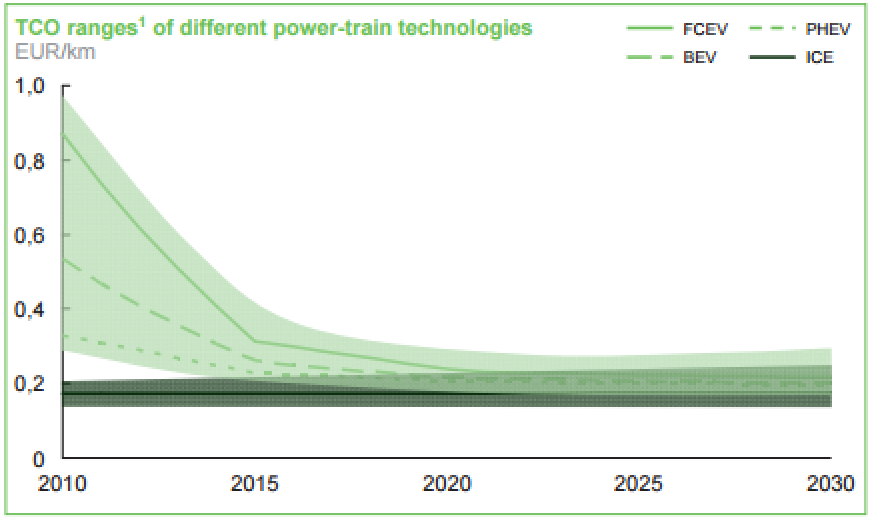
Assumptions

- 15 year ownership, 12,000 km/yr
- "Fuel" – includes production and distribution cost
- "Infrastructure" – includes retail cost

ICEV = internal combustion engine vehicle (diesel), PHEV = plug-in hybrid electric vehicle, BEV = battery electric vehicle, FCEV = fuel cell electric vehicle.

4 The need for grants / incentives for FCEVs is expected to decrease as costs fall over time, leading to cost-competitive vehicles by around 2025

Following cost reductions FCEVs will be affordable at scale (on a TCO basis)

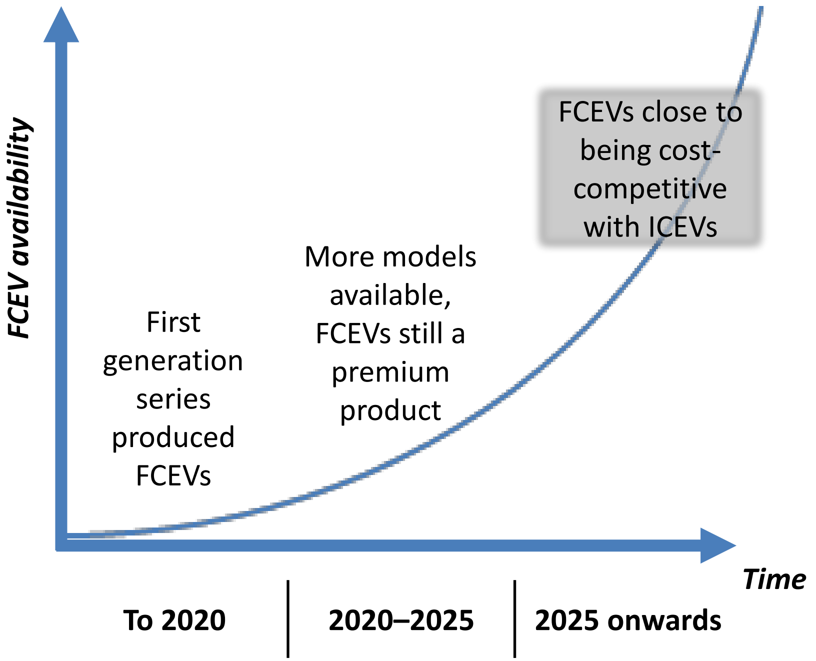


1 Ranges based on data variance and sensitivities (fossil fuel prices varied by +/- 50%; learning rates varied by +/- 50%)

SOURCE: Study analysis

By 2030, BEVs, FCEVs, PHEVs are all cost-competitive with ICEs in relevant segments

Source: A portfolio of power-trains for Europe (2010), Exhibit 28, p.39.



- The cost premium for FCEVs is forecast to fall significantly over the next five to ten years.
- At the same time, a greater choice of FCEVs is expected to become available as more OEMs bring vehicles to market.

Presenting the evidence

5 *Infrastructure will be affordable at scale and there is a clear strategy for rollout in London, which has already begun.*

[See all arguments]

5 Hydrogen fuelling stations have been operating in London for five years, reliably fuelling fleets of zero emission vehicles

Existing hydrogen refuelling stations in London

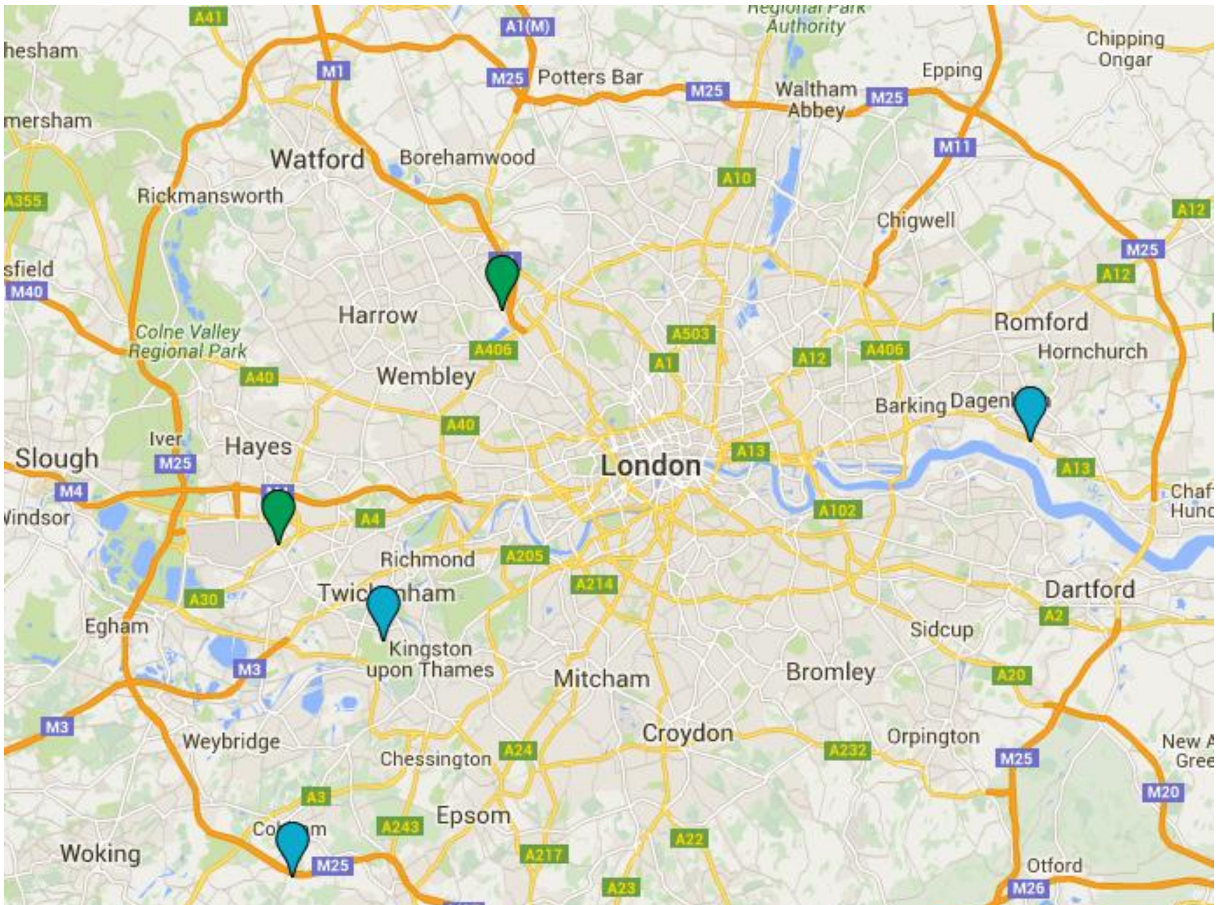
Hatton Cross (2012)
(publicly accessible)

Hendon (2015)
(publicly accessible)

Lea Interchange (2010)
(bus depot)

5 Deployment plans in and around London will see another six permanent stations added in the next two years

HRS in London (operational / in build as of early 2016)



Delivered H_2 (currently sourced from steam methane reformation)

On-site H_2 production using renewable electricity

- Funding is in place for a further five HRS in and around London (siting work is on-going).
- These additional HRS will bring the total number of publicly accessible stations in the London area to at least ten within the next couple of years.
- Funding is also in place for two mobile HRS, which could further support the development of the hydrogen transport sector in London over the coming years.*

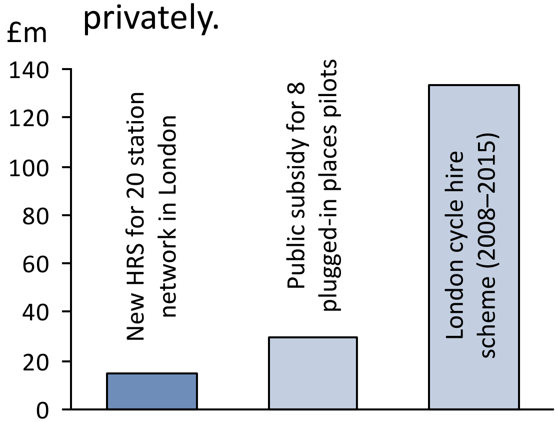
* www.gov.uk/government/news/government-revs-up-motorcycle-market.

5

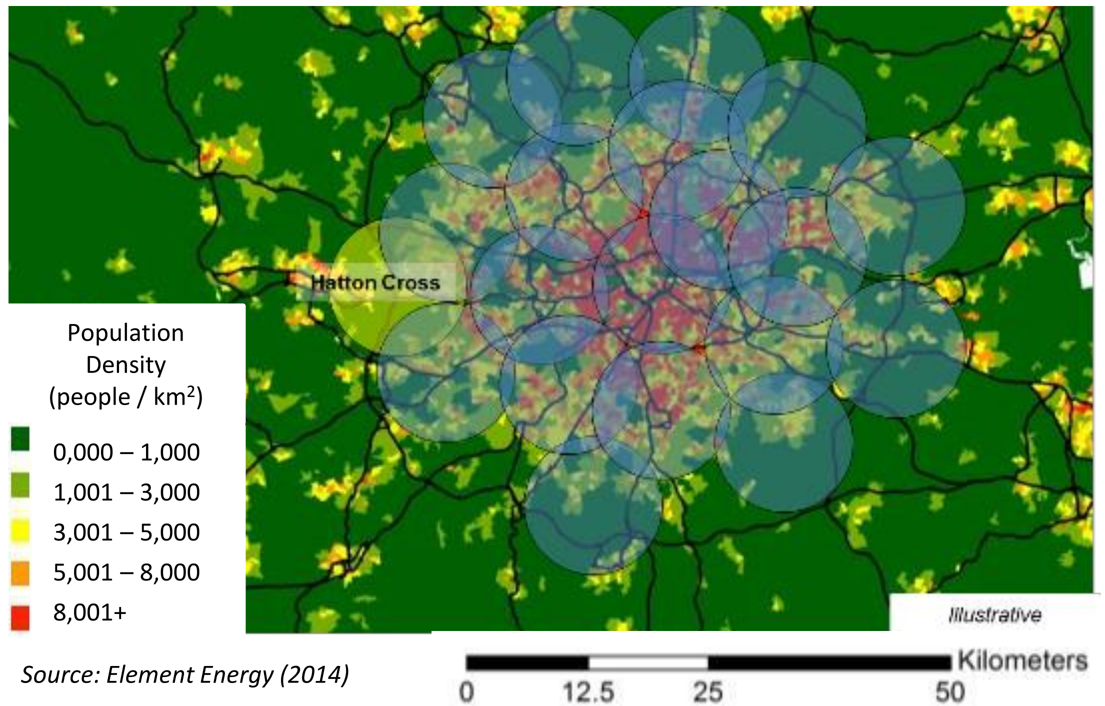
Hydrogen London has a strategy for expanding coverage of the publicly accessible hydrogen refuelling station as part of a national network

A vision for expanding London's HRS network has been developed

- A hydrogen transport strategy for London was developed as part of the HyTEC project.
- This included a vision of twenty hydrogen refuelling stations (HRS) as an initial network to provide a reasonable level of coverage for drivers of hydrogen vehicles.
- The net financing need for new stations to deliver this vision was estimated to be around £15m, of which much could be sourced privately.



A 20 station network covering London (7km radius)



Source: Element Energy (2014)

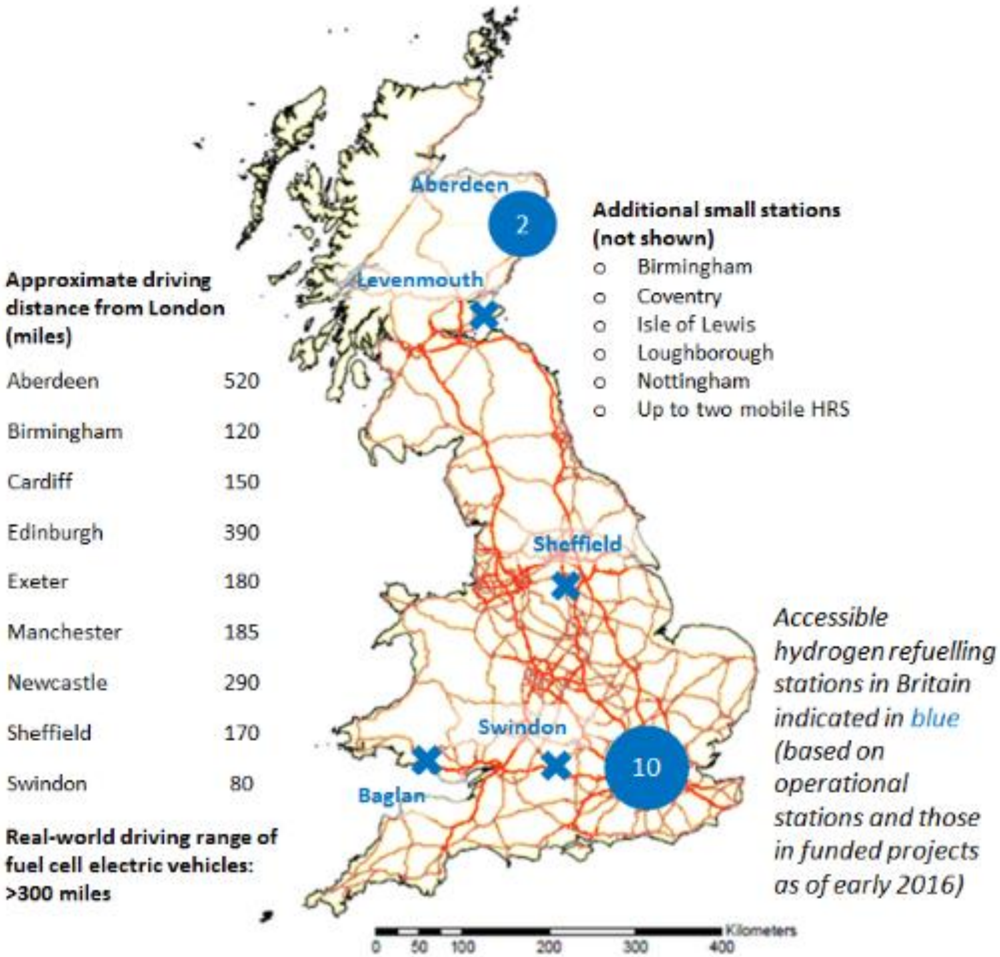
This map indicates areas in which HRS could be built to provide full coverage of London in an efficient manner. The circles show 7km radii (with HRS being positioned at the centre of each circle). This level of coverage corresponds to all populated areas being within c.14 minutes' drive (maximum), or 10 minutes on average, of an HRS. The network would be expected to be developed over a number of years.

www.gov.uk/government/uploads/system/uploads/attachment_data/file/3986/plug-in-vehicle-infrastructure-strategy.pdf
http://content.tfl.gov.uk/fpc-20141014-part-1-item-14-cycle-hire-imp-chei-close.pdf

Plans are in place to expand the national network of hydrogen refuelling stations beyond London

5

Planned national network of publicly accessible HRS across the UK (based on announced / funded stations as of early 2016)



Notes

- This map shows not just operational stations, but also those that are due to be constructed over the coming months and years.
- The figure of ten in London includes stations that may be installed in the London area (i.e. not necessarily all within the M25).
- The vision outlined in the UK H_2Mobility project is for a national network of around 65 hydrogen refuelling stations by 2020.

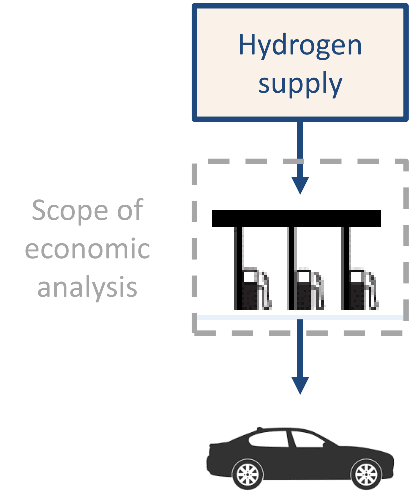
5 There can be a positive business case for hydrogen refuelling infrastructure with tens to hundreds of vehicles per station

Illustrative hydrogen refuelling station cash flow – introduction

- The following high level analysis illustrates the dynamics of hydrogen refuelling station (HRS) investments.
- It is based on consideration of the cash flows (costs and revenues) for an HRS operator. In order to simplify the analysis we assume a fixed cost of hydrogen delivery to the station and a fixed selling price (which caps the revenues available).

	Very small	Small	Medium
Capacity (kg/day)	20	80	400
Total installed cost (£)	400k	700k	1,300k
Maintenance costs (£/yr)	10k	15k	25k
Lifetime (years)	10	10	10

Cost of hydrogen supply (£/kg)	4.5	In practice the cost of hydrogen depends on a range of factors.*
Hydrogen selling price (£/kg)	7.5	Based on offering fuel cost parity for a FCEV compared to diesel.
Discount rate	10%	Typical value (which would vary by investor).

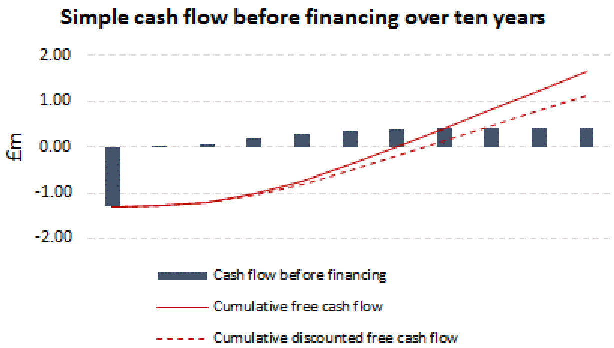


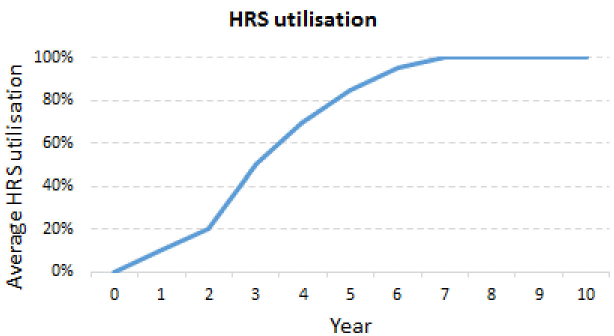
* Including production method, volumes ordered, location of station relative to source of supply, etc. £5/kg is a low figure for small volumes but relatively high compared to what should be feasible at large scales.

5 A medium-size HRS can offer a positive return even with low utilisation in the early years, but losses are high if H_2 demand does not grow

Simple cash flow modelling results – 400kg/day HRS

Growing hydrogen demand

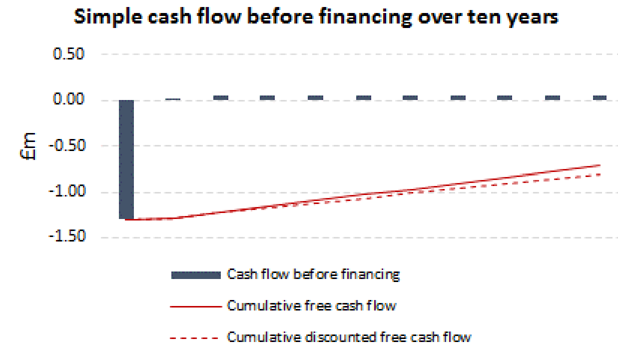


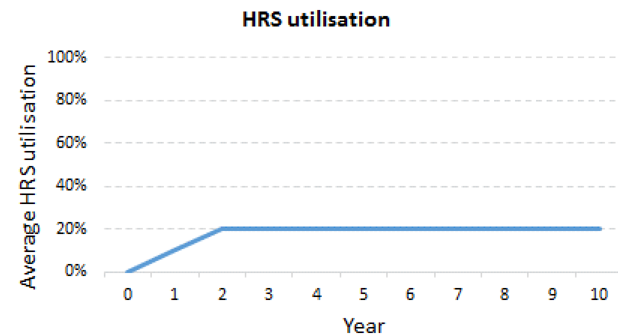


Profitable operation of the HRS can be achieved within the station lifetime provided that throughput reaches sufficient levels.

400kg/day corresponds to around 20 fuel cell bus refuelling events or 80 complete fills of an OEM fuel cell car.

Lack of growth in H_2 demand



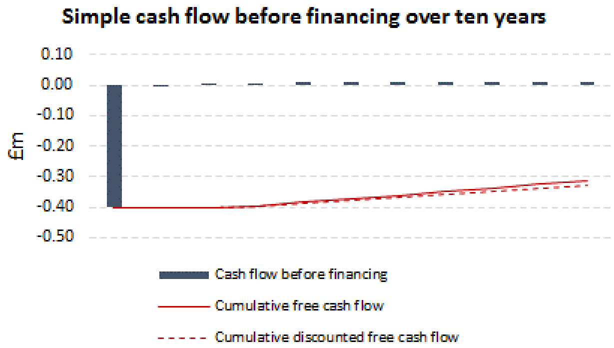


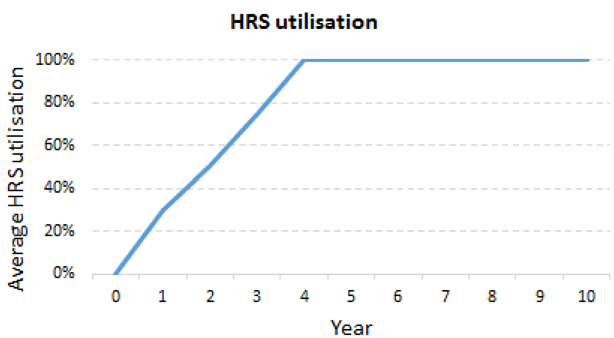
- Although a positive case is possible after a number of years of low utilisation for a station of this size, the business model collapses if demand for hydrogen fails to grow (i.e. if additional hydrogen vehicle roll-out does not materialise).
- Hence there is considerable demand risk associated infrastructure deployment, which must be overcome to justify investment.

5 Revenues available from very small stations are unlikely to be sufficient to cover the capital and fixed operating costs

Simple cash flow modelling results – 20kg/day HRS

Very small station – baseline



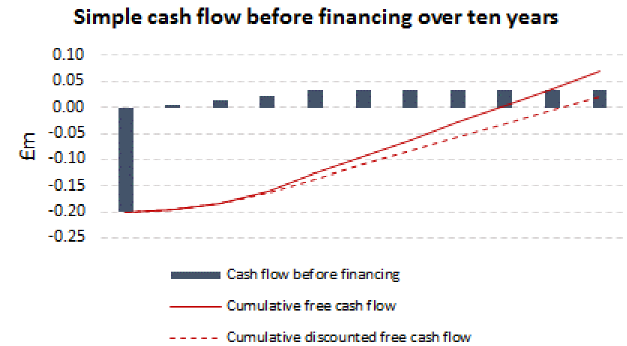


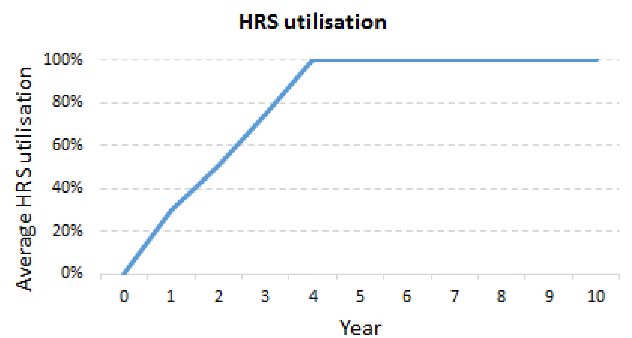
Low throughput of hydrogen limits revenues, making it difficult to cover fixed opex.

A positive case may be possible under very optimistic assumptions (capex reduced to £200k, opex at £7.5k/yr, selling price increased to £10/kg).

20kg/day corresponds to around four complete fills of an OEM fuel cell car per day.

Very small station – optimistic



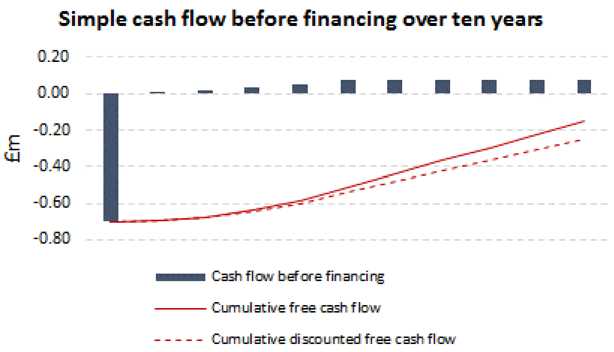


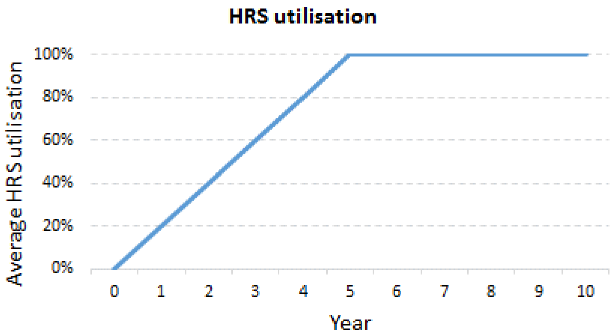
- This type of station may be viable if there is substantial public sector support to seed an HRS network (e.g. 100% capex funding) and ultra low fuel consumption vehicles that allow hydrogen sale price to be increased while still offering an attractive ownership cost to customers (e.g. small, lightweight FCEVs).

5 Small stations may be better suited to the fleet sizes expected in the near term and can offer a positive case under certain conditions

Simple cash flow modelling results – 80kg/day HRS

Small station – baseline



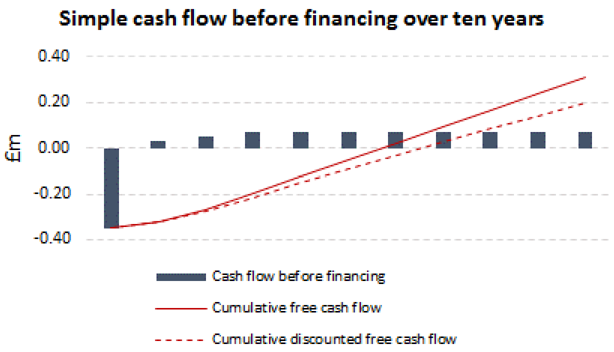


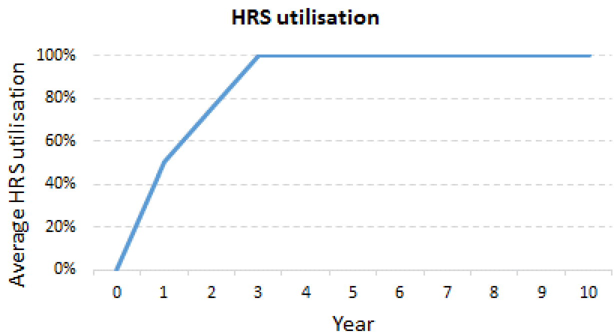
This size station suffers from the same issue as the very small HRS (low revenues).

A positive case may be possible with reduced station costs (e.g. with 50% capex grant funding) and a reasonable level of hydrogen demand secured.

80kg/day corresponds to around 16 complete fills of an OEM fuel cell car, four fuel cell bus refuelling events, or 80 range extended vans per day.

Small station – with grant + captive fleet





- Stations of around 80kg/day capacity can offer a positive return with some level of capex subsidy and a relatively high level of utilisation. Matching fleets of vehicles to stations helps secure demand for hydrogen, reduces risks, and hence makes HRS more investable.

6 *When made from electricity via water electrolysis, the production of hydrogen can act as a responsive source of demand and thus can support an electricity system with increasing levels of renewables.*

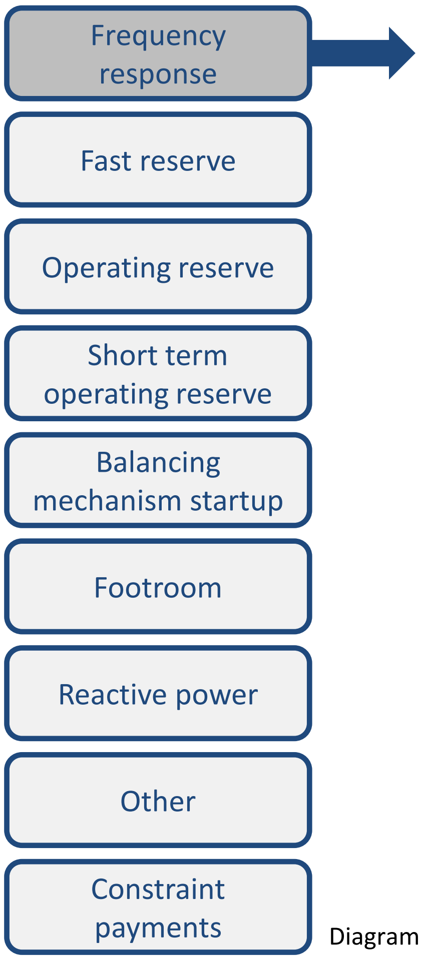
See all arguments

6

Even today electrolysers could provide demand shifting and grid services to support an electricity system with increased renewables

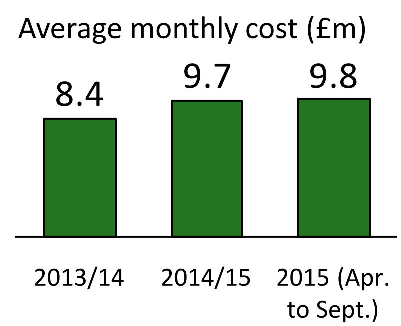
The role of electrolysers in grid balancing

Categories of balancing services



- National Grid procures over 20 different types of balancing services in order to meet its obligations to ensure that electricity demand and supply match at all times. National Grid must ensure that system frequency remains within statutory limits.
- **Frequency response** services are provided by generators and suppliers and are relatively high value as they require near-instantaneous action to address the effects of a sudden drop in generation capacity / increase in demand.
- National Grid spent c. £100m on commercial frequency response services in 2013/14 and c.£116m in 2014/15.*
- **Electrolysers can provide frequency response services**. E.g. ITM Power recently demonstrated that its electrolyser-based refuelling stations can achieve full system "turn on" response of 40 cycles (800ms) and "turn off" in 7 cycles (140ms). This qualifies the systems for frequency response services.
- Various factors may impact future UK balancing activity (e.g. evolution of generation base, roll-out of smart meters and demand side response, etc.) and the value of balancing services. However, electrolysers are well placed to compete in this market.

Commercial frequency response cost



Source: National Grid (MSBS reports)

Diagram based on *Electricity Balancing Services: Briefing*, National Audit Office, Figure 10, p.19 (2014).

* Source: National Grid (MSBS reports). Commercial frequency response is a collection of services provided by demand side participants and generation plant (e.g. frequency control by demand management and firm frequency response).

7 *Hydrogen refuelling facilities can be integrated with existing refuelling infrastructure, providing a non-disruptive, space efficient infrastructure for low emission transport and giving customers a familiar user experience*.

See all arguments

7

Hydrogen refuelling stations are starting to be installed at forecourts in the UK, giving FCEV drivers a familiar refuelling experience

Forecourt-hosted / forecourt-integrated HRS – examples

- Hydrogen refuelling stations can be located alongside / on forecourts, providing a non disruptive, space efficient infrastructure for ultra low emission transport and giving customers an equivalent user experience to existing fuels.
- Guidance for hydrogen refuelling will soon be included in the official industry guidance for the construction of petrol filling stations (the APEA Blue Book).
- In March 2015 the UK's first supermarket-hosted HRS opened in Hendon (NW London), with the HRS alongside the existing forecourt.
- Shell has installed hydrogen stations on existing forecourts in Germany and California, and recently announced plans to establish hydrogen refuelling points at three of their petrol stations in / around London, in partnership with ITM Power.*

HRS alongside a forecourt in Hendon, NW London

Shell hydrogen stations in Germany and California

Hydrogen refuelling facilities for fuel cell buses

HRS at the Lea Interchange bus depot

- Fleets of fuel cell buses can be refuelled using depot-based HRS (subject to sufficient space being available within / around the depot).
- This provides operators with a refuelling option for zero emission vehicles that is close to their existing operations (diesel buses are typically refuelled at depots).

* https://transportevolved.com/2015/09/10/shell-oil-partners-with-itm-in-uk-to-sell-hydrogen-fuel-at-london-filling-stations/.

Commercial opportunities for hydrogen and fuel cell technologies today

Focus on transportable applications

Go to contents

Fuel cells can compete without subsidies in a number of applications today

Commercial opportunities for fuel cells – summary

- In addition to transport and fixed stationary applications, there is a wide range of other applications for fuel cells, targeting smaller markets where the specific advantages of this technology create a competitive edge. These include:
  - Uninterruptable power supplies (UPS)
  - Forklift trucks
  - Unmanned aerial vehicles (drones)
  - Portable power applications
- Of these, small **transportable fuel cell systems** are already competitive in certain applications without subsidy and are the focus of this section.

Fuel cells in transportable power

- Transportable power systems are defined here as those that can be **readily moved between sites**, without requiring civil works in order to be used, and can be used independently from other infrastructure.
- Applications typically have a relatively low power demand, ranging from less than 50W up to around 20kW.
- Applications include remote sensing, construction power, and many more.

Note, this document does not focus on forklifts (as the applications (large warehouses) within London are limited). The market for UPS is limited at present by relatively high costs, which means there is only a market in the most environmentally sensitive locations.

Key arguments for hydrogen and fuel cells in transportable power

Transportable fuel cells can compete without subsidy in specific applications today

1. These systems can outcompete all other alternatives for providing small loads (5W to 500W) for long periods. This is because conventional generators are very inefficient at low power and because batteries cannot store enough energy for these applications.* Evidence

2. Transportable fuel cells are available now from a number of London based suppliers and can be procured with short lead times. Evidence

3. The implementation of these solutions brings local environmental benefits in terms of reduced emissions and noise. This is beneficial on a London-wide basis, but particularly valuable in terms of the health impact on those working or living close to the generators (e.g. there is zero possibility of NOx emissions from these products). Evidence

4. The cost of hydrogen supply for these units will fall with a) improved logistics and b) widespread availability of refuelling stations and the economic case will become attractive for more applications (higher power, allowing increased competition with conventional generators e.g. for construction). Evidence

5. Pushing the development of niche commercial markets can **support the overall market for HFC applications** by a) increasing exposure and familiarity with the technology, b) developing the skills needed to support hydrogen technologies, c) creating a supply chain for hydrogen and fuel cell components, and d) establishing platforms to deploy larger numbers of units. Evidence

* Over 30 units are currently operating in London on a commercial basis in applications such as mobile lighting, mobile surveillance cameras, sensing and some leisure applications (see below).

1

Transportable FC generators are mature, reliable, and safe; and already competitive in certain applications

Transportable fuel cell products – overview

Key characteristics

- **Zero emissions** – allowing indoor use and use in restricted spaces, areas where air quality is a concern, or in environmental monitoring applications. Replacing diesel generators with these products leads to health (and welfare) benefits for workers nearby.
- **Low noise** – operation in noise-sensitive environments, or those where noise restrictions apply is possible.
- **Portable** – lightweight, compact products that are highly portable.
- **Vibration-free operation** – particularly advantageous for sensitive environmental monitoring, or for increased comfort in working or leisure environments.
- **Long unattended run times** – systems designed for extended periods of unmanned operation (a major cost saving compared to other solutions).*
- **Zero contamination risk** – unlike solutions that rely on liquid fuels, there is zero risk of contamination from fuel spillage.

Example products

Illustrative (non-exhaustive)

BOC HYMERA® II

150 W

Developed in and supported from London

BOC
A Member of The Linde Group

SFC products

Tens to hundreds of watts, methanol fuelled

- ***Many hundreds of systems have been sold in the UK to date (without subsidy)***
- ***Of which approximately 30 operating in London (as of early 2016)***

* High energy density compared to battery-based solutions.

1

Transportable fuel cell systems can compete without subsidy, particularly in applications requiring low, continuous power

Other generators vs. fuel cells – overview

- Off-grid power is typically provided by portable diesel generators or batteries (for small loads only).

- **Diesel systems –** have limited ability to modulate fuel consumption at low electrical output. E.g. diesel generators offer a minimum output of around 600 watts and have a minimum diesel consumption of around 0.4 litres/hr. These figures imply an electrical efficiency of c. 15% (compared to 50%+ from fuel cells). Diesel generators also require regular servicing (e.g. every 200 hours of operation for small units), which can significantly increase operating costs.

- **Batteries –** are limited by their energy storage potential, which means long duration loads need unfeasibly large / heavy batteries.

- Fuel cell-based portable generators are far more flexible and operate at high efficiency across a range of power outputs. This means they are **highly competitive on an ownership cost (TCO) basis for applications requiring long life (days) and an average power demand up to ~ 0.5 kW**.*

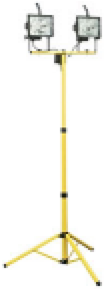
Source: BOC

* Despite the fact that the capital cost of a fuel cell generator is likely to be of the order double that of a similarly sized diesel generator.
TCO = total cost of ownership.

There is a wide range of relatively low power applications that require off-grid energy supplies and could be suitable for fuel cells

1

Transportable fuel cell generators – example applications



- Temporary lighting towers (construction sites, outdoor events, etc.)
- Security cameras (for temporary applications and / or to replace security guards)
- Remote monitoring (environmental indicators – e.g. water industry)
- Road signs (where access to grid electricity is restricted)
- Refrigeration
- Information signs / advertising
- Cycles / scooters etc.
- Drones
- Charging consumer electronics (phones, laptops etc.)

Fuel cell products are particularly attractive solutions in environmentally sensitive areas (strict limits on noise / air pollution) where there may be no other viable power source.

The following arguments are evidenced by the applications currently in use in London, examples of which are shown in the case studies

2 Transportable fuel cell products are available in London today

3 Fuel cell solutions for transportable power provide local environmental benefits in terms of emissions and noise

Case study 1 – The Ecolite-TH2, a lighting tower with integrated fuel cell power, has been used by Costain during upgrade work for Network Rail

The application

- Lighting for night-time construction work, led by Costain, on the Great Eastern Main Line for Network Rail. Shifts of 6 hours.

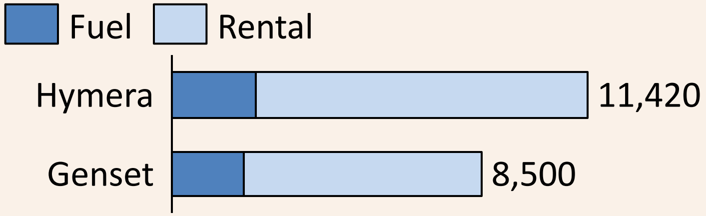
Product specifications

- 150W hydrogen fuel cell integrated with 80–100W lighting towers. Low noise.
- Can be used for over 1,500 shifts with minimal maintenance requirements, leading to significant savings over diesel generators.

Estimated addressable market size

- Up to 30,000 units in the UK; thousands of units in London.

Indicative total cost comparison (£ in 1 year)



Costain's experience:

"The use of the Ecolite-TH2 lighting unit on our project has significantly enhanced our mission to protect the environment by reducing our carbon emissions and noise impact of work on Network Rail's lineside neighbours."

Requirements & benefits	Fuel cell	Diesel	Battery
Long runtimes	✓	✓	✗
Low servicing needs	✓	✗	✓
Portability	✓	✓	✗
Zero noise and emissions	✓	✗	✓

Case study 2 – Methanol fuel cells were used by Simulation Systems to power off-grid CCTV cameras at a key junction on the M6

The application

- Power for CCTV security cameras on major roads where grid connection would be prohibitively expensive and there is insufficient sunlight to make solar panels a viable option.

Product specifications

- Methanol fuel cell of up to 150W.
- Fuel cell lifetimes can typically enable over a year of 24/7 operation, with very low maintenance needs.

- In many applications, security cameras achieve significant cost savings compared to hiring a security guard.

Estimated addressable markets

- Traffic monitoring, mobile signage, construction sites, event security.
- Growing market – potentially 10s of thousands of units in London.

Simulation Systems' experience:

"As we're based in Bristol our maintenance teams would have faced 200 mile return trips to the West Midlands every couple of days to replace discharged batteries. The fuel cell saved us a considerable amount of time and money. It can look after itself and isn't affected by its environment, unlike other sources of power such as renewables."

Requirements & benefits	Fuel cell	Battery	Security guard
Long unattended runtimes	✓	✗	✗
Low servicing needs	✓	✓	N/a
Low noise and emissions	✓	✓	N/a
Compact	✓	✗	N/a

Case study 3 – A fuel-cell hybrid power system developed by Arcola was used to provide power for a small off-grid site office

The application

- Heat and power for an off-grid cabin as a demonstration for welfare cabins and site offices: used by paying customers over several months.

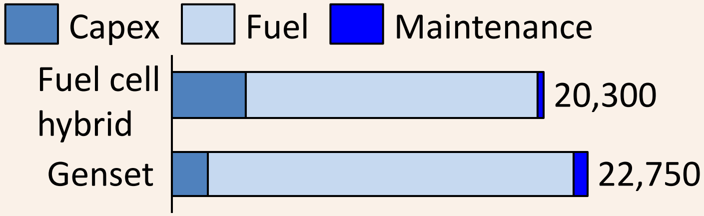
Product specifications

- Inefficient diesel genset and oil filled radiators replaced by a *hybrid system* comprising a 150W hydrogen fuel cell, combined with a battery & a low voltage diesel heater.

Estimated addressable market size

- Addressable rental market fleet for London consists of thousands of units.

Indicative total cost comparison (£ in 1 year)



Arcola's experience:

"We have demonstrated heating and powering a cabin (70sqm) over several months (including winter) and used by paying customers."

Requirements & benefits	**Fuel cell hybrid power**	**Diesel genset**
High efficiency → cost savings	✓	✗
Long unattended runtimes	✓	✗
Lower noise and emissions	✓	✗

These solutions are supplied by specialised logistics systems for either hydrogen or methanol

4

Fuel logistics – hydrogen

- Hydrogen for the HYMERA® is supplied as a compressed gas (at 300 bar) in GENIE® gas cylinders.
- A full cylinder weighs c.22kg and contains enough hydrogen to run the HYMERA® for c.40 hours at full load (150W).
- The cylinders can be ordered online and are delivered within 24–48 hours. A click & collect service is available from selected locations.

Fuel logistics – methanol

- Methanol for the SFC direct methanol fuel cells is supplied as a liquid in 5, 10, or 28 litre containers, which are safety tested and IATA (air travel) approved.
- Users can be alerted of low fuel levels via the REMO® service offered by UPS Systems (a *remote monitoring solution for generators, UPS and fuel cells*).*
- Methanol can be purchased directly from Fuel Cell Systems (online).

Source: BOC, Fuel Cell Systems.

* See www.remo.co.uk.

4

As supply of hydrogen improves, the economic case will become attractive for a wider range of applications

Development of the hydrogen supply chain

- Through time the supply of hydrogen in London will become easier, due to:
  - Availability of hydrogen stations for refuelling of vehicles.
  - New solutions for hydrogen logistics (higher pressure vessels, novel concepts for hydrogen delivery).
- This is likely to provide (at least) two beneficial effects for transportable fuel cells: (i) greater access to hydrogen, and (ii) lower cost hydrogen becoming available as the market develops.
- This in turn will open up **new commercial opportunities** for existing and new transportable fuel cell products, further increasing the addressable market size (essentially increasing the power range over which the product is competitive).
- Fuel costs for fuel cells are not much greater than that of diesel generators for a several applications, due to the greater efficiency of fuel cells compared to diesel generators. As such, if hydrogen was available at lower cost, some of the following applications could become competitive for hydrogen fuel cells:

Construction generators

Welfare cabins

Delivery motorbikes

Indicative comparison of total ownership costs for different hydrogen fuel & supply prices

5 Existing commercial opportunities could build demand for hydrogen and prepare the market for higher impact applications

Further roll-out of fuel cells in specific applications supporting the wider sector

Further development of certain commercial markets could **support the wider market for HFC applications with greater positive impacts** by:

a) Developing the **skills** needed to support hydrogen technologies – increased exposure to hydrogen as a fuel, handling high pressure gases etc.

b) Creating employment – the BOC HYMERA® is already developed in and supported from premises in London.

c) Creating a **supply chain** for hydrogen and fuel cell components – further roll-out helps strengthen the overall supply chain for all hydrogen activities.

d) Clearly demonstrating that **profitable markets** can be created from hydrogen and fuel cells – as opposed to remaining a "one-day technology".

e) Increasing **exposure** to the technology – by allowing more Londoners to interact with hydrogen technology, negative perceptions about the fuel will be mitigated.

These benefits suggest action to expand the market for the early commercial opportunities is consistent with the wider aspirations of increased use of hydrogen and fuel cell technology.

Addressing London's energy system challenges

Focus on large stationary applications

Go to contents

Key arguments for large scale stationary applications

Hydrogen and fuel cells can address some of the biggest energy system challenges for London

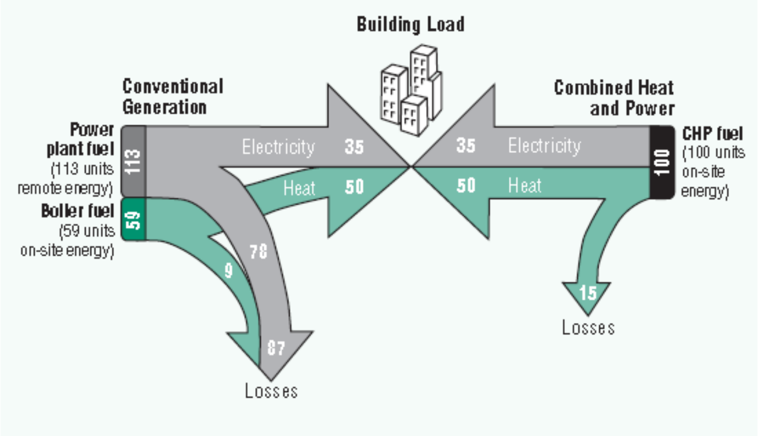
1. Increased use of decentralised heat and power generation is a key part of London's plan for decarbonisation and energy security. Evidence
2. Fuel cells can generate electricity, heat, and cooling for these networks and provide best in class CO_2 savings amongst decentralised energy options, with even greater efficiency savings expected from future products. This technology is future-proofed as it is compatible with decarbonised gas grids, which would yield even greater CO_2 savings. Evidence
3. Stationary fuel cells produce **negligible air pollutant emissions** and are therefore well suited to areas where air quality is a concern. Evidence
4. Unlike other prime mover technologies, fuel cells suffer no loss in efficiency between 100% and 50% load. Evidence
5. Stationary fuel cells have proven reliability and can operate with availability of >98%. Evidence
6. Other advantages over alternative large engines include: **vibration-free, relatively low noise**, **long life**, and **low maintenance** requirements. This makes them *urban-friendly* solutions. Evidence
7. Large stationary fuel cell generators are already available from a number of suppliers, using robust, reliable, proven technology. Three systems are installed in London, which has the largest installed base of large fuel cells of any European city. Evidence
8. While the current costs for fuel cell CHP are higher than for conventional engines, a combination of research and development and economies of scale are leading to falling costs, with scope for further reductions over time. Evidence

1 The benefits of decentralised energy are relatively well known but are yet to be fully realised in London

Generic arguments for decentralised energy / CHP

- Higher overall efficiency of fuel use (potential to make use of waste heat, elimination of T&D losses).
- Energy saving and CO_2 emission reductions → improved competitiveness / alleviation of fuel poverty.
- Cost savings.
- Proven, reliable technology.
- Enhanced security of supply; range of fuel sources.
- Increased flexibility and reliability of energy supply.

Stationary fuel cells can substantially contribute to London's plans for decentralised electricity and heat generation.



Source: *Laboratories for the 21st Century: Best Practices*, US EPA, US DoE, Figure 1, p.3 (2011)

Relevance for London – The London Plan, Policy 5.5: Decentralised energy networks

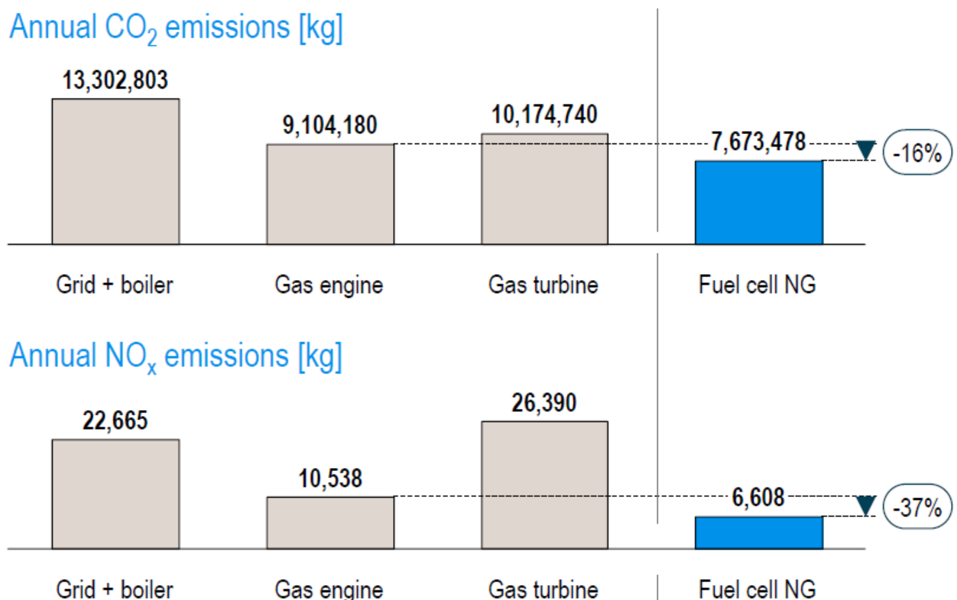
The Mayor expects 25 per cent of the heat and power used in London to be generated through the use of localised decentralised energy systems by 2025. In order to achieve this target the Mayor prioritises the development of decentralised heating and cooling networks at the development and area wide levels, including larger scale heat transmission networks.

Source: www.london.gov.uk/what-we-do/planning/london-plan/current-london-plan/london-plan-chapter-5/policy-55-decentralised.

2 Substantial CO_2 savings are available from fuel cells as they are highly efficient

Fuel cells offer best in class CO_2 savings amongst decentralised energy options

Base-load power demand	11,600 MWh
Heat demand	29,000 MWh
Heat temp. req.	> 130 °C
H_2 emissions	2,000,000 m³
Plant operation	24/7
Gas/ power grid connection	yes

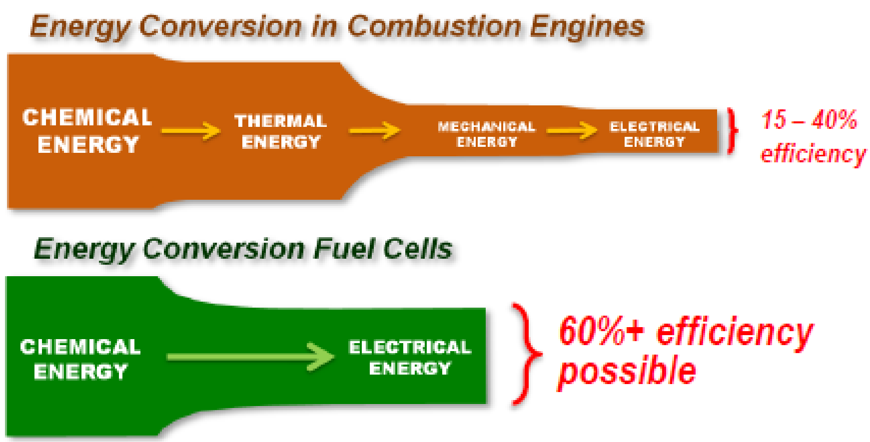


1) Considering the total annual balance of emissions attributable to the building, i.e. for power and heat consumption. Any power feed-in is thus credited with the primary energy equivalent.

Source: Advancing Europe's energy systems: Stationary fuel cells in distributed generation, Roland Berger for the FCH JU (2015)

The CO_2 emissions above are based on fuel cells running on natural gas. Greater savings would be possible in future where fuel cells are supplied with a low carbon source of hydrogen – i.e. fuel cells are compatible with visions of a zero carbon economy.

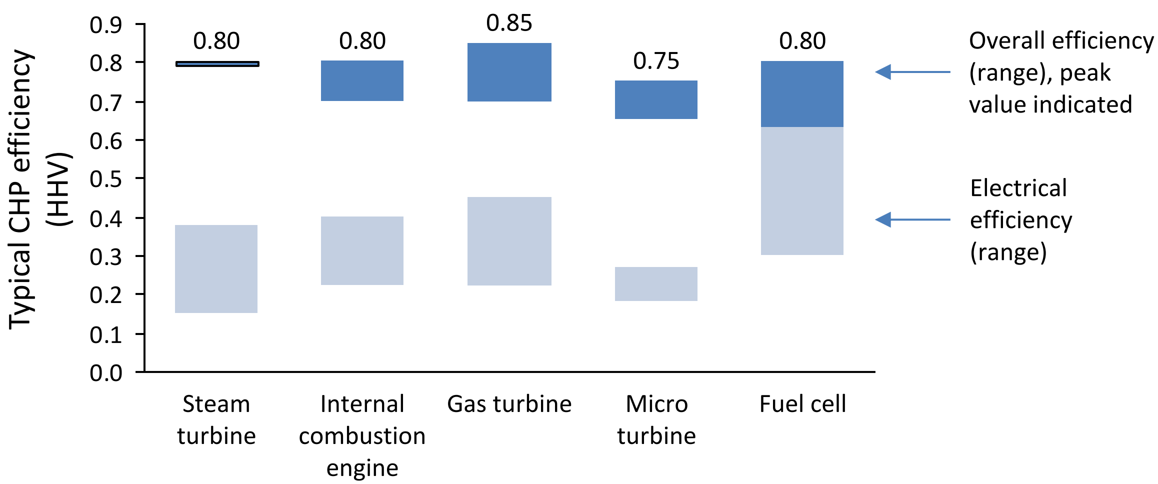
2 Fuel cell CHP systems offer high overall efficiencies and can provide best in class electrical efficiency



Combustion Engines — convert chemical energy into thermal energy and mechanical energy, and then into electrical energy.

Fuel cells — convert chemical energy directly into electrical energy, bypassing inefficiencies associated with thermal energy conversion. Available energy is equal to the Gibbs free energy.

Source: *Fuel Cells Technology Overview*, US DoE (2012) http://energy.gov/sites/prod/files/2015/07/f25/sunita_satyapal.pdf



By using an electrochemical rather than combustion process, fuel cells are not limited by the same fundamental efficiency constraints and can theoretically achieve very high electrical efficiencies.

Source: Data from *Laboratories for the 21st Century: Best Practices,* US EPA, US DoE, Table 1, p.3 (2011).

Fuel cells produce very low harmful emissions and could therefore offer substantial environmental and health benefits

3

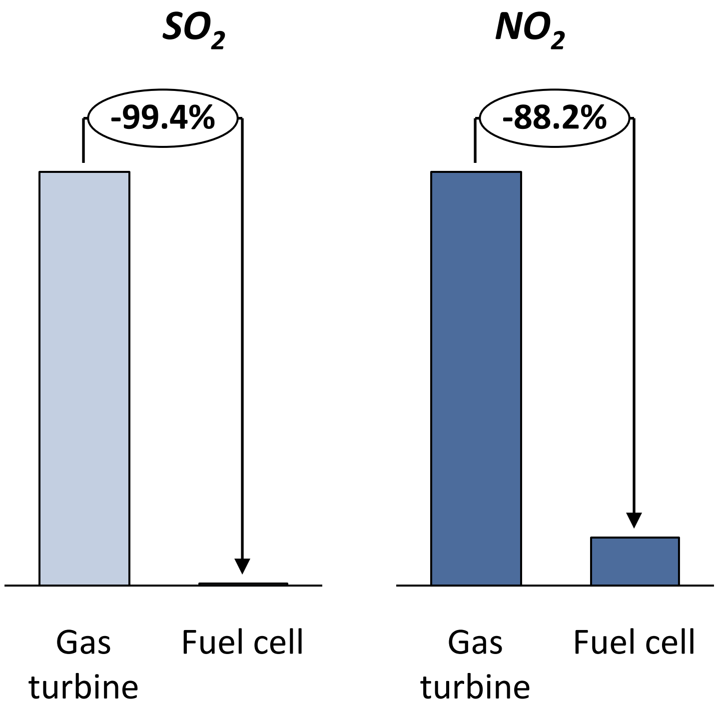
Further local environmental benefits of fuel cells

- Being based on an electro-chemical (rather than combustion) process, fuel cells provide the lowest harmful emissions of all CHP technologies.

- This is particularly advantageous in cities with air quality issues such as London.

- Certain stationary fuel cell systems are designed to operate in *water balance* and hence provide significant water savings during normal operations compared to conventional power generation.*

Emissions characteristics of gas turbine vs. fuel cell CHP

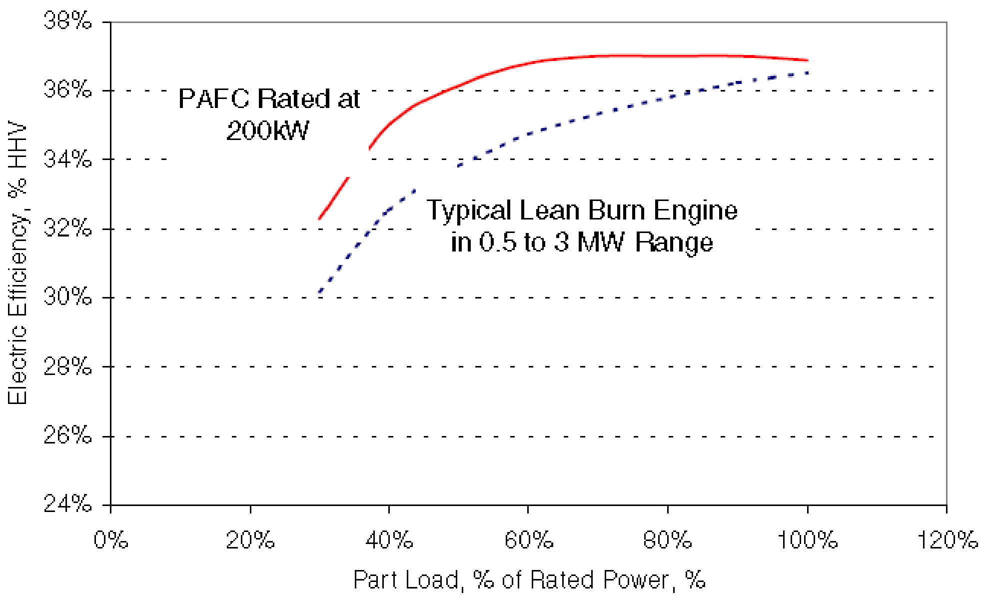


Source: Data from *Laboratories for the 21st Century: Best Practices,* US EPA, US DoE, Tables 3, 5, 8 (2011).

4 Stationary fuel cells offer high electrical efficiency even at part load – e.g. no loss in efficiency between 100% and 50% of rated output

Part load performance of fuel cells – summary

Comparison of part load efficiency derate (engines vs. fuel cells)



Source: Gas Technology Institute, Caterpillar, Energy Nexus Group as reported in Technology Characterization: Fuel Cells, Energy Nexus Group for the Environmental Protection Agency (2002*)*

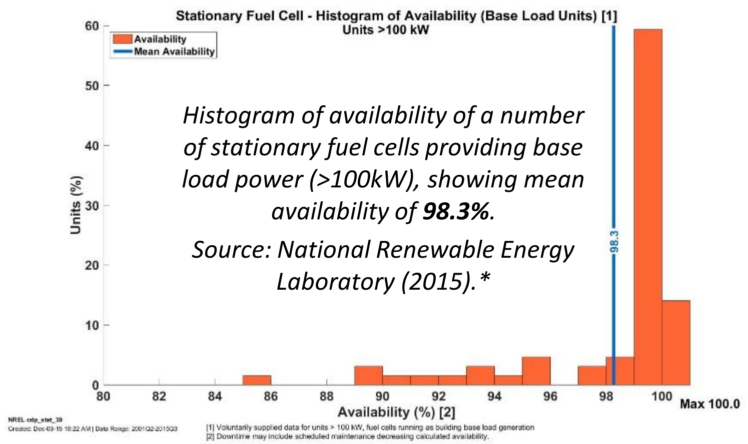
- This graph shows the electrical efficiency of a typical phosphoric acid fuel cell at different power outputs.
- The profile for a typical lean burn engine is also plotted (dotted line).
- Fuel cells have a better ability to maintain efficient performance at partial loads compared to reciprocating engines – in this example the efficiency at 50% load is within 2% of the full load value.

- Stationary fuel cells (e.g. PAFCs) can respond within seconds to fluctuations in power demand while maintaining the same overall efficiency.
- This is not the case for gas engines, which are typically configured to meet steady state base loads and suffer losses in efficiency when operated at part loads.

Large stationary fuel cells can operate with very high availability (>98%)

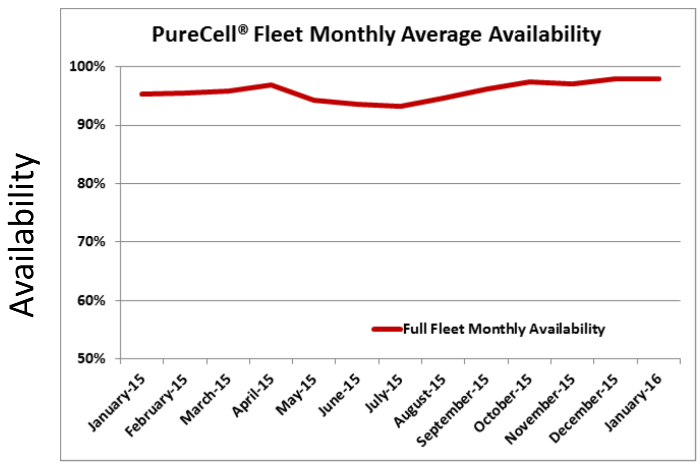
5

Real-world availability data for large scale fuel cell systems



*Histogram of availability of a number of stationary fuel cells providing base load power (>100kW), showing mean availability of **98.3%**.*

*Source: National Renewable Energy Laboratory (2015).**



*Empirical data from one supplier (Doosan) show a 12 month rolling average fleet availability figure of around 98%.***

- Reliability and availability are important issues for CHP systems.
- These terms may be defined as follows^:
  - Reliability = T – (S + U)/T – S x 100
  - Availability = T – (S + U)/T x 100

    S = scheduled maintenance shutdown (hrs/yr)

    U = unscheduled shutdown (hrs/yr)

    T = period plat is required to be available for service (hrs/yr)
- According to DECC's CHP guidance, typical figures based on manufacturers' guarantees are:
  - Reliability = 94.95%
  - Availability = 90.21%

^ Source: *CHP Technology: a detailed guide for CHP developers – Part 2*, p.11 (2008).

* Source: www.nrel.gov/hydrogen/images/cdp_stat_39.jpg.

** Source: Doosan. Availability calculation during normal operation.

6 Fuel cells offer advantages in terms of emissions and performance compared to other large CHP technologies

Large CHP will help to achieve decentralisation of energy

Technology	Steam Turbine	Intrnl. Combustion	Gas Turbine	Micro Turbine	Fuel Cell
Power Efficiency (HHV)	15% - 38%	22% - 40%	22% - 45%	18% - 27%	30% - 63%
Overall Efficiency (HHV)	80%	70% - 80%	70% - 85%	65% - 75%	55% - 80%
Typical Capacity (Mwe)	0.5 - 250	0.01 - 5	0.5-250	0.03 - 0.25	0.005 - 2
Part Load	OK	OK	Poor	OK	Good
CHP Installed Costs ($/kW)	430 - 1,100	1.100 - 2,200	970 - 1300 (5 - 40MW)	2,400 - 3,000	5,000 - 6,500
O&M Costs ($/kWh)	Less than 0.005	0.009 - 0.022	0.004 - 0.011	0.012 - 0.025	0.032 - 0.038
Availability	Near 100%	92% - 97%	90% - 98%	90% - 98%	Greater than 95%
Fuels	All	Natural gas, biogas, propane, landfill gas	Natural gas, biogas, propane, landfill gas	Natural gas, biogas, propane, landfill gas	Hydrogen, natural gas, propane, methanol
Thermal Output Uses	Low pressure (LP) - high pressure (HP) steam	Hot water, LP steam	Heat, hot water, LP - HP steam	Heat, hot water, LP steam	Hot water, LP - HP steam

Comments

Stationary fuel cell suppliers continue to develop the technology and pursue cost reduction programmes, hence lower costs than the ranges indicated in this 2011 report are now available.

Latest prices are available from fuel cell suppliers (see following slides).

Source: *Laboratories for the 21st Century: Best Practices,* US EPA, US DoE, Table 1, p.3 (2011). NB: developments in FC technology mean that progress has been made in a number of areas over the past five years, e.g. availability (see previous slide) and installed costs.

- Fuel cells offer relatively high electrical efficiency and overall efficiency comparable to the best available other prime movers.
- Fuel Cell CHP systems also generate relatively little noise (unlike the other technologies listed above there is no need for a dedicated enclosure for noise control when using fuel cells).*

* Stationary fuel cells are suitable for use in a range of building types, including residential (e.g. blocks of flats / primary energy supply for district heating schemes), and non-residential buildings (hospitals, hotels, universities, data centres, etc.)

7 Large stationary fuel cell systems are available from a number of suppliers, using robust, reliable, proven technology

Major suppliers of large fuel cells

Non-exhaustive

Supplier	Headquarters	FC technology	Key product(s)
Bloomenergy	California, US	Solid Oxide (SOFC)	Energy Server® (200kWe)
Doosan	Connecticut, US	Phosphoric Acid (PAFC)	PureCell® (440kWe)
Fuel Cell Energy Inc.	Connecticut, US	Molten Carbonate (MCFC)	DirectFuelCell® (2.8MWe / 1.4MWe / 400kWe)

Note: Bloomenergy products are not currently available in the UK.

Other companies developing large stationary fuel cell products include: Fuji (PAFC), GE Energy (SOFC), Mitsubishi Hitachi Power Systems (SOFC), LG Fuel Cell Systems Inc. (SOFC). Redox Power Systems are also developing an advanced SOFC solution, with an initial product based on a 25kWe unit (not current on sale).

Doosan can supply PureCell® units through its UK business, which can also support on-going operation of the product throughout its 20 year lifetime.

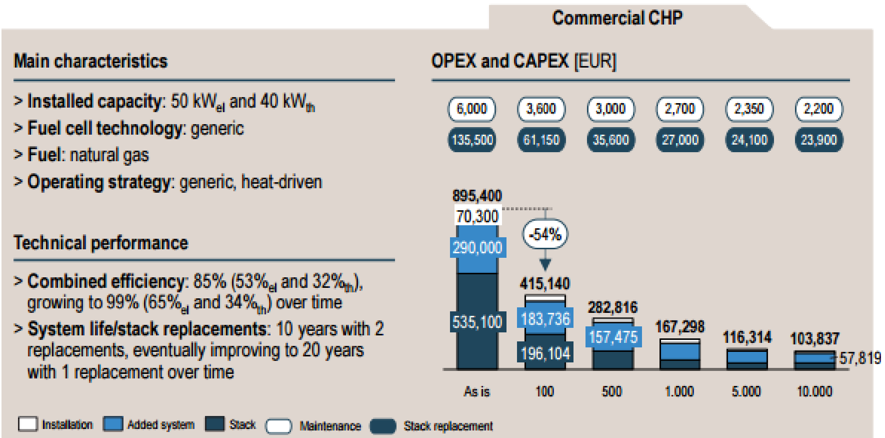
Logan Energy is an example of a UK-based company with expertise in the supply and installation of stationary fuel cells.

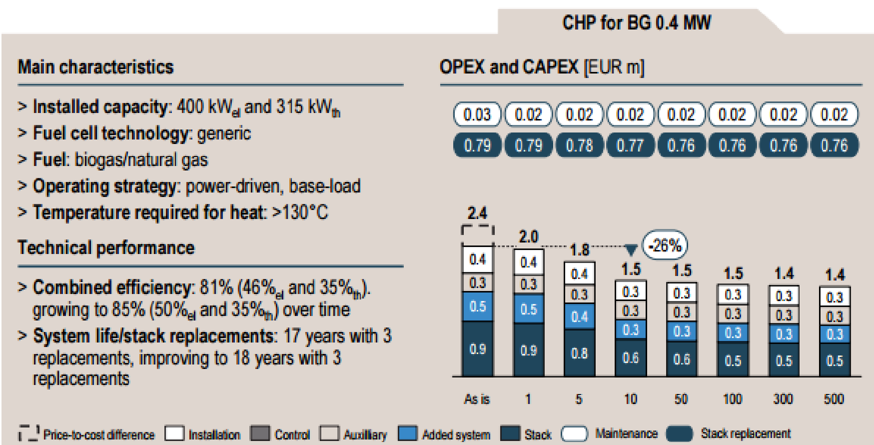
Global installed base of fuel cells

In total the suppliers listed above have many hundreds of megawatts of large stationary fuel cells installed worldwide, which have accumulated tens of millions of operating hours in the field.


The costs of stationary fuel cell systems are on a downward trajectory, with potential for significant further savings at higher order volumes

Technology cost profiles of generic fuel cell CHP systems





Total capex and opex of fuel cell CHP as a function of cumulative production volumes per supplier

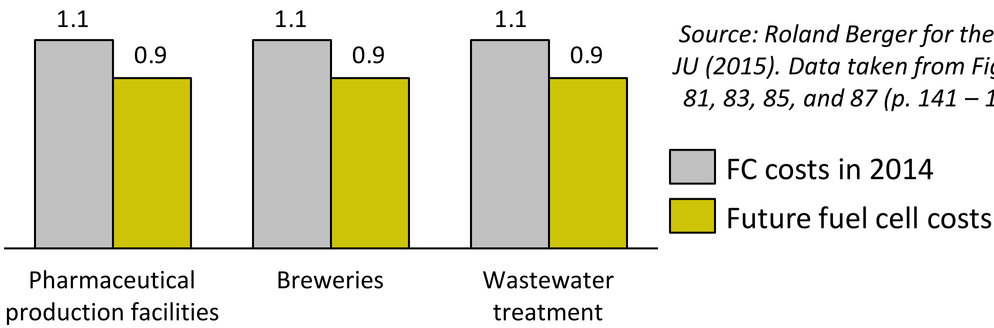
- These graphs illustrate the scale of cost reductions (capital and operating costs) anticipated for fuel cell CHP at two different scales (tens of kWe and hundreds of kWe).
- The figures are based on analysis undertaken in 2014 (report published in 2015), and represent generic fuel cell systems.
- Recent industry feedback suggests that some progress on cost reduction has already been made, and that significant further savings are feasible if production is scaled up and localised.
- The cost of energy from stationary fuel cells vs. other sources is considered on the following slides.

Source: *Advancing Europe's energy systems: Stationary fuel cells in distributed generation*, Roland Berger for the FCH JU (2015). *Fig. 40, p.90, Fig.43, p.99*

8 Achieving cost reductions through economies of scale will allow fuel cell CHP to compete with energy from boilers and grid electricity

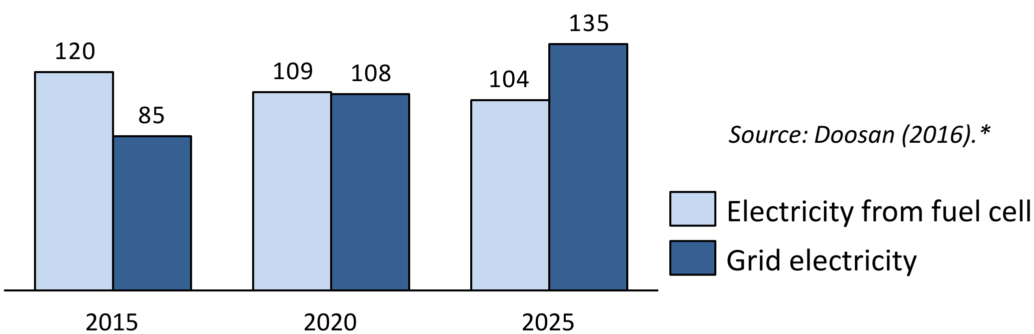
Fuel cell system total cost of energy benchmarking against grid electricity + gas boiler

Ratio of fuel cell total energy cost compared with grid electricity + gas boiler



Source: Roland Berger for the FCH JU (2015). Data taken from Figures 81, 83, 85, and 87 (p. 141 – 144).

Levelised cost of electricity from large stationary fuel cells vs. grid electricity (£/MWh)



*Source: Doosan (2016).**

- While energy from stationary fuel cells is generally currently more expensive than grid power (+ gas boiler), increasing production volumes will lead to cost savings over time.
- For example, data from the FCH JU's distributed generation study suggest that following scale up to 5MWe cumulative installed capacity per supplier, Fuel Cell CHP could compete with grid electricity and heat from boilers.
- Recent analysis by one supplier (Doosan) supports this conclusion and highlights the key challenge facing the sector – i.e. to achieve the economies of scale necessary to bring about these cost reductions.

* Source: (Grid Price) – DECC Reference Scenario 2015. Future cost projections for cost of fuel cell electricity based on cost reductions arising from economies of scale and further R&D. Indicative figure based on 98% availability and current level of gas price at 3.0p/kWh.

8

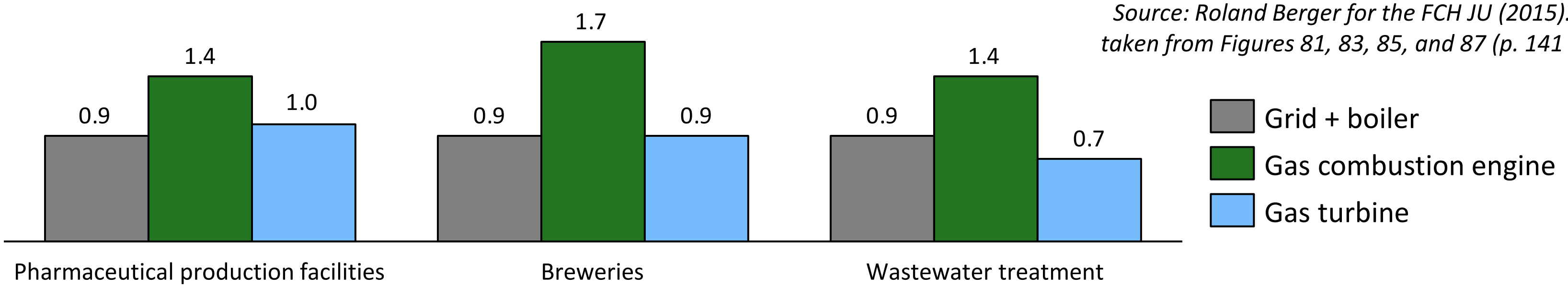
Although there may be lower cost ways of meeting energy demands, Fuel Cell CHP is a versatile solution with few constraints

Fuel cell system total cost of energy benchmarking against grid electricity + gas boiler

Ratio of fuel cell total energy cost compared with other prime mover technologies (future cost scenarios)

A ratio >1 implies that the FC solution is more expensive than the reference technology

Source: Roland Berger for the FCH JU (2015). Data taken from Figures 81, 83, 85, and 87 (p. 141 – 144).



- These figures suggest that after fuel cell cost reductions have been achieved this technology can offer lower cost energy than a traditional solution of grid electricity and gas boilers in a range of applications.*
- While there may be lower cost decentralised energy solutions in some situations, not all of the alternative technologies are suitable in all locations due to higher noise, vibration, emissions, etc. The impact of decentralised energy solutions in terms of harmful emissions is of particular concern in London where many areas suffer from poor air quality.
- The characteristics of Fuel Cell CHP (see evidence on previous slides) make this technology well suited to urban environments and hence fuel cells offer a means of decarbonising energy supplies in buildings in a wide range of situations.

* The example applications are those from the distributed generation study (Roland Berger for the FCH JU) specifically related to the UK context. While applications in other buildings (hospitals, university buildings, offices etc.) are also relevant to London, further analysis for these types of buildings was beyond the scope of this study.

Stationary fuel cell case studies – large Fuel Cell CHP installations in London

Site	***Palestra Building, 197 Blackfriars Road*** 	***Quadrant 3, Regent Street*** 	***20 Fenchurch Street (Walkie Talkie building)*** 
Overview	TfL decided to install what at the time was London's largest fuel cell as part of the Palestra Building's CCHP system, demonstrating leadership in reducing energy consumption and GHG emissions.	Driven by tight planning restrictions and a desire to reduce emissions and save costs, The Crown Estate selected a fuel cell CCHP system for the mixed use Quadrant 3 development.	This 38-storey tower was developed jointly by Canary Wharf Group and Land Securities. A fuel cell was selected to make this one of the most sustainable buildings of its type in London. This is the first FC to be installed in the City of London.
Installation date	2008	2013	2015
Details	200kWe FC as part of an integrated tri-generation system (providing electricity, heat, and cooling).	300kWe FC combined cooling, heat and power	300kWe FC combined cooling, heat and power
Benefits	• Reduction in carbon emissions of c.40% • Very low NOx emissions, negligible particulates, SOx, non-methane hydrocarbons • Cost saving (£90,000/yr) • Enhanced building energy performance – increased BREEAM rating to Excellent	• Energy cost saving £172,000/yr • 550t/yr carbon saving • In January 2016, supplied 16% of total electricity demand and 11% of heat demand for the four Quadrant blocks[1] • High availability, high reliability – excellent security of energy supply • Ultra low emissions of NOx, SOx, and CO • Quiet energy generation • BREEAM Excellent rating	• Allowed planning conditions to be met • Reduced CO_2 emissions of at least 270t/yr • Reduced energy costs • Ultra low emissions of NOx, SOx, and CO • Quiet energy generation

1 – ARUP, Fuel Cell performance summary, data from Quadrant 3 Performance Review

Reducing emissions from dwellings

Focus on small stationary applications

Go to contents

Key arguments for hydrogen and fuel cells in small stationary applications

Fuel cell microCHP could contribute to the decarbonisation of London's housing stock, whilst alleviating fuel poverty

1. Fuel cell microCHP powered by natural gas is one of the very few options which can make substantial reductions in the carbon emissions from London's older housing stock. Evidence
2. Fuel cell micro CHP systems can replace a conventional boiler, with no additional inconvenience to the householder (low vibrations, minimal noise and negligible emissions). Evidence
3. Advances in technical performance, mean this technology is now entering the industrialisation phase – large manufacturers are scaling up production lines to produce at volume and lower the costs of the products. Evidence
4. While fuel cell micro CHP systems currently come at a price premium, with volume the cost of the systems will reduce and lead to an affordable option for achieving reductions in fuel bills – hence contributing to reducing fuel poverty for London. Evidence
5. The characteristics of FC micro CHP units give advantages over other micro CHP options: Evidence
    a. High electrical efficiency maximises the CO_2 savings available.
    b. No moving parts means maintenance costs are reduced.
    c. Scalability of the technology means costs should be very low with volume production.
6. CO_2 savings are available in the short term using natural gas as the fuel. longer term savings can be increased with low carbon gas into the grid and / or using 100% hydrogen fuel cells. Evidence

Options for reducing emissions from dwellings and other small buildings are limited for a high proportion of London's building stock

Significant reductions in emissions will require measures to address *hard to treat* buildings

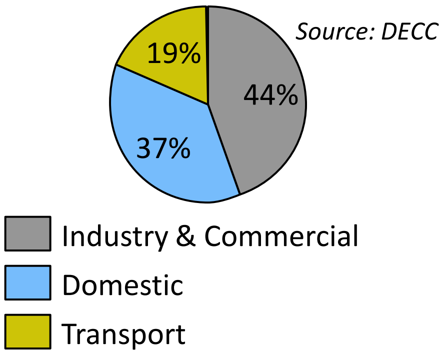
- Energy use in dwellings is responsible for around 37% of London's annual CO_2 emissions.

- Much of London's housing stock is hard to treat – i.e. characterised by:
  - **Poor thermal efficiency** – this means that heat pumps are not a viable low carbon heating option.
  - **Relatively low heat density** – supply of low carbon sources of heat via a district heating network is unlikely to be economically viable.
  - **Limited space** for renewable energy systems – e.g. limited roof space for solar thermal / solar PV, not suitable for biomass heating systems due to space constraints (for boiler and fuel storage).

- Micro-CHP is one of the very few options for reducing the carbon emissions from these properties.

- By simply swapping a boiler for a micro-CHP unit, savings of up to 30% of CO_2 emissions become viable, with larger savings available as the gas grid is decarbonised.

Estimated CO_2 emissions in London by source, 2013



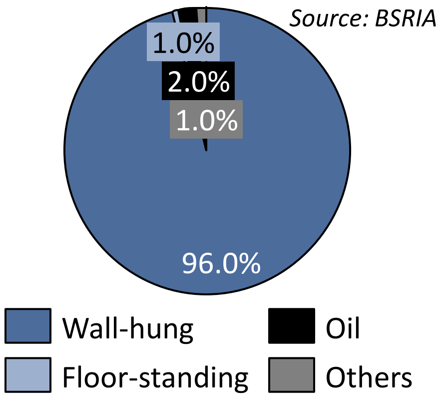
FC micro CHP systems are being developed as direct replacements for heat only boilers

2

Fuel cells are the most viable of the available technologies able to deliver the *micro CHP vision*

- ✓ FC micro CHP systems can be packaged and plumbed like a conventional boiler.
- ✓ Output temperatures – similar range to conventional boilers.
- ✓ No need for advanced thermal performance of building (which heat pumps require).
- ✓ No moving parts, hence vibration-free and very low noise.

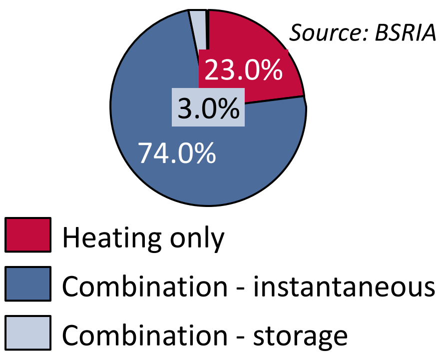
UK boiler sales by type, 2010



They will not work everywhere:

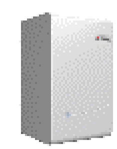
- x Payback depends on high annual run hours – first markets are in large well occupied homes or housing complexes.
- x Need for thermal energy storage (hot water tank) – at present most systems incorporate a thermal store, which will require space.
- x At present most systems are floor standing – wall hung designs may be needed for many London homes.

UK boiler sales by type, 2010



BSRIA: Building Services Research and Information Association.

FC micro CHP units are available in the UK from at least four different suppliers – the majority will provide a full boiler replacement

OEM	Model	Technical details	
Viessmann	Vitovalor 300-P	0.75 kWe, 1 to 19 kWth Electrical efficiency ~37% Overall efficiency ~90% Launched in Germany April 2014, UK launch in 2015 – based on Panasonic technology (extensive trial under ENE.FARM)	
Solidpower	BlueGEN	1.5 kWe, ~ 5.22 kWhth Electrical efficiency: up to 60% Overall efficiency: up to 85% Products developed and trialled by CFCL in UK and Europe until 2015	
Solidpower	EnGEN2500	2.5 kWe Electrical efficiency: up to 50% Overall efficiency: up to 90% Product currently in trial in partnership with British Gas in the UK	
Elcore	Elcore 2400	High temperature PEM 0.3 kWe, 0.7 kWth	

3 With more products coming to market in the coming months and years

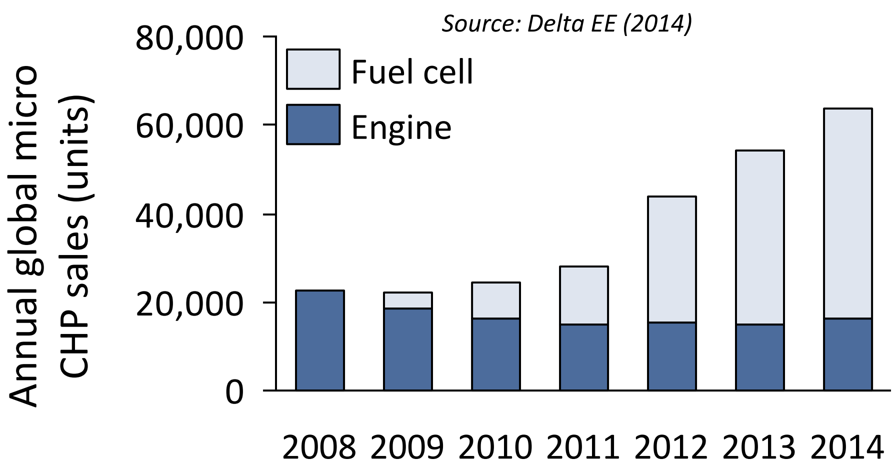
OEM	Model	Technical details	
SenerTec	Dachs InnoGen	Low temperature PEM – Floor standing 0.70 kWe First trial in Germany in 2015 – based on Toshiba technology (extensive trial under ENE.FARM)	
Bosch	Cerapower FC10 Logapower FC10	SOFC – Floor standing 0.70 kWe	
Vaillant	G5+	SOFC – Wall hung 0.70 – 1.0 kWe	
Hexis	Galileo 1000 N	SOFC 1kWe, 1.8kWth Electrical efficiency ~30 – 35% AC (LHV) Overall efficiency ~95% (LHV)	
RBZ	Inhouse 5000+	PEM FC 1.7 to 5.0 kWe, 3.0 to 7.5 kWth Electrical efficiency ~34% Overall efficiency ~92%	

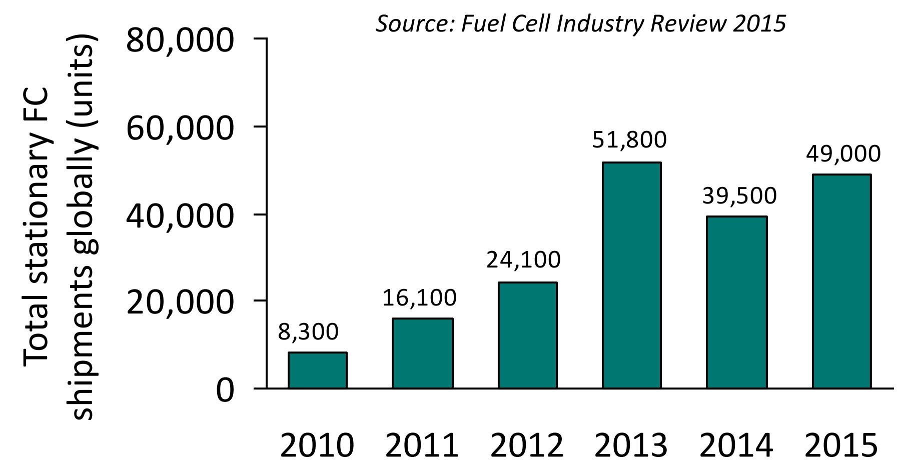
3 Advances in technical performance, ownership costs, and choice of units mean this technology is being deployed in increasing numbers

Fuel cell CHP suppliers

Japanese OEMs (e.g. Panasonic, Toshiba) have deployed tens of thousands of FC micro CHP units in Japan and are working with European boiler OEMs to bring products to Europe.

Annual shipments of micro CHP - fuel cells are now the global market leader for micro-CHP





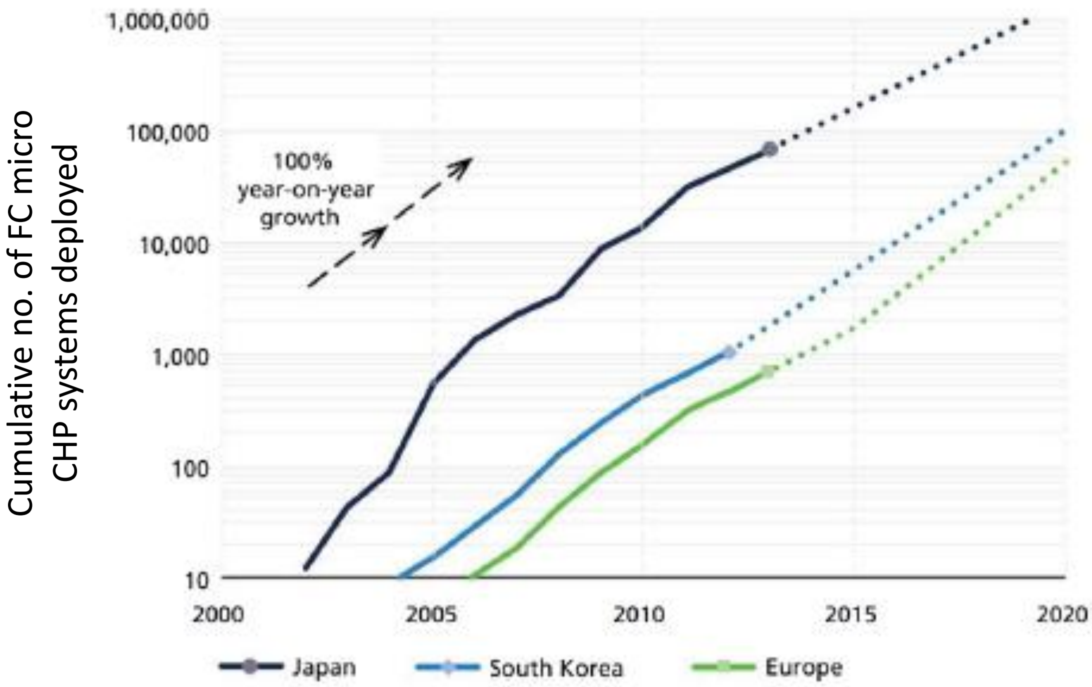
- Around 140,000 FC micro CHP units installed in Japan by October 2015.
- Around 850 FC micro CHP systems installed in Germany as part of funded projects (2008 – 2015).

3 Japan has the highest level of FC micro CHP uptake – further deployment in all markets will rely on smart subsidies and cost reductions

Fuel cell micro CHP deployment by region

FC micro CHP deployment by region

Historical growth (solid lines) and near-term projections (dotted lines)



High uptake of FC micro CHP in Japan largely driven by subsidies.

The majority of the installations in Europe are in Germany (through the Callux and ene.field projects).

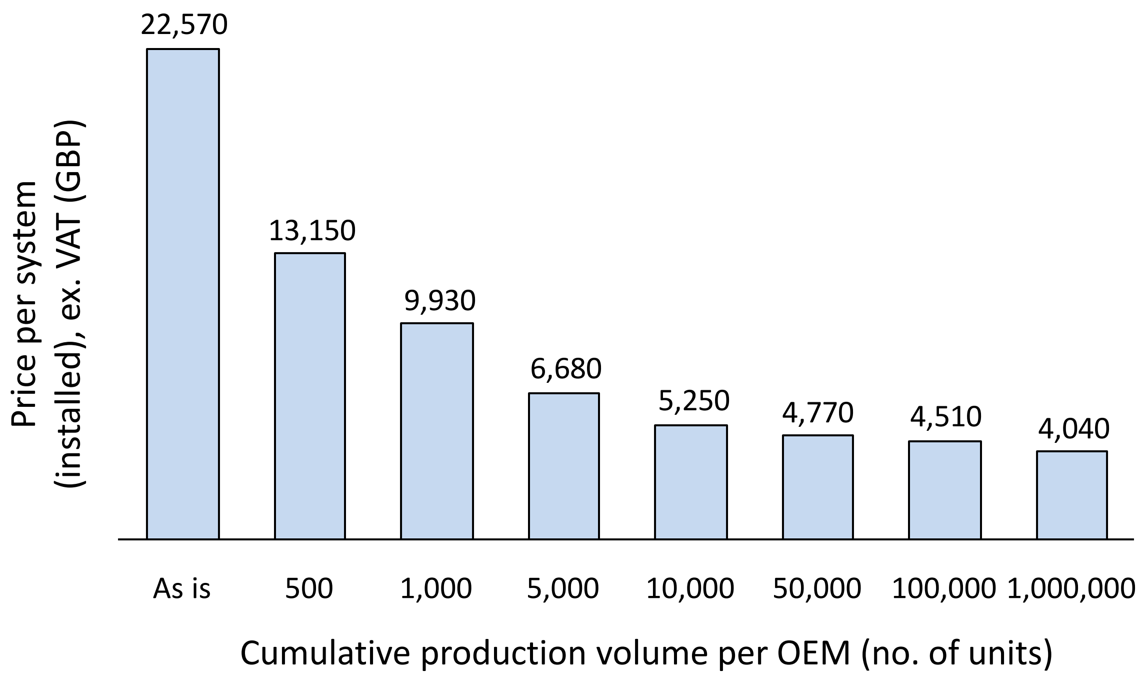
Source: Hydrogen and fuel cell technologies for heating: a review (2015), Dodds et al, International Journal of Hydrogen Energy 40, Figure 2, p.2068.

- The ene.field project is seeking to deploy a total of 1,000 FC micro CHP systems in Europe by 2017.
- A successor project is due to start in 2016 seeking to deploy thousands more systems in Europe.

Cost and performance characteristics of FC micro CHP systems are expected to improve with increasing deployment

4

Technical and cost profile of generic fuel cell micro CHP



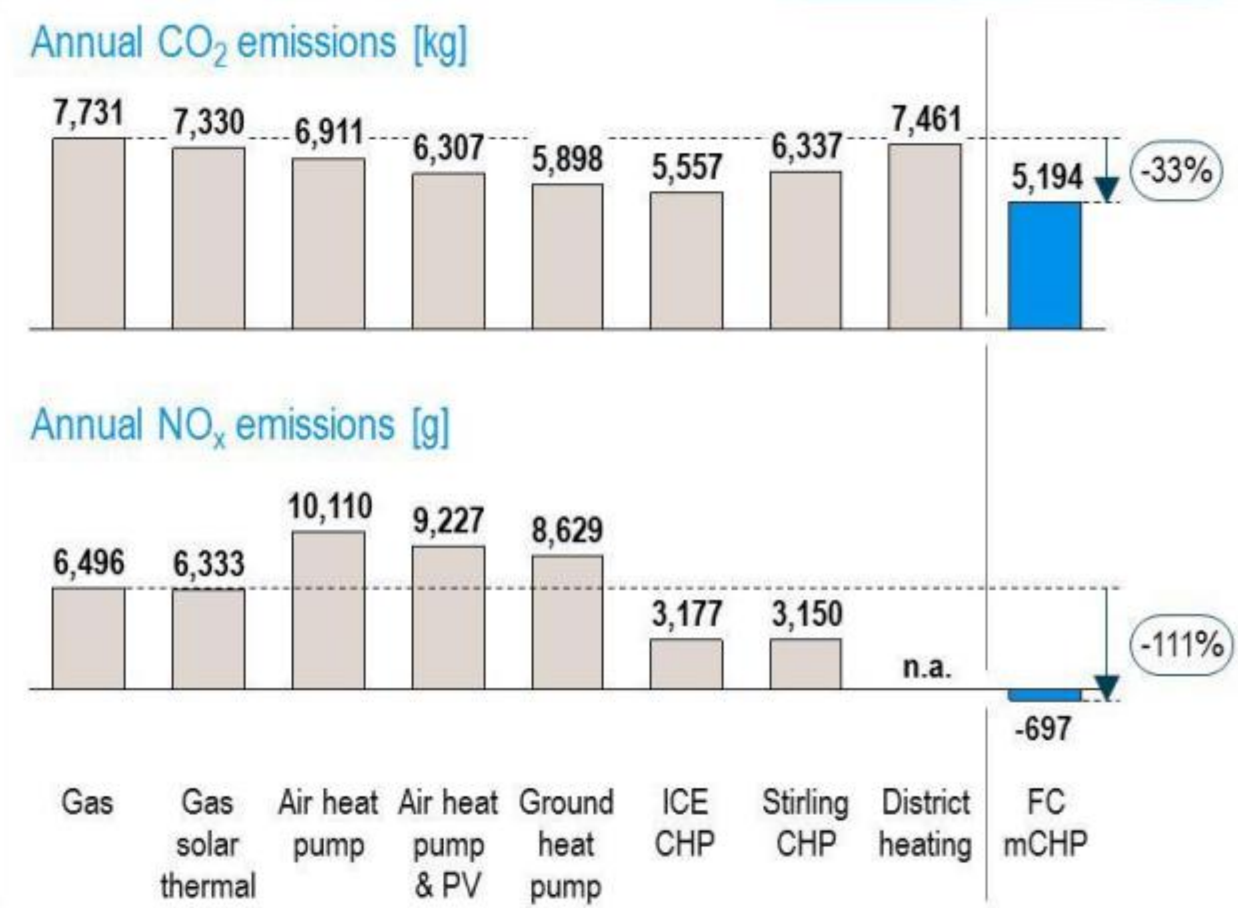
Key characteristics

- Installed capacity 1kWe, 1.45kWth
- Fuel: natural gas
- Overall efficiency: 88% increasing to 95% over time
- Electrical efficiency: 36% increasing to 42% over time
- System life / stack replacement: 10 years with two replacements, improving to 15 years without replacement over time
- Annual maintenance cost c.£360 falling to £145 over time

Source: Advancing Europe's energy systems: Stationary fuel cells in distributed generation, Roland Berger for the FCH JU (2015), Figure 38, p.82. Costs in EURO converted at 1.38 EUR per GBP.

4 High capex means that FC micro CHP is currently an expensive option, but cost reductions could see it compete with other low carbon solutions

Residents	4
Heated space	103 m²
Year of construction	1962
Heat demand	21,438 kWh
Electricity demand	5,200 kWh
Central heating	



Source: Advancing Europe's energy systems: Stationary fuel cells in distributed generation, Roland Berger for the FCH JU (2015)

ST = solar thermal, A-HP = air source heat pump, PV = solar photovoltaics, G-HP = ground source heat pump, ICE CHP = internal combustion engine combined heat and power, DH = district heating, FC CHP = fuel cell combined heat and power.

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The technical characteristics of FC micro CHP units give advantages over other prime movers

Technical and cost characteristics of micro CHP technologies – a comparison

Characteristic	Unit	Gas boiler (condensing)	Micro CHP (combustion engine)	Micro CHP (Stirling engine)	Micro CHP (fuel cell)
Thermal capacity of main system	kWth	<35	2.5	5.3	1.45
Electrical capacity of main system	kWe	-	1	1	1
Heat to power ratio	-	-	2.5	5.3	1.45
Thermal capacity of auxiliary system	kWth	-	<35	<35	<35
Thermal efficiency of main system	-	95%	65%	81%	52%
Electrical efficiency of main system	-	-	26%	15%	36%
Thermal efficiency of auxiliary system	-	-	95%	95%	95%
Total installed cost of packaged system (ex. VAT)	GBP	1,260–2,030	12,030–14,640	11,020–14,840	22,570
Annual maintenance cost (ex. VAT)	GBP	40–140	650–800	90–310	360
Lifetime	Years	15	15	15	15

High electrical efficiency and high power to heat ratio of fuel cell CHP gives more favourable economics on opex basis (more high value electricity generated).

Capex of FC CHP systems remains higher than for alternative solutions. Data from a recent case study suggests total installed capex of a SOFC micro CHP system in London in 2015 was around £16,000.*

Source: tabulated data from Advancing Europe's energy systems: Stationary fuel cells in distributed generation, Roland Berger for the FCH JU (2015), Figure 47, p.109. Costs in EURO converted at 1.38 EUR per GBP.

* www.cibseblog.co.uk/2015/03/case-study-cibse-fuel-cell-part-2-of-3_80.html.

CO$_2$ savings can be achieved by fuel cells running on natural gas today, and could be increased through use of decarbonised gas supplies

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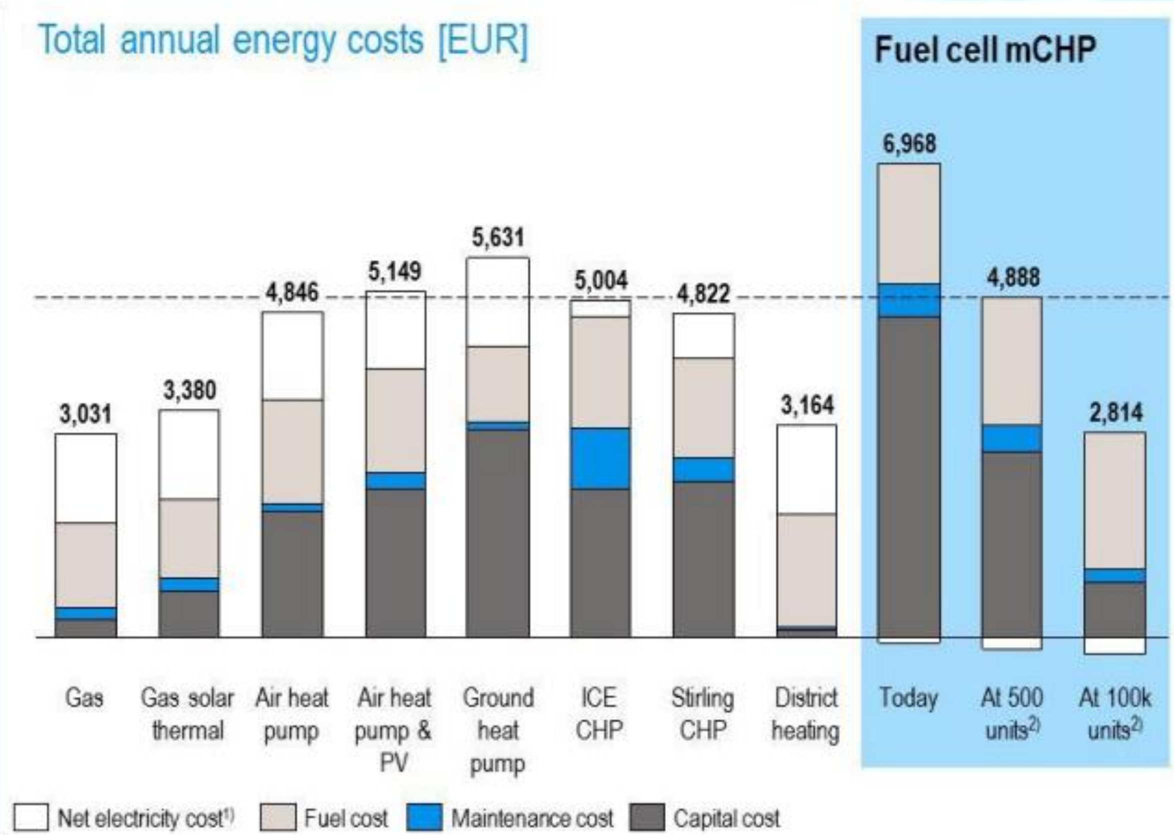
MUNICH

Fuel cell micro-CHP system

Electric capacity	1 kW$_{el}$
Thermal capacity	1.45 kW$_{th}$
Electric efficiency	36%
Thermal efficiency	52%
System lifetime	15 years
Required stack replacements	2



1) Negative electricity cost reflect higher earnings from power feed-in than residual purchase of grid power. 2) Cumulative production volume per company.

These figures imply the FC CHP system gives a CO$_2$ saving of ~30% compared to the gas boiler (+ grid electricity). In practice emissions savings from micro CHP are sensitive to a range of factors: electrical efficiency of the system, ratio of heat to power demands of the building, carbon intensity of grid electricity, etc.

Source: Advancing Europe's energy systems: Stationary fuel cells in distributed generation, Roland Berger for the FCH JU (2015) ST = solar thermal, A-HP = air source heat pump, PV = solar photovoltaics, G-HP = ground source heat pump, ICE CHP = internal combustion engine combined heat and power, DH = district heating, FC CHP = fuel cell combined heat and power.