Polymer Fuel Cells – Cost reduction and market potential

A report by the Carbon Trust based on independent analysis

September 2012

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1. Executive Summary

UK breakthroughs in polymer fuel cells could make fuel cell cars cost competitive with combustion engine cars – doubling the number of fuel cell cars on the road globally by 2030 versus current projections

Battery electric vehicles are more efficient and potentially have lower carbon emissions than traditional internal combustion powered cars, but issues with recharging, range and price mean that a third alternative – fuel cell electric vehicles (FCEVs) – could take over 30% of the mid-sized car market by 2050. That's a long way off, but by 2015 the major car manufacturers expect to roll-out their first few thousand FCEVs into countries such as the UK, Japan, Germany and the US, where plans are already developing to build the hydrogen infrastructure needed to refuel them. The Polymer Electrolyte Membrane Fuel Cell (PEMFC) technology to power such vehicles is forecast to steadily reduce in cost, but this will take time. This report looks at three breakthrough UK technologies that could bring about a disruptive step-change in cost reduction to accelerate consumer uptake, leading to approximately double the number of fuel cell cars on the road globally by 2030 versus current expectations. Some of the technologies discussed in this report could be under the bonnet of the next generation of FCEVs as early as 2020.

PEMFCs operate at lower temperatures and are smaller and lighter than other fuel cells, making them more suitable for use in cars and vans. PEMFCs have no moving parts and use electrodes on either side of a polymer membrane to convert hydrogen fuel and air into electrical power, heat and water, with the help of a platinum catalyst. In vehicle applications, electrical power produced by a series of cells (a fuel cell stack) is used to drive electric motors that drive the wheels. The result is that FCEVs typically have significantly higher real-world drive cycle efficiencies than internal combustion engine vehicles, and have no tailpipe emissions besides water when fuelled by pure hydrogen.

According to independent analysis commissioned by the Carbon Trust, current state-of-the-art polymer fuel cell technology is predicted to cost $49/kW in automotive applications when manufactured at mass scale (i.e. 500,000 units per year). However, in order to be competitive with internal combustion engine vehicles, automotive fuel cells must reach approximately $36/kW. Cost savings can be achieved by reducing material costs (notably platinum use), increasing power density, reducing system complexity and improving durability.

The Carbon Trust recognised both the need and potential for cost breakthroughs in vehicle fuel cells in 2009 and set up the $10m Polymer Fuel Cells Challenge to find and accelerate the development of technologies that could meet the $36/kW target, as illustrated in Figure 1. This initiative is now in its second phase, in which three groups developing fuel cell systems that could achieve this step-change in cost are moving from feasibility testing towards commercial development with partners:

- **ITM Power** have developed a membrane that has the potential to roughly double the power density of a cell, producing more 'bang' for the platinum 'buck';
- **ACAL Energy** have developed a liquid cathode that has the potential to reduce platinum use by at least two thirds, and eliminates the need for some standard components of a fuel cell; and
- **Imperial College (IC) London and University College London (UCL)** have developed a novel stackable cell architecture that uses low-cost materials and manufacturing techniques with breakthrough potential in terms of cost reduction. Note that this technology is at an earlier stage than those of the other companies.

Carbon Trust is also working with **Ilika** in Phase 2 – a company specialising in developing new materials – to test their palladium ternary alloy which has the potential to deliver a 70% reduction on catalyst costs on a cost / performance basis against platinum.[1]

Details of work to be carried out in the next phase are given below:

- **ITM Power** – Conduct performance and durability testing of membranes at low catalyst loading; address scale up to full size (250cm^2) automotive cells; engage with automotive partner(s).
- **Acal Energy** – Develop a 10 kW (1/8th scale) automotive stack capable of achieving car makers' current targets for cost, size, weight and durability; demonstrate ability to handle cold start requirements; facilitate partnering with automotive OEM's.
- **IC / UCL** – Create an investable Special Purpose Vehicle (SPV); demonstrate a 1 kW stack in 9 months.
- **Ilika** – Select a partner to manufacture 1 kg scale quantities of the catalyst; send material to car companies for pre-commercialisation testing; confirm the stability of the material at higher voltages.

This report presents the results of independent analysis commissioned by the Carbon Trust. This analysis indicates that each of the three system-level technologies has the potential to meet the $36/kW cost target, and shows that fuel cells with this level of cost performance could increase the deployment of FCEVs by 200m by 2050. These extra FCEVs would increase the value of the global FCEV market by $30bn to $261bn by 2050. The market modelling takes into account a number of factors that a typical car buyer might consider when making a purchase, including vehicle performance and total cost of ownership.

The carbon case is also projected, considering how hydrogen production might change from natural gas reforming to using renewable or low carbon powered electrolysis. This shows that if the $36/kW cost target can be achieved, it would reduce global carbon emissions from vehicles by an additional 260 million metric tonnes per year (260 $MtCO_2e$ per year – approximately equivalent to the annual emissions of Taiwan) by 2050. This step-change in cost is also likely to unlock other markets for PEM fuel cells besides FCEVs, such as combined heat and power (CHP) and stationary power applications, leading to an additional 160 $MtCO_2e$ per year of savings (approximately equivalent to the annual emissions of Pakistan) by 2050.

[1] See Annex D for further details

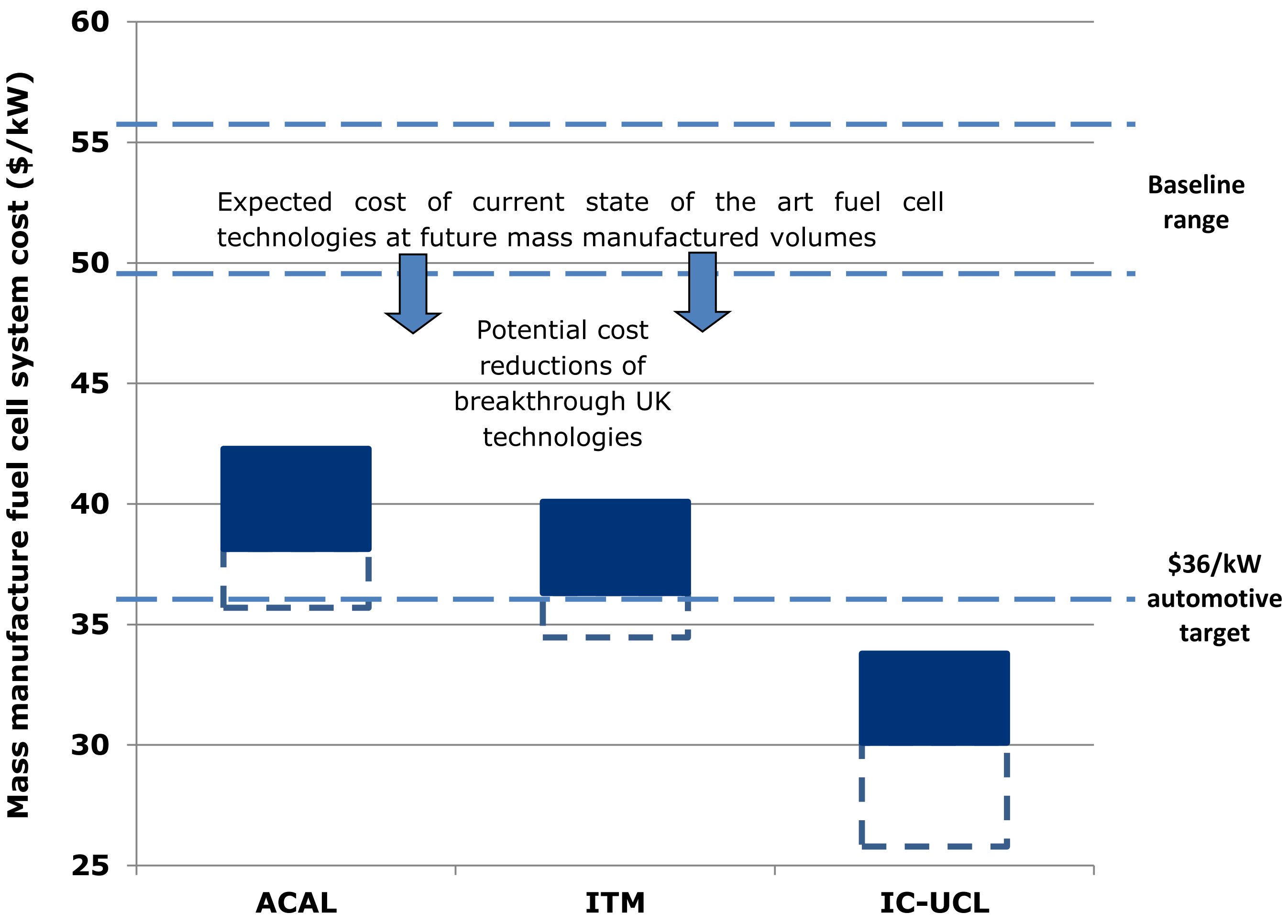

Figure 1: Ranges of automotive fuel cell system costs at mass manufactured volume.
Notes: The industry baseline and technology of each Polymer Fuel Cells Challenge (PFCC) system-level project team are shown. Solid blue bars represent the range of model outputs, and dotted bars estimate inclusion of benefits outside the standard fuel cell system boundary. Source: Carbon Trust, E4Tech and Austin Power Engineering analysis. Underlying data: from PFCC teams and, for the industry baseline, publicly available data related to competing technologies.

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2. Background and Context

The role of fuel cells

All fuel cells are similar in structure. At their heart is an electrochemical device, which allows the transfer of ions (but not electrons) through a membrane, forcing electricity to flow round an external circuit. This electro-chemical process is highly efficient and requires no moving parts.

Subsystems and peripherals control the flows of fuel and oxidant, product water, power and heat. Fuel cells need fuels (e.g. hydrogen); they are not energy sources in their own right, but better described as energy conversion devices.

In a PEMFC, hydrogen molecules are split into positive hydrogen ions (protons) at the cathode and (negative) electrons at the anode. Once they have flowed their separate ways, they recombine with oxygen to form water at the cathode on the other side of the membrane (see Figure 2).

Catalysts – such as the precious metal platinum – are usually deposited in small amounts on the cathode and anode to speed up both reactions.

FCEVs use electric drivetrains powered by a fuel

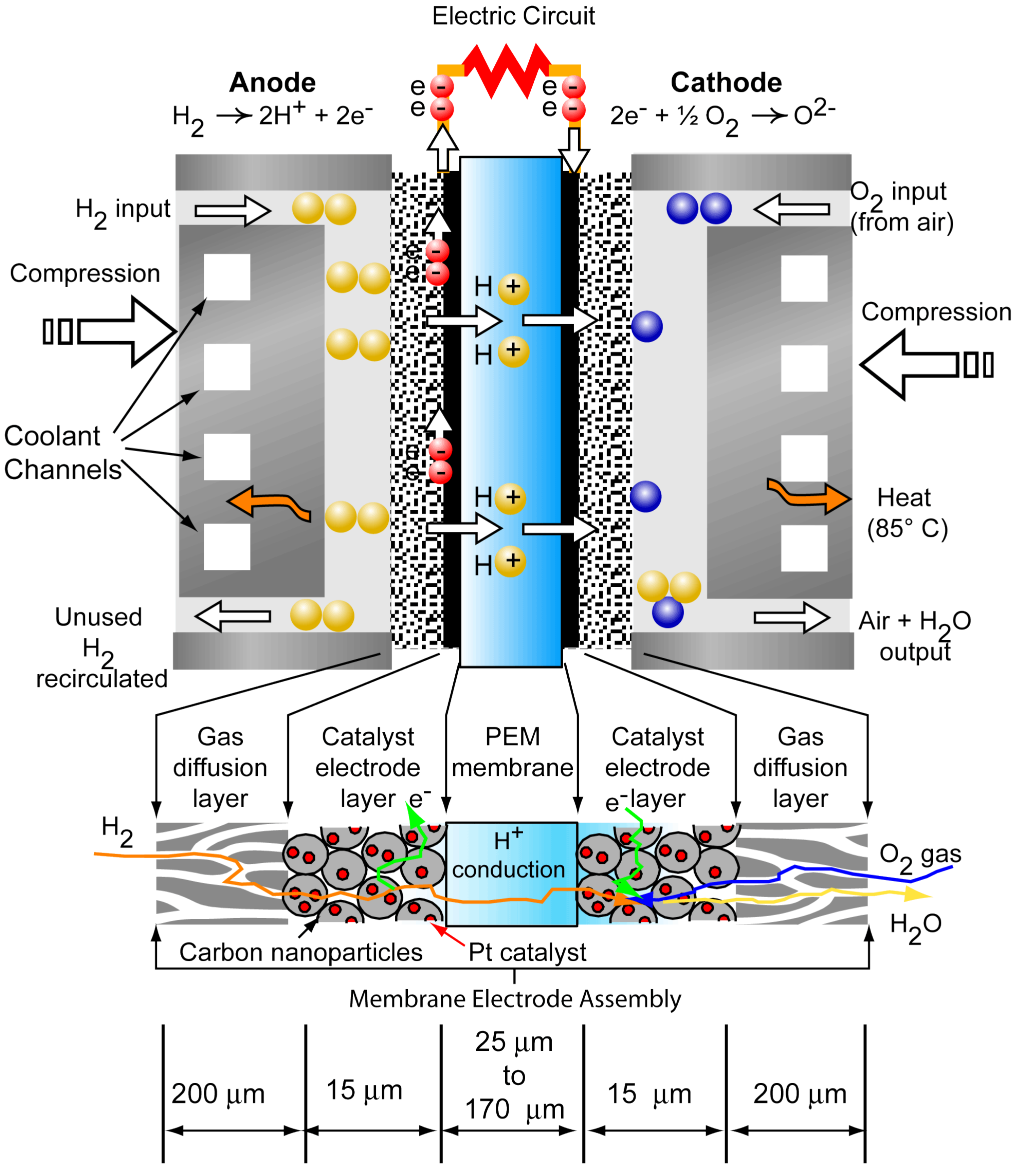


Figure 2: Diagram of a PEM fuel cell.
Source: US National Institute of Standards and Technology

cell. Several types of fuel cell exist, but PEMFCs are particularly well-suited to automotive applications due to their low weight, small size, high durability, quiet operation, and responsive power output.

Fuel cells could be powering up to 491 million cars by 2050 (Carbon Trust, E4Tech and Austin Power Engineering analysis) – a third of all the cars on the road. Governments around the world increasingly recognise the role FCEVs could play in the future low carbon transport mix, and several countries have made serious commitments to accelerate their uptake. Meanwhile, car makers have spent billions of dollars on the development of FCEVs to date, and stated their intentions to start low-volume mass production and commercial sales in 2015 (see Box 1 for further information about global commitments to fuel cells).

Box 1 - Global commitments to fuel cell vehicles

In September 2009, leading car manufacturers signed a Letter of Understanding stating their intentions to target 2015 for the commercial roll-out of FCEVs. The signatories included Daimler, Ford, GM/Opel, Honda, Hyundai, Kia, Renault, Nissan and Toyota. Recognising the importance of FCEVs as one of their main options to meet CO_2 reduction regulations, automotive companies have spent over $6bn on the development of FCEVs to date (Source: comment by Daimler at the World Hydrogen Energy Conference, 2012).

In certain markets – such as fork-lift trucks, back-up power for telecoms base stations, and leisure activity auxiliary power units – fuel cells are already seeing initial commercial success. The main challenge preventing PEM fuel cells from entering larger markets – including micro-CHP and automotive markets – is their cost; pre-commercial fuel cell vehicles currently cost over $130,000.

According to Carbon Trust, E4Tech and Austin Power Engineering analysis, projected economies of scale and learning effects are expected to reduce this cost to approximately $49/kW (at mass production volumes, i.e. after the year 2030). However, according to that same analysis, **to compete with ordinary internal combustion engine (ICE) vehicle costs on a total cost of ownership (TCO) basis, automotive fuel cells must reach approximately $36/kW** (see Box 2). This is equivalent to $3,060 for an 85kW system, which would be suitable for an average mid-size car. These PEM fuel cell system-level cost reductions will also unlock other markets such as combined heat & power (CHP). Breakthrough cost reductions, beyond current trends, are required to reach this $36/kW automotive target.

Box 2 – Why the $36/kW target

Prior to the 2009 market modelling, Carbon Trust commissioned analysis to establish what price a FCEV would need to reach to be cost competitive with an ICE vehicle on a TCO basis. The TCO for the ICE was calculated by modelling:

- Retail Price (power train, energy storage, transmission, control, chassis, body and markup costs)
- Fuel costs
- Maintenance costs

and summing the outputs. Using a bottom-up modelling approach for a FCEV to calculate the retail price (minus the power train), fuel costs and maintenance costs, a target power train cost could be calculated to make the FCEV cost competitive with the ICE.

Consumer attitudes towards the safety of hydrogen fuelled vehicles could potentially be a factor limiting their uptake. However, the issues around safety are being addressed through the development of sufficient codes and standards for equipment design, manufacturing practices, operation and maintenance procedures, and through extensive research and testing (European Commission, 2006[2]). It is expected that the misconception that hydrogen vehicles are less safe than internal combustion engine vehicles can be corrected through public

[2]ftp://ftp.cordis.europa.eu/pub/fp7/energy/docs/hydrogen_22002_en.pdf

information campaigns and appropriate field tests and demonstrations (NETL, 2002[3]).

In addition, Liquid Petroleum Gas (LPG), which potentially has similar issues related to perception of safety, has been used for road transport applications in a number of countries for several decades.

Hydrogen Infrastructure

FCEVs fuelled by hydrogen will produce no tailpipe emissions other than water, and will have the long driving range and fast refuelling that car users have come to expect. If the hydrogen is generated from clean sources, fuel cells could offer a very low carbon means of transport.

Approximately 60 million tonnes of hydrogen are produced annually (IEA 2007[4]). The cost is heavily dependent on the cost of the particular fuel or electricity used as a feedstock, but current estimates indicate a cost of about $2/kg (NETL, 2002). To support the market deployment scenarios presented in this report, an additional 70 million tonnes of hydrogen will need to be produced annually by 2050.

Significant investments are being made to scale-up hydrogen production. It is expected that costs of existing higher-carbon production methods such as steam methane reforming (SMR) and coal gasification will increase in the future due to increasing fossil fuel prices and costs of carbon – partly offset by technology advancements. At the same time, it is expected that a variety of technologies and feedstocks will be developed that are able to produce clean, CO_2-free hydrogen in the future. These include:

- Thermo-chemical conversion of fossil fuels with carbon capture and storage (CCS), using SMR or coal gasification. These are expected to be the most cost effective future production methods;
- Biomass gasification, with or without CCS, and
- Use of renewable or nuclear (i.e. low carbon) electricity for water electrolysis.

Figure 3 compares the future costs and emissions of various hydrogen production methods.

Costs of water electrolysers are expected to reduce due to efficiency and design improvements. In calculating vehicle fuel costs, the power price assumed ($0.21/kWh) reflects that electrolyser units can be run intermittently, providing a balancing solution for the power grid, although this is dependent on scale and location.

Sufficient hydrogen to fuel the projected FCEV fleet can be produced cost effectively on both a small and large scale – from 0.4 to 1,000 tonnes per day – from centralised or decentralised production (McKinsey[5], 2010).

Hydrogen with negative CO_2 emissions could also be produced using biomass gasification with CCS, although is likely to be expensive. Biogenic carbon taken from the atmosphere would be sequestrated underground as CO_2, with only the hydrogen extracted from the syngas.

Sales of FCEVs are obviously dependent on the existence of the hydrogen infrastructure required for fuel and the interest of car manufacturers in entering this market. We are relying on national hydrogen initiatives such as UKH2Mobility to overcome the obstacles there which include: the current high cost of hydrogen production as discussed already; the cost of installing hydrogen re-fuelling infrastructure; and space restrictions at fuel stations where there will be a need to continue to store conventional fuels while also creating the underground space required to safely house hydrogen tanks (see Box 3 for global commitment to hydrogen infrastructure).

[3] http://www.netl.doe.gov/technologies/hydrogen_clean_fuels/refshelf/pubs/The%20National%20Hydrogen%20Vision.pdf

[4] http://www.iea.org/techno/essentials5.pdf

[5] http://www.iphe.net/docs/Resources/Power_trains_for_Europe.pdf

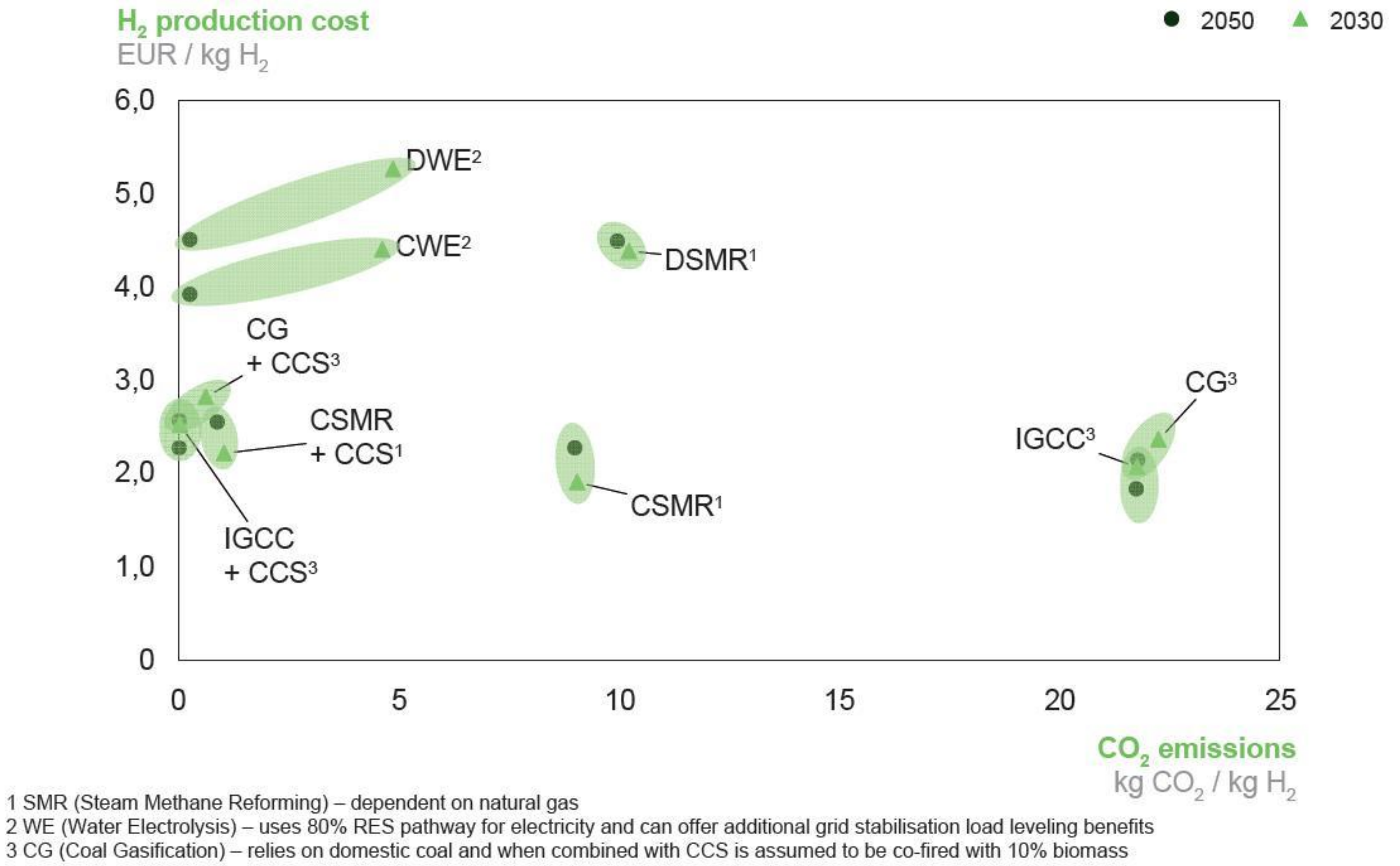


Figure 3: Carbon intensity and future costs of different H_2 production methods

Source: McKinsey, 2010

Key: CCS – CO_2 Capture and Storage; CG – Coal Gasification; CSMR – Central Steam Methane Reforming; CWE – Central Water Electrolysis; DSMR – Distributed Steam Methane Reforming; DWE – Distributed Water Electrolysis; IGCC – Integrated Gasification Combined Cycle

The modelling underpinning this report follows the assumptions about hydrogen infrastructure made in the McKinsey 2010 Powertrains for Europe study. Hydrogen production, delivery and storage technologies for vehicles are close to technically mature, but to achieve suitable utilisation and make them cost-effective, an orchestrated investment plan is required to build up the first critical mass of hydrogen supply.

Box 3 - Global commitments to hydrogen infrastructure

Germany launched the H2Mobility[6] initiative in September 2009, to evaluate options for an area-wide roll-out of hydrogen fuelling stations in Germany, then agree and implement a joint business plan to deliver. Partners involved include Daimler, EnBW, Linde, OMV, Shell, Total and Vattenfall.

The UK Government launched its own UKH2Mobility[7] initiative in January 2012, to analyse the case for introducing FCEVs to the UK, and then develop an action plan for roll-out by 2015. The industry partners involved include Air Liquide, Air Products, BOC Group, Daimler, Hyundai, Intelligent Energy, ITM Power, Johnson Matthey, Nissan, Scottish and Southern, Tata Motors, Toyota and Vauxhall.

Major "Hydrogen Highway" schemes have also been set up in California[8], Scandinavia[9] and Japan[10].

[6] http://www.greencarcongress.com/2009/09/h2-mobility-20090910.html
[7] http://nds.coi.gov.uk/content/Detail.aspx?ReleaseID=422877&NewsAreaID=2
[8] http://www.hydrogenhighway.ca.gov/
[9] http://www.scandinavianhydrogen.org/
[10] http://www.japantimes.co.jp/text/nn20110118f1.html

3. The role of UK technology in reducing fuel cell costs

When the Carbon Trust launched the PFCC in 2009 it carried out a detailed analysis to determine the target cost reduction that would be needed to make FCEVs cost competitive with ICEs. A breakthrough in PEM fuel cell technology is needed in order to achieve the $36/kW automotive cost target that this analysis implied.

The Carbon Trust identified that breakthroughs in the following PEM fuel cell areas would have large cost benefits:

- Improving the power delivered per unit weight and volume;
- Reducing the amount of platinum used in the catalysts;
- Reducing the fuel cell system complexity and the number of air, fuel, heat and water management components; and,
- Improving durability, especially of many of the novel materials being used.

The UK has world-renowned industrial and academic expertise in the areas of polymer fuel cell technology, chemical processes and materials science – all these are directly relevant to addressing the cost challenge. Recognising these strengths, the Carbon Trust launched the PFCC[11] in September 2009 (see Box 4 for further information about the PFCC).

A nationwide competition was run to select the most promising UK PEM fuel cell technologies. After an extensive due diligence process, three teams out of 15 were selected for Carbon Trust Phase 1 funding:

- ACAL Energy;
- ITM Power; and,
- Imperial College London & University College London.

Box 4 – The Carbon Trust Polymer Fuel Cells Challenge

The PFCC aims to accelerate the commercialisation of breakthrough polymer fuel cell technologies to enable the step-change in cost needed to unlock mass-market applications. Its objectives are to:

1. Reduce system cost to $36/kW;
2. Demonstrate a system at 5-10kW scale; and
3. Secure a development and supply agreement for at least one technology.

To achieve these ambitious objectives, the Carbon Trust has been working with internationally renowned polymer fuel cell experts to structure the programme so that it is market-oriented and end-user focused, using the following approach:

- Selection of the best UK technologies with the help of leading experts;
- Structuring of investments to accelerate commercialisation, and recoup capital;
- Provision of leading expert technical support to guide technology development; and
- Provision of business support and network to engage auto-OEMs (Original Equipment Manufacturers).

The $10m initiative has two phases:

$3.5m	**Phase 1**: De-risk technologies and demonstrate feasibility. Carbon Trust support and network used to build industry partnerships and set development targets meeting customer specifications
$6.5m	**Phase 2**: Industry partners and Carbon Trust investing to accelerate the commercialisation of the most promising technologies leading to a development licence or supply contract with a major customer/manufacturer

[11] http://www.carbontrust.co.uk/emerging-technologies/current-focus-areas/fuel-cells/pages/fuel-cells.aspx

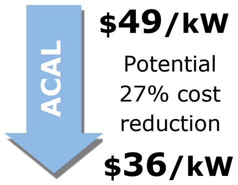
4. The breakthrough UK fuel cell technologies

Outlined below are the three system-level breakthrough UK technologies that could meet or beat the automotive cost target of $36/kW:

- **ACAL Energy**: zero-platinum liquid catalyst;
- **ITM Power**: high power density membrane; and,
- **IC-UCL**: novel stackable board architecture

Full case studies for each of these projects are provided in Annexes A to C. In addition, in Annex D there is a case study for the Ilika project developing new catalyst materials. For each system-level breakthrough technology, the down arrow icons show the scale of potential cost reduction achievable versus the expected costs of conventional state of the art technologies at mass production volumes ($49/kW).

ACAL Energy



ACAL Energy's patented FlowCath® fuel cell design, illustrated in Figure 4, uses a liquid polymer cathode solution, which replaces the platinum-based solid cathode used in standard PEM fuel cells. This represents a fundamental design breakthrough that has the potential to reduce expensive platinum use by at least two thirds, reduce the number of components within the overall system (by avoiding fuel humidification and water recovery), and increase durability (as it replaces the solid cathode of typical systems, which usually suffers performance degradation that limits product lifetime). It is the world's highest performing system with a platinum-free cathode, and shows potential for power densities of 1 W/cm^2 and higher.

The Carbon Trust invested £1m of funding to support ACAL Energy's development of FlowCath® for automotive applications in March 2011 and in July 2012 provided a further investment of £850k. These funds will contribute towards the development of a 10 kW (1/8th scale) automotive stack capable of

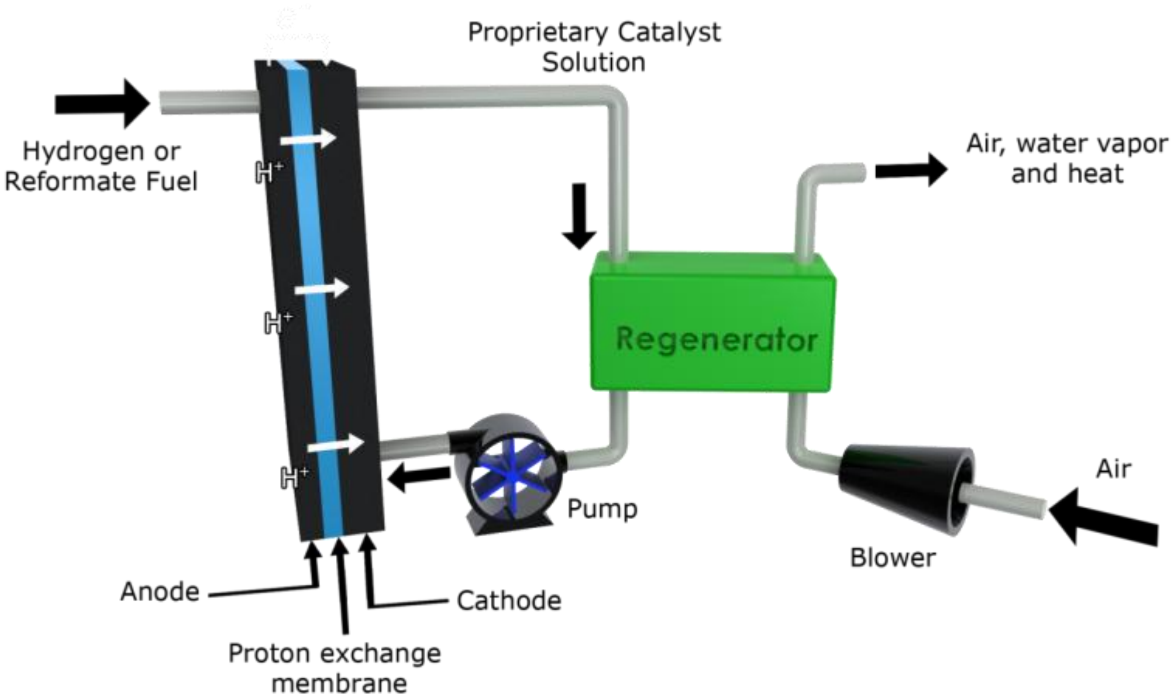
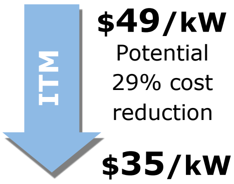


Figure 4: FlowCath® half-cell and regeneration system

achieving car makers' current targets for cost, size, weight and durability.

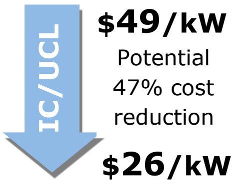
ITM Power



ITM Power's patented membranes use low-cost, low toxicity materials (ionic polymers) instead of the perfluorosulfonic acid membranes that are the current industry standard. ITM Power have the highest ever published power density of >2.1 W/cm^2 in H_2-air, as illustrated in Figure 5. This ultra-high power density membrane has the potential to radically reduce the cost, size and weight of PEM fuel cells. This is because higher power densities translate into more power per cell; hence a much smaller, lighter stack can meet the same power output.

ITM Power's original testing used oxygen as the oxidant, while automotive applications use air, simplifying the system but reducing power densities. In Phase 1 of the PFCC the Carbon Trust provided £200k of funding for ITM's initial membrane work and H_2-air testing, which produced power densities that are double the norm (>2.1W/cm^2). ITM Power have since worked with other commercial organisations including OEMs and industry leaders globally, who have replicated these results using ITM Power's membranes in their own systems. In July 2012 the Carbon Trust invested £1.1m in ITM Power to contribute towards the development of a full-scale active area automotive cell capable of achieving a power density of 2 W/cm^2 at low platinum loading (0.3 mg/cm^2).

Imperial College & University College London



IC and UCL have developed a new fuel cell stack design. This modular 'Flexi- Planar' design uses a layered arrangement of laminated, printed circuit board materials, bonded on top of each other to create a fuel cell stack with internal fuel, water and air channels. These boards lead to cost benefits over conventional fuel cell systems by eliminating the need for several components that are normally used in a conventional fuel cell. The biggest areas for potential cost reduction are air-, fuel- and water-management, sealing (no gaskets or

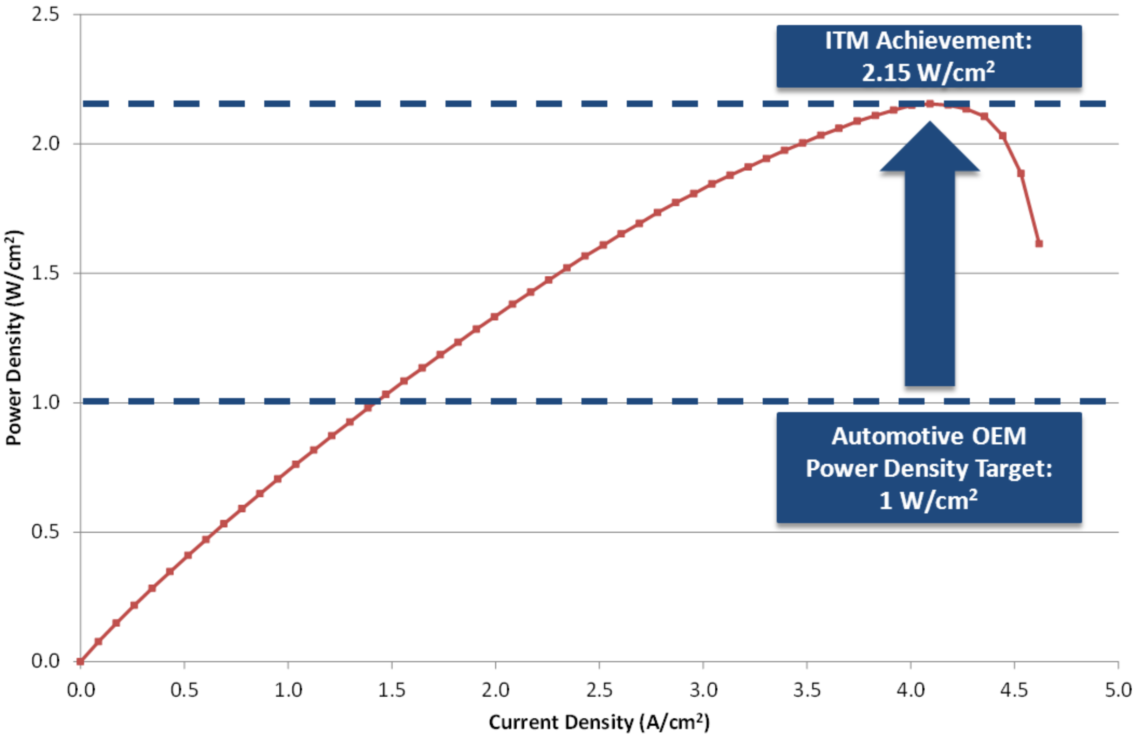


Figure 5: Performance of ITM Power membrane in H_2/air compared to automotive target

frame required) and stack assembly. The boards are also easy to assemble, and can be made using low-cost, high volume manufacturing techniques. The team's Flexi-Planar technology can also be used with many types of fuel cells, and the inherent fault tolerance means the systems are more tolerant of materials variations, allowing the use of lower cost materials and components. The team is engaging with customers in both automotive and micro-CHP applications to develop product-specific requirements for the next stage of technology development.

To date, the Carbon Trust has provided £750k of PFCC funds to develop a proof of concept prototype arrangement of flexi-planar cells.

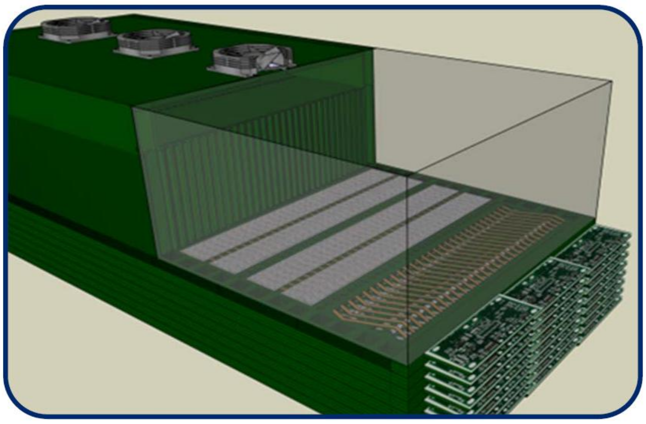


Figure 6: Model of a Flexi-Planar stack, with cut-away

5. Modelling Methodology

The cost and market modelling undertaken for this study used the following steps:

1. Gather input technical parameters from each PFCC team
2. Bottom-up cost modelling gives $/kW fuel cell system costs (and external benefits included)
3. Evaluate technical competitiveness of FCEV, PHEV and ICE
4. Evaluate cost competitiveness based on total cost of ownership (TCO) over 3 years for FCEV, PHEV and ICE
5. Estimate purchase probability, based on normal distribution of technical and cost competitiveness
6. Monte Carlo analysis to determine most likely long-run market shares
7. Bass Diffusion to determine uptake deployment curves
8. Calculate sales figures based on deployment and retirement of each vehicle type
9. Calculate market value of PEMFC drivetrains based on vehicle sales plus ongoing fuel and maintenance costs
10. Calculate CO_2 savings based on difference in Well-to-Wheels emissions factors and projected vehicle deployment

Cost modelling by vehicle

Each project team provided E4tech and Austin Power Engineering with the necessary cost modelling input data including operating points, power densities, platinum loadings, a bill of materials for their system, and information about how their innovation affects key system components.

Fuel cell system costs for each project team were then projected at mass manufacturing volumes by E4tech and Austin Power Engineering, using a cost model specifically developed for the PFCC. This uses a bottom-up approach, complimented by experience-based methodologies, to determine the cost of major stack and balance of plant components.

The case studies give further detail of the cost savings by component. A platinum price of $1,600/troy oz has been used throughout the cost modelling, based on traded prices in early 2012. This is a conservative assumption, compared with expected platinum price rises in future. See Box 5 for further discussion of platinum costs and use.

Box 5 - Platinum use

Platinum (Pt) is a precious metal, with around 250 tonnes/yr[12] currently mined in South Africa, Russia and North America. Estimated[13] world reserves are >30,000 tonnes. Pt trades[14] on international markets for around $1,600/troy oz ($52/g) currently, although its price has been volatile[15]. Given its high value, the majority of Pt used in FCEVs is likely to be recycled at the end of life of the vehicle.

Figure 7 – Platinum prices 2002-2012
Source: Johnson Matthey[16]

FCEVs using a baseline PEM fuel cell technology are estimated to require around 17g ($884) of Pt per mid-sized passenger car, although car makers are looking at reducing this to only 10g ($520) in the future. With an estimated 491 million FCEVs on the road globally in 2050, this would equate to 4,910 tonnes of Pt in use. At global sales of 37 million FCEVs in 2050, the Pt requirement in that year alone would be 370 tonnes of Pt ($19bn at current prices), and 148% of 2012's Pt market. While considerable Pt resource remains to be exploited, a risk of future short supply nevertheless exists.

However, both ACAL Energy's and ITM Power's technologies have the potential to use as little as approximately 4g ($208) of Pt per FCEV. With these technologies adopted across the global fleet, this would only require 208 tonnes of Pt/year to be produced or recovered by 2050 (valued at $11bn at current prices). The PFCC therefore has potential to minimise expansionary pressures placed on the Pt market, despite increased FCEV deployment.

[12]http://www.platinum.matthey.com/uploaded_files/Int_2011/press-release-tonnes-final.pdf
[13]http://www.lenntech.com/periodic/elements/pt.htm
[14]http://platinumprice.org/
[15]http://www.regalgoldcoins.com/platinum-price-chart

Fuel cell system costs also depend on factory scale/manufacturing volumes, which were set at current automotive standards of 500,000 units per year (i.e. a level not likely to be seen before 2030). Different scenarios can be run, with altered parameters and the choice of components and fabrication processes included, to determine key cost sensitivities. The key factors that influence fuel cell system costs are power density, platinum loading, and complexity of system-level componentry.

Each project team intends to bring to market different fundamental research breakthroughs, each with the potential to disrupt current fuel cell industry paradigms, and bring down system costs. At mass manufacture volumes, the PFCC technologies are projected to achieve system-level cost reductions of between **14% and 39%** versus what fuel cells are currently expected to achieve in 2050 without these interventions, depending on the level of optimism regarding the input parameters. This is shown by the solid blue bars in Figure 8. Also shown in this figure for comparison are the baseline costs at mass-manufacture volumes for current state-of-the-art technology based on the most recent published advances in polymer fuel cell technology by competitors. However, some of the benefits of the PFCC technologies are not fully captured in the cost modelling – either because of the system boundary definition (e.g. IC-UCL have electronic power controls within each module, which are not included within the baseline system costs), or because these capital costs do not include some of the operational cost and technical benefits (e.g. improved fault tolerance and durability). In order to display the impact that including some of these additional benefits within the fuel cell system boundary would have on the overall $/kW capital costs, dotted bars are included to show the potential minimum cost estimate. These additional benefits have the potential to increase system-level cost savings to reach a level of between **19% and 48%** vs. the baseline. Including these additional benefits

[16]http://www.platinum.matthey.com/pgm-prices/price-charts/

means that the Acal, ITM and IC/UCL PFCC technologies all have the potential to meet the $36/kW target as indicated in Figure 8.

Figure 9 shows the estimated long-term total cost of ownership of FCEVs (with and without the PFCC), ICEs and PHEVs, once all these vehicles are produced at mass manufacturing volumes. The trend is for non-motive parts such as the chassis, body and mark-ups to make a much larger contribution to the overall vehicle purchase price than the power train.

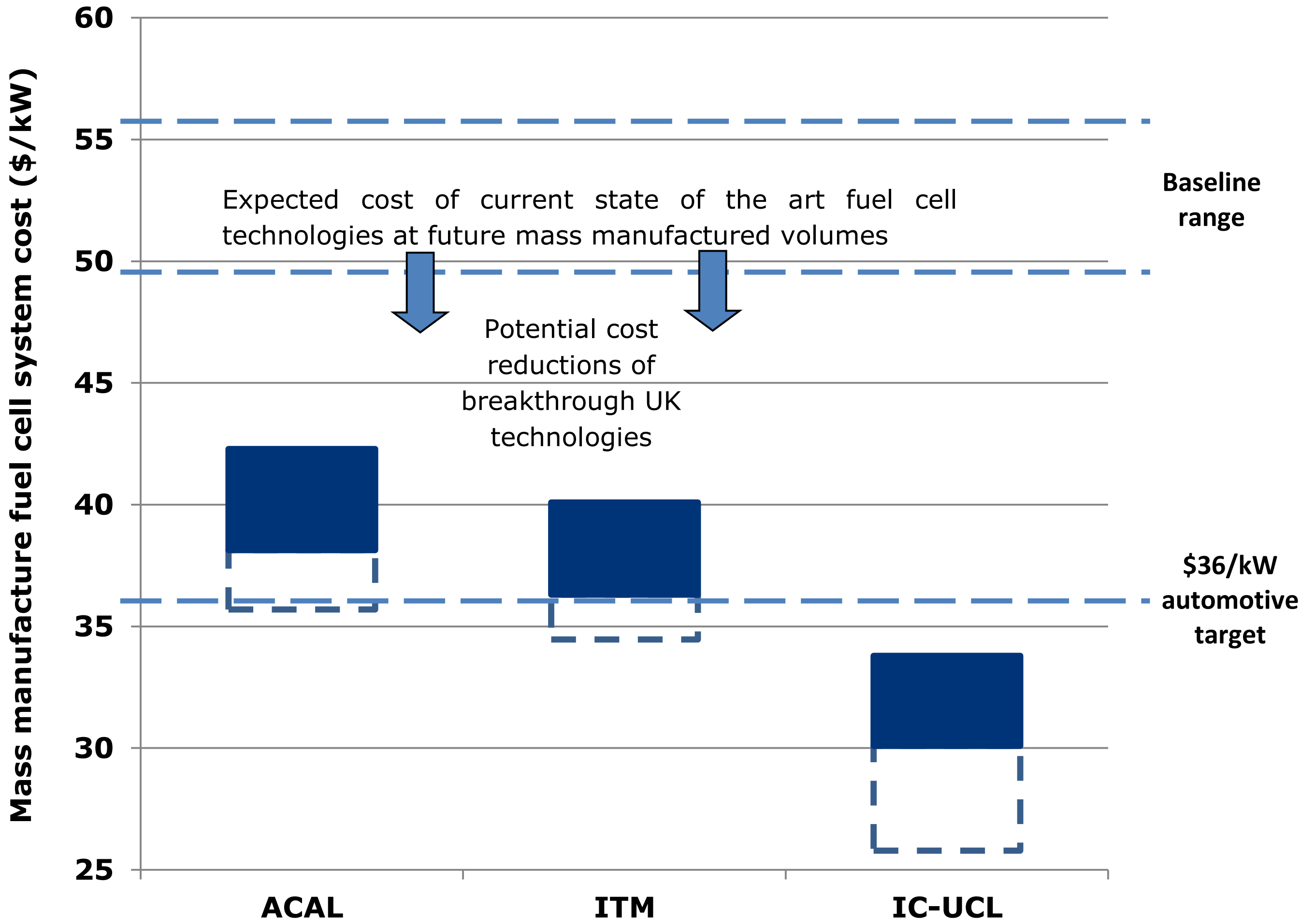


Figure 8: Ranges of automotive fuel cell system costs at mass manufactured volume.
Notes: The industry baseline and technology of each Polymer Fuel Cells Challenge (PFCC) system-level project team are shown. Solid blue bars represent the range of model outputs, and dotted bars estimate inclusion of benefits outside the standard fuel cell system boundary. Source: Carbon Trust, E4Tech and Austin Power Engineering analysis. Underlying data: from PFCC teams and, for the industry baseline, publicly available data related to competing technologies.

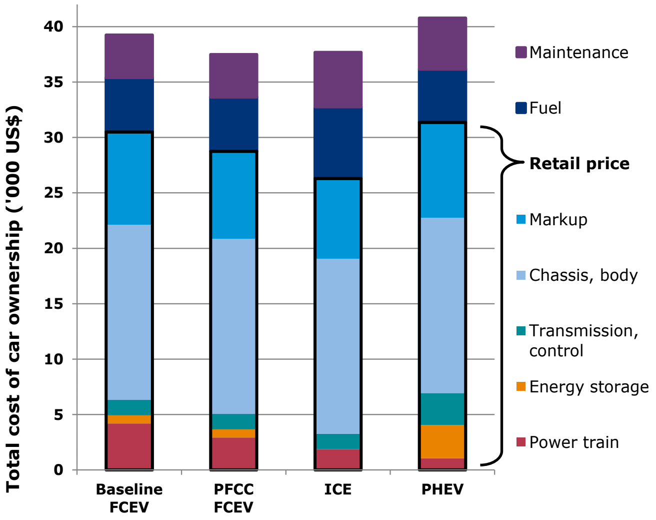


Figure 9: Long-term (15-year) total cost of ownership for representative passenger road vehicles

Source: Carbon Trust, E4Tech and Austin Power Engineering analysis. Underlying data: McKinsey 2010

For a mid-sized passenger vehicle, a baseline PEM fuel cell technology with a system cost of $49/kW at mass-production volumes would give a total power train cost of $4,165 (for a mid-sized car requiring an 85kW fuel cell). A successful PFCC technology meeting a $36/kW mass production target would have a power train cost of only $3,060 – a cost saving significant enough to enable FCEVs to compete with ICEs on a total cost of ownership basis. The *relative* impact on the overall FCEV purchase price equates to about 6%, based on typical long-term vehicle retail costs, which are estimated to lie in the range $26-31k, as shown in Figure 9.

In summary, the purchase price of a FCEV is expected to remain slightly higher than an ICE, even with a successful PFCC breakthrough. However, many customers will also consider annual fuel and maintenance costs in their purchase decisions[17] – i.e. a total cost of ownership. Therefore, since FCEVs are more energy efficient than ICEs, adding in annual fuel (and maintenance) costs leads to FCEVs achieving cost competitiveness with ICEs on a TCO basis.

FCEV uptake modelling and model outputs

The output from the cost analysis was then used in a market sizing model to estimate PFCC-specific impacts on future market penetrations, market values and CO_2 savings using the ITM cost profile. The results of this new analysis are given in the following sections of this report.

Customers take a range of factors into consideration when purchasing a car, including a number of intangibles such as comfort, appearance, image and brand name, which are not quantified in this study (a full list of intangible factors is provided in Figure 10). However, in common with other studies of this type (e.g. McKinsey, 2010), it is assumed that customers are unlikely to consider annual costs across the full 15 year lifetime of the vehicle – they are more likely to only include costs within a limited time horizon (e.g. 3 years) when making a purchase decision. The market penetration modelling is based on a 3 year TCO to reflect the limited time horizon of consumer purchasing decisions.

FCEVs were compared with two competing technologies: PHEVs, and ICEs. They were scored in terms of their technical competitiveness (e.g. reliability, perceived safety, refuelling time, noise and emissions) and their TCO at a manufacturing volume of 500,000 units per year.

It has been assumed throughout the analysis presented in this report that FCEVs are most likely to compete in the mid-size passenger car (C/D segment) market (McKinsey 2010), against ICE and emerging PHEV technologies. As such, the automotive application modelled is the same as the C/D segment light duty passenger vehicle modelled in the McKinsey, 2010 study. In addition, it has been assumed that pure battery electric vehicles (BEVs) are unlikely to compete in this market due to limited range.

[17]The King Review of Low Carbon Cars Part I, 2007

The FCEV modelled has a peak power output of 85kW, annual distance driven of 12,000km/yr and an average product lifetime of 15 years (with a standard deviation of 7 years). As in the McKinsey study, no taxes, carbon price or subsidies have been considered in the analysis. The total cost of ownership only includes the purchase cost of the vehicle and the first 3 years of fuel and maintenance, which is a conventional modelling approach. A longer timescale would make the FCEV more attractive, as operating costs become more important. Consumers take into account many cost, technical and intangible factors when considering the purchase of a car, as given in Figure 10 below (King Review, 2007). The probability of purchase in this study is only based on the relative total cost of ownership and the relative technical competitiveness scores of each of the vehicle options. In calculating total cost of ownership, fuel and maintenance costs were discounted over three years at a rate of 10%, to represent consumers' attitudes to future costs.

Most important	Medium importance	Least important
Vehicle price	Performance	Depreciation
Size	Power	Sales package
Reliability	Image	Personal experience
Comfort	Brand name	Dealership
Safety	Insurance costs	Insurance cost
Running costs	Engine size	Engine size
Fuel consumption	Equipment	Equipment
Appearance		Recommendation
		Road tax
		Environment
		Recommendation
		Road tax
		Environment
		Vehicle emissions
		Alternative fuel

Source: LowCVP Car Buyer Research Report.

Figure 10: Factors that are important to consumers in deciding which car to buy
Source: King Review, 2007

Each powertrain technology was assigned a technical competitiveness value vs. the others (better, same or worse) for each of a number of technical criteria:

- Reliability / maintenance
- Lifetime
- Start-up time
- Ease of use
- Fuel availability
- Safety
- Time spent refuelling / recharging
- Range (time between refuelling / recharging)
- Robustness
- Portability
- Operating noise
- Emissions

These technical competitiveness scores were then weighted by 'market needs', i.e. whether each criterion was: a key purchasing criterion for the consumer; not essential but evaluated by the consumer during purchase decision; or not considered by the consumer. The sum of these weighted competitiveness scores gives an overall technical competitiveness rating for each technology.

In general, technical scores are similar, although FCEVs and PHEVs have noise and emissions advantages over ICEs, and PHEVs have the disadvantage of long recharging times in some scenarios.

The technical competitiveness was then combined with cost competitiveness (giving a heavier weighting to cost-competitiveness) to produce an overall competitiveness value for each technology in each application, which was then used to determine the market shares by Monte Carlo simulation. Monte Carlo analysis involves the substitution of probability distributions in place of values that are uncertain, and involves repeated calculation of results using random values from the probability functions. This enabled the model to resolve purchase probabilities into likely long-run market shares.

In the model, a fall in FCEV purchase price leads to lower TCO, which leads to a higher purchase probability vs. the competing vehicle options, and hence higher deployment of FCEVs.

A 10% fall in baseline FCEV purchase price equates to a 14 %-point increase in long run market share. A 10% increase in FCEV purchase price over the projected baseline equates to a 9 %-point decrease in market share[18].

At present, ICEs are assumed to have 100% of the market. PHEVs are assumed to become commercially available in 2012, and FCEVs in 2015. Forecasts for the total car fleet size were taken from the IEA/WBCSD Transportation Model[19].

Bass diffusion market modelling was then used to determine uptake deployment curves, along with sales and retirements figures. Market innovation and imitation factors from industry and academic studies[20] were used to form the shape of the deployment curve. The innovation rate was taken to be 0.00075, and the imitation rate was 0.28036.

CO_2 savings

The 'well-to-wheel' emissions factors of different vehicle types are mainly dependent on two factors[21]; average vehicle energy efficiency (km/kWh input energy) and the carbon intensity of the energy consumed (gCO_2e/kWh). Combined, these lead to the well-to-wheel emissions factors shown in Figure 11, which fall over time as the input fuel decarbonises and vehicle efficiencies improve.

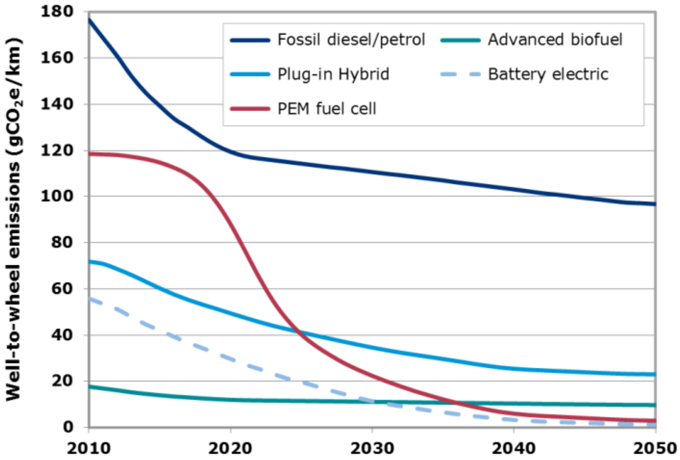


Figure 11: Car well-to-wheel emission factors over time Source: Carbon Trust, E4Tech and Austin Power Engineering analysis

This shows that FCEVs can save a significant amount of CO_2 compared to ICEs (even when using hydrogen produced from natural gas in early years), and versus PHEVs even once grid electricity has decarbonised. However, clean sources of H_2 must be produced and consumed in order to achieve these savings.

The total CO_2 saved in the transport sector is measured as the difference in total $MtCO_2e/yr$ emissions between "with PFCC" and "without PFCC" scenarios, i.e. including the effect of the slight decrease in PHEV deployment as FCEVs take a larger market share from both ICEs and PHEVs.

Note that the CO_2 savings calculated in this modelling using are based on vehicle deployments and their well-to-wheel emission factors.

[18] Note that this is not a traditional measure of linear price elasticity, but is the result of several competition and stochastic steps in the model, and therefore the sensitivities above will change non-linearly with the baseline costs.

[19] http://www.wbcsd.ch/plugins/DocSearch/details.asp?type=DocDet&ObjectId=MTE0Njc

[20] NREL (2005) "R&D Advancement, Technology Diffusion, and Impact on Evaluation of Public R&D"
CET (2009) "Electric Vehicles in the United States: A New Model with Forecasts to 2030"
Meyer (2008) "Modeling technology diffusion of complementary goods: The case of hydrogen vehicles and refueling infrastructure"
Park et al. (2011) "Development of a market penetration forecasting model for Hydrogen Fuel Cell Vehicles considering infrastructure and cost reduction effects"

[21] Average vehicle energy efficiency (km travelled/kWh of input energy): 2.4km/kWh diesel for an ICE, 4.83km/kWh for a PHEV (driving 75% on electricity, 25% on petrol), 4.46km/kWh H_2 for a FCEV. The carbon intensity of the energy consumed (gCO_2e/kWh): Fossil diesel/petrol based on IEA OECD data, electricity based on EU grid average, H_2 from McKinsey (2010)

6. Results

Reaching the automotive cost target could boost fuel cell vehicles' market share for cars from 25% to 34%. By 2050, the extra 200 million FCEVs on the roads would increase the PEM fuel cell market value by $30bn (reaching $261bn). CO_2 savings due to FCEVs would also increase by 260 million tonnes per year (reaching 924 million tonnes per year overall – similar to Germany's current annual emissions). A summary of the key findings of the analysis is shown in Table 1 and the key modelling insights are shown in Box 6.

Box 6 - Key Modelling Insights

Cost reductions achieved by the PFCC are the key driver for increased FCEV market penetrations:

PEM fuel cell system costs at mass volumes are reduced from $49/kW, reaching ~$36/kW

↓

Long-term FCEV power train costs are reduced (from $4,165 to $3,060)

↓

FCEV total cost of ownership falls to become more competitive with that of an ICE (5% decrease in 3-year TCO)

↓

Improved chance customers will purchase FCEVs

↓

Higher market penetration of FCEVs, displacing ICEs and PHEVs in projected markets (market share increases from 25% to 34%)

↓

Increased FCEV sales drive higher market values (additional $30bn globally)

↓

Low per km emissions using clean H_2 leads to increased transport fleet CO_2 savings (additional 260Mt CO_2e saved per year)

Deployment potential

In the case of a successful PFCC, a 6% decrease in FCEV purchase price leads to about a 5% decrease in 3-year TCO, thereby increasing FCEV market penetration from 25% to 34%. This means an extra 3.3 million FCEVs could be on UK roads by 2050, and an extra 200 million globally, reaching 691 million FCEVs overall (see Figure 12).

The 5% reduction in 3-year TCO is important enough to improve the cost competitiveness of FCEVs versus PHEVs and ICEs, which will in turn increase the likelihood of FCEVs being purchased by customers. This probability of purchase was estimated using the ratio of TCOs, and a weighted technical score based on key consumer criteria – how much more or less attractive the performance of an FCEV is compared to an ICE or PHEV, and how it differs technically.

A discussed in Section 5, a number of standard modelling techniques were then used to derive the values in Figure 12. In the UK, vehicle ownership is expected to plateau in 2030. As the vehicles considered in this analysis are technically similar, and the costs of ownership of the vehicles converge in the future (when including the effects of the PFCC), the model shows a plateau in UK market share for PHEVs and FCEVs towards 2050. FCEVs could only continue to capture further market share in the UK (and the rest of Europe) if their technical or cost competitiveness continued to improve beyond that achievable by the PFCC. However, the global FCEV market is forecast to continue to grow beyond 2050, as the global market for cars continues to grow (see Figure 13).

	Number of cars (million)			Additional FCEVs due to the PFCC (million)			Number of FCEVs with the PFCC (million)			Additional PEM fuel cell market value due to the PFCC ($bn)			PEM fuel cell market value with the PFCC ($bn)			Additional GHG savings due to the PFCC ($MtCO_2e/yr$)			GHG savings due to all FCEVs displacing ICEs ($MtCO_2e/yr$)		
	2020	2030	2050	2020	2030	2050	2020	2030	2050	2020	2030	2050	2020	2030	2050	2020	2030	2050	2020	2030	2050
UK	33	33	33	0.06	0.9	3.3	0.1	2.0	11.4	0.06	0.6	0.4	0.2	2.3	3.5	0.01	0.7	3.2	0.05	2.1	13
Rest of EU	231	234	235	0.4	6.1	23	0.8	14.0	81	0.4	4.7	3.5	1.3	17.2	31	0.3	7.4	30	0.5	17.3	108
USA & Canada	318	349	406	0.6	9.2	40	1.1	21	140	0.6	7.1	6.0	1.8	26	53	0.4	11	53	0.7	26	187
OECD Pacific	108	111	119	0.2	2.9	11.9	0.4	6.6	41	0.2	2.2	1.8	0.6	8.1	16	0.1	3.5	15	0.3	8.2	55
Rest of World	379	561	1,217	0.7	15	121	1.3	33	419	0.7	11	18	2.2	41	159	0.4	18	158	0.9	41	561
Global	1,069	1,289	2,009	1.9	34	200	3.8	77	691	2.0	26	30	6.1	94	261	1.2	41	260	2.5	95	924

Table 1: Summary of key findings.
Note that some numbers in this table differ slightly to those given in the report text, due to rounding.

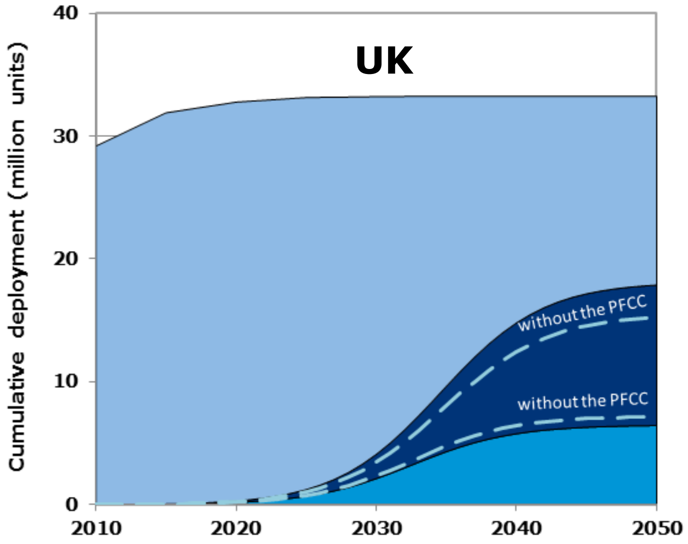


Figure 12: UK & global car deployment, with (solid areas) and without (dashed lines) the PFCC
Source: Carbon Trust, E4Tech and Austin Power Engineering analysis. Underlying global car fleet numbers are based on 2004 IEA/WBCSD data.

The extra FCEV deployment comes mainly at the expense of ICEs, with PHEV deployment largely unchanged by the PFCC (only decreasing slightly).

Market values

With commercial deployment of FCEVs starting in 2015, market values increase rapidly from 2020 to the mid-2030s, as shown in Figure 14. By the late 2030s, new sales have started to drop. This is caused by market saturation of $36/kW FCEVs (note that relative cost competitiveness for all vehicle types modelled were fixed over the modelling period such that the effect of further cost reductions on the market penetrations of different vehicles beyond their cost targets are not shown), but approaching 2050, the total market value increases again as FCEVs being retired at the end of their life are replaced.

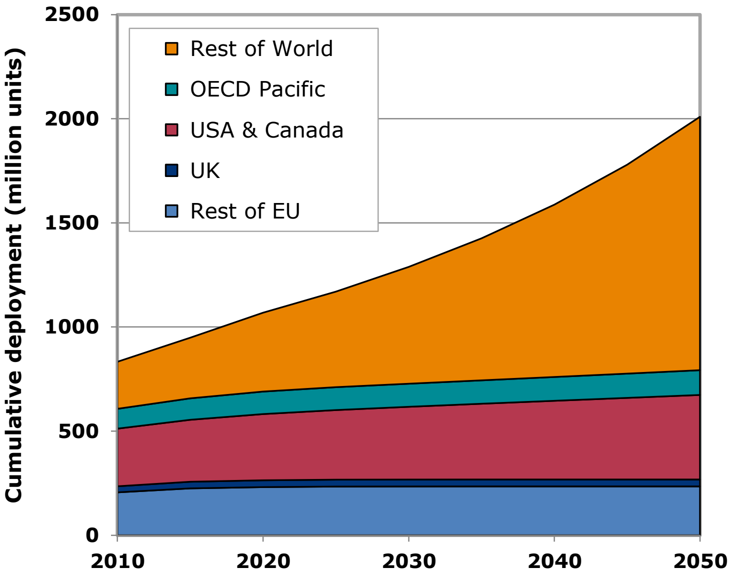


Figure 13: Number of cars globally
Source: Carbon Trust, E4Tech and Austin Power Engineering analysis. Data from: IEA & WBCSD (2004) Transport model

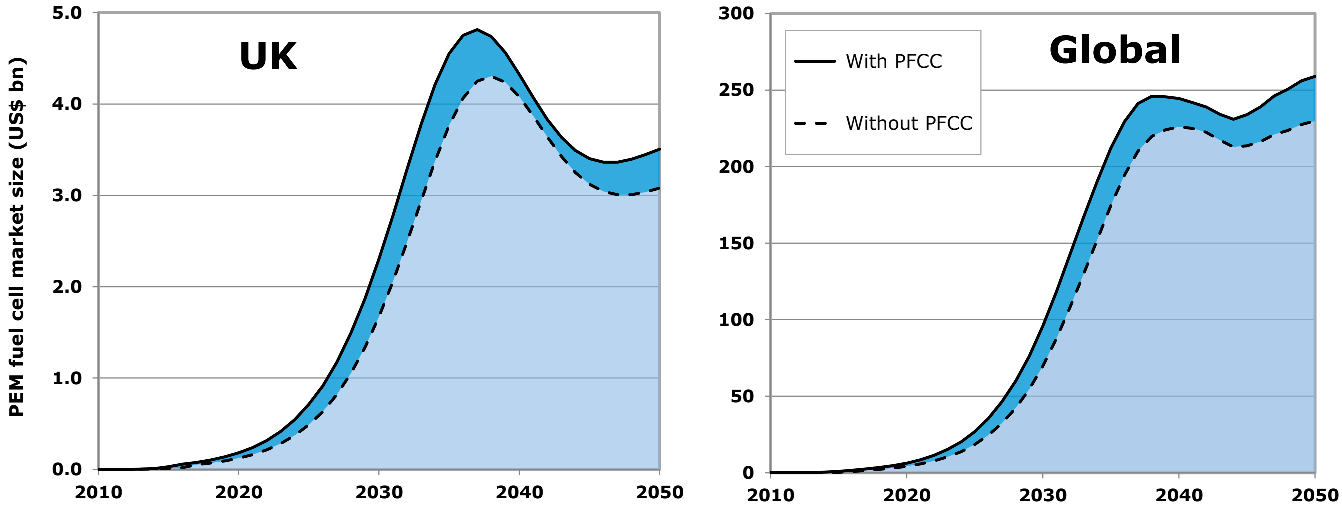


Figure 14: UK & global passenger car PEM fuel cell market values, with and without the PFCC
Notes: the drop in sales between the mid-2030s and mid-2040s is due to market saturation of FCEVs (note that relative cost competitiveness for all vehicle types modelled were fixed over the modelling period), but as the first FCEVs sold in the 2020s and 2030s reach the end of their useful life (15 years), sales of new vehicles begin to pick-up again from about 2045. Source: Carbon Trust, E4Tech and Austin Power Engineering analysis

A successful PFCC is estimated to lead to an increase in the FCEV market value of $59m in the UK in 2020, and $2.0bn globally. In 2050, the difference in market values with and without the PFCC could be as high as $425m in the UK, and $30bn globally. Using the annual FCEV sales data from the market modelling, the FCEV market size is calculated as the applicable capital costs in every FCEV sale in that year. These costs relate to the power train (including the fuel cell system), transmission, control, and energy storage components and equate to about $5,000 per FCEV in the market value results.

Note that the high costs of the chassis, body and markups, which are not specific to FCEVs, are not included. If they were to be included, FCEV sales in 2050 would be valued at $1,490bn. Adding annual maintenance and fuel costs for all the FCEVs on the road in 2050 would increase this value up to $2,075bn.

CO_2 savings

The CO_2 savings due to FCEVs are negligible in 2020 as comparatively few FCEVs are on the road, but by 2050 they could reach 13 million metric tonnes of carbon dioxide equivalent per year ($MtCO_2e$/yr) in the UK, and 924 $MtCO_2e$/yr globally (similar to the current annual emissions of the UK and France combined). These CO_2 savings, shown in Figure 15 are based on the total FCEV deployments with a successful PFCC shown in Figure 12, and the difference in well-to-wheel emissions from ICEs (Figure 11), due to a move to cleaner hydrogen sources over time (e.g. from steam methane reforming to renewable electrolysis).

By modelling both FCEV deployments with the PFCC and without the PFCC, it was possible to calculate the incremental GHG savings from the **extra** FCEVs due to a successful PFCC. The higher and earlier deployment of FCEVs due to the PFCC, as shown in Figure 12, will displace more ICEs (and some PHEVs), changing the overall car fleet emissions, as shown in Figure 16. Global emissions plateau in 2030 with the introduction of FCEVs and PHEVs, then rise again after 2040 due to the continued underlying growth in the car market. By contrast, UK car fleet emissions fall rapidly as the grid and hydrogen supply decarbonise and remaining ICE vehicles become more efficient. Figure 10 shows these effects and the additional impact that the PFCC is likely to have through displacement of only mid-sized cars by FCEVs.

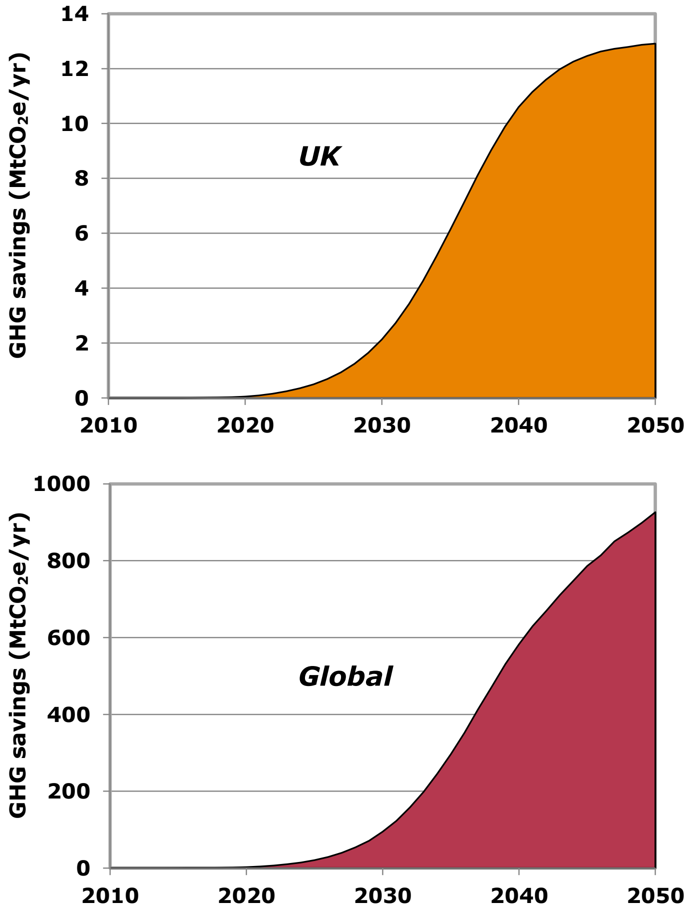


Figure 15: GHG savings due to FCEVs displacing only ICEs
Source: Carbon Trust, E4Tech and Austin Power Engineering analysis.

By 2050, the GHG savings **due to the PFCC** are therefore 3.2 $MtCO_2e$/yr in the UK, and 260 $MtCO_2e$/yr globally (equivalent to the current annual emissions of the Netherlands). The technologies being supported by the PFCC have similar energy efficiencies to the baseline FCEV technologies and will therefore have similar CO_2 benefits.

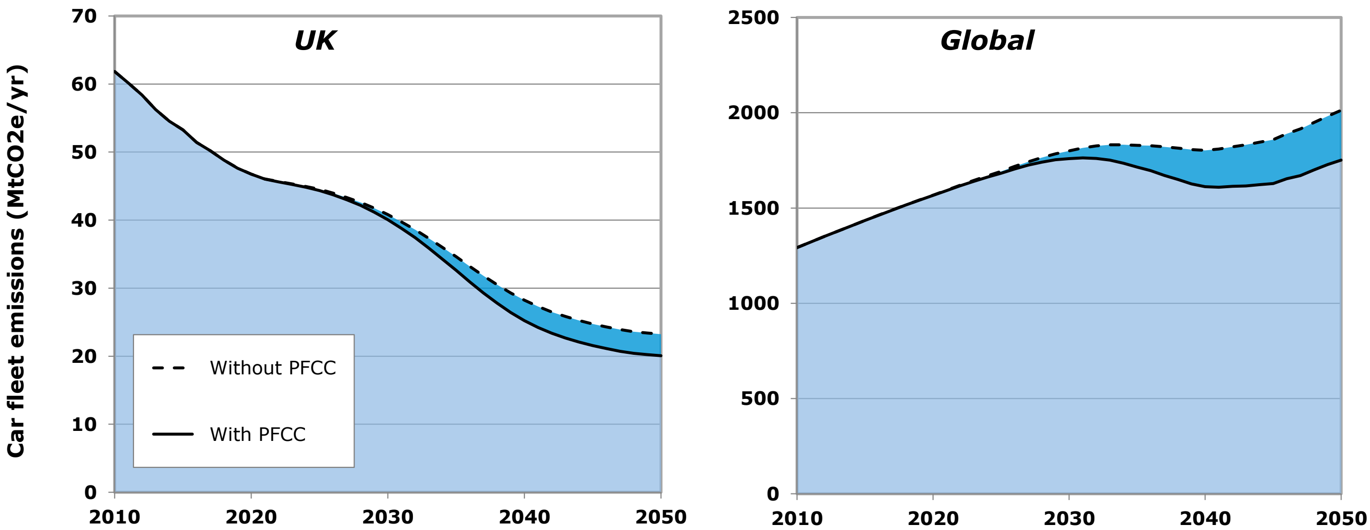


Figure 16: Car fleet emissions in the UK and globally, showing the effect of reduced mid-sized passenger vehicle emissions due to the PFCC
Source: Carbon Trust, E4Tech and Austin Power Engineering analysis

Other applications for fuel cells

Although passenger cars represent by far the largest future market for PEM fuel cells, there are other potential mass markets and nearer term niche markets that would benefit from the cost reductions enabled under the PFCC.

Increased PEM fuel cell deployment, market values and CO_2 savings could be achieved in a variety of transport, stationary and portable applications. The values in Table 2 are indicative of the PEM fuel cell deployments that could be achieved with a successful PFCC.

	Market share (%)	2050 deploy-ment (GW)	2050 market value ($bn)
Cars	34%	58,580	261
Buses	36%	310	16
Materials handling	93%	210	4
Domestic CHP	18%	260	8
Commercial CHP	26%	145	4
Telecom UPS	70%	15	0.4
Gensets	83%	345	13

Table 2: PEMFC deployments in other markets with a successful PFCC

Cars = % of light duty passenger cars, Buses = % of all buses, Materials handling = % of all forklifts, Dom CHP = % of all residential heating systems and power supply (incumbent = gas boiler + grid electricity), Commercial CHP = % of all commercial heating systems and power supply, Telecom UPS = % of mobile phone base transceiver stations, Gensets = % of portable generator market (holiday camping, backup power, etc.)

Note that market values only include the PEM fuel cell system capital costs, but not other vehicle or equipment capex, operating or fuel costs.

Further indications of the potential savings can be seen in Table 3, Table 4 and Figure 17.

	Market share (%)		2050 deployment (GW)		2050 market value ($bn)	
Scenario:	**Baseline**	**PFCC**	**Baseline**	**PFCC**	**Baseline**	**PFCC**
Cars	25%	34%	41,845	58,580	231	261
Buses	32%	36%	275	310	14	16
Materials handling	81%	93%	185	210	4	4
Domestic CHP	12%	18%	175	260	6	8
Commercial CHP	21%	26%	125	145	4	4
Telecom UPS	56%	70%	10	15	0.4	0.4
Gensets	78%	83%	330	345	13	13

Table 3: Market share, deployment and market value with and without reaching the $36/kW cost target of the Carbon trust Polymer Fuel Cells Challenge

	2020	2030	2050
Cars	1.2	40.8	260.0
Buses	0.1	1.6	15.5
Materials Handling	5.9	18.5	92.0
Domestic CHP	-3.9	7.2	4.1
Commercial CHP	3.9	27.7	41.8
Gensets	1.0	6.3	6.9
	8.2	**102.2**	**420.3**

Table 4: Increase in global carbon emission savings (Mt CO_2e/yr) assuming that the $36/kW cost target of the Carbon Trust Polymer Fuel Cells Challenge can be achieved

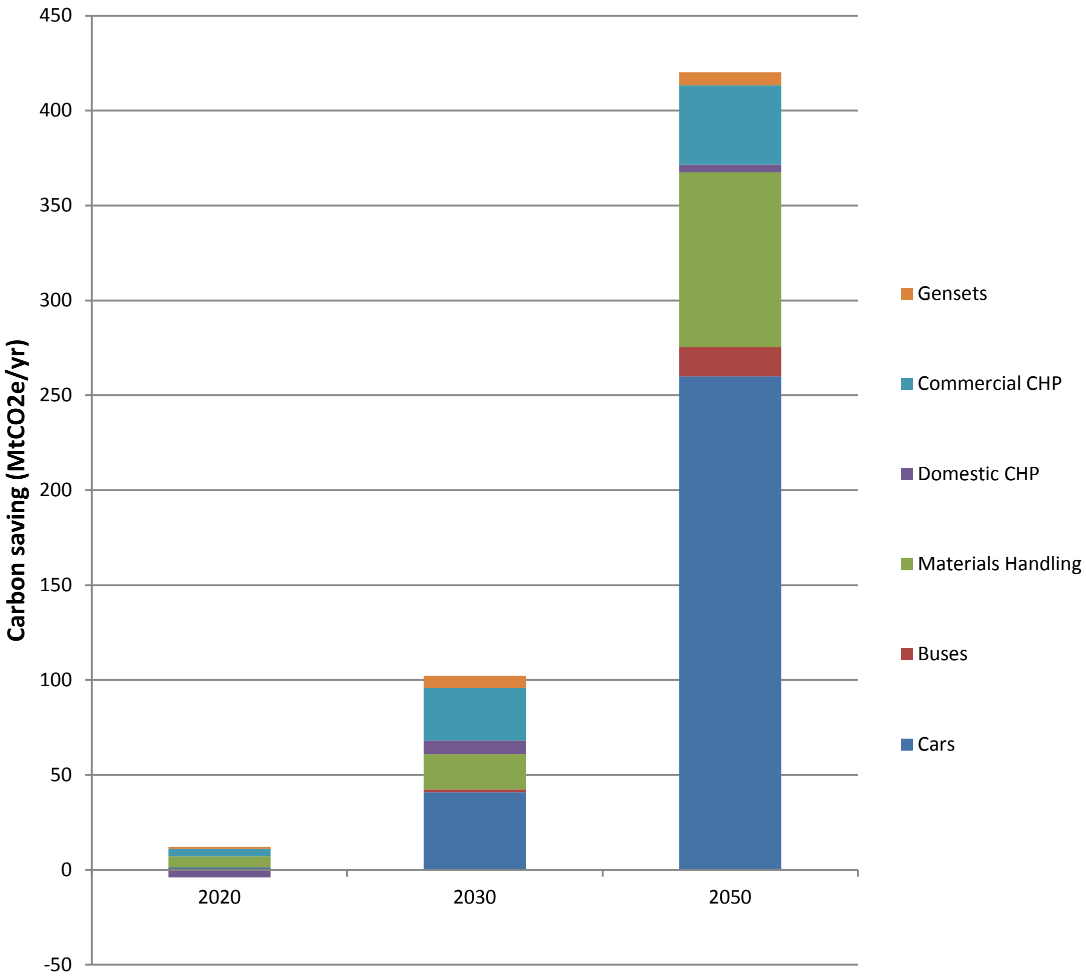


Figure 17 - Increase in global carbon emission savings assuming that the $36/kW cost target of the Carbon Trust Polymer Fuel Cells Challenge can be achieved

7. Conclusions

Reducing the cost of automotive fuel cell systems could significantly boost their market share. Our modelling shows that system costs of below \$36/kW (a level potentially achievable by PFCC technologies), could boost the total market share of FCEVs from 25% to 34% - or 200 million vehicles worldwide – by 2050. These extra FCEVs equate to an additional \$30bn PEM fuel cell market value, along with an additional 260 million tonnes of CO_2 savings globally. The overall FCEV market in 2050 could be worth \$261bn, and save 924 million tonnes of CO_2. Further PEM fuel cell deployment and CO_2 savings will be realised in other markets (such as CHP), benefitting from lower system costs developed under the PFCC, leading to additional carbon savings of 160 $MtCO_2e$/yr.

Several UK organisations are focused on achieving a step-change in PEM fuel cell system costs, by developing technologies that remove platinum, increase power densities and radically simplify system designs. The Carbon Trust Polymer Fuel Cell Challenge aims to support and commercialise the best of these technologies, so that future mass-produced FCEVs reach cost competitiveness with ICEs.

Given their high efficiency, PEM fuel cells using clean sources of H_2 have significant potential for decarbonising the road transport sector. However, the PFCC alone cannot ensure FCEV success – current FCEV costs are high, and the supporting H_2 production, storage and refuelling infrastructure is still to be rolled-out, needing investment from many stakeholders. Car makers, industry, investors and government will need to be fully involved if the potential future economic value and CO_2 savings of FCEVs are to be realised.

Implications for stakeholders

Based on the findings of the analysis that has been undertaken and the related work of the Carbon Trust in this area, the following recommendations are made:

Car makers

- Auto OEMs have made significant strides to reduce FCEV costs in recent years, and many plan commercial roll-outs in 2015. However, as baseline FCEV costs of conventional PEM FCEVs will still be higher than ICEs in the long term, car makers must now focus on developing the next generation of low cost technologies, such as those being developed by ACAL Energy, ITM Power, IC-UCL and Ilika, supported by the PFCC.

Industry

- The UK will be one of the first markets to deploy FCEVs, along with Germany, Scandinavia, California, South Korea, Japan and possibly China. Industry should establish partnerships in these first markets to support the development of new technologies that have the potential to address common barriers to the deployment of fuel cells and hydrogen infrastructure. In particular, appropriate investment and support should be channelled towards the development of lower cost fuel cell systems and components, as well as H_2 production, storage, distribution and refuelling infrastructure.

Investors

- The investment community is urged to take a fresh look at fuel cells, given the extent to which the sector has matured since the hype of 2000. There has been rapid growth in early markets, and the technology status and potential are now much better understood.
- Given the evolution of the value chain, and potential opportunities for consolidation, moving quickly to take advantage of new opportunities could be key as firms in the sector grow.

Governments

- Few viable options exist for deep reductions in CO_2 emissions from transport. To keep these options open, policy makers need to have a long-term vision for H_2 and fuel cells, and support their acceleration in a coherent, overarching fashion - from deployment incentives back to the underlying science base.

- Continued support is required for R&D programs to demonstrate and validate disruptive PEM fuel cell technologies that could bring about a step-change in cost reduction, such as the PFCC in the UK and other initiatives from around the world, including the Japanese FC Cubic[22], and the US DOE[23] programmes.
- Fuel cell electric vehicles fall within the broader family that includes hybrids and battery electric vehicles. When designing policy frameworks to support electric drivetrain vehicles, policy makers need to recognise that no single either/or solution will work and all options must be suitably supported.

[22]http://www.brennstoffzelle-nrw.de/fileadmin/Japan-Profile/FC-Cubic_Dec_07.pdf
[23]http://www1.eere.energy.gov/hydrogenandfuelcells/fuelcells/doe_rd.html

Annex A: ACAL Case Study

A UK fuel cell design mimicking the body's lungs and bloodstream is ready for serious consideration by the automotive industry

ACAL Energy's unique fuel cell technology offers a cost saving of up to 25% on current leading-edge fuel cell technology. Mimicking the workings of the human lung it replaces the platinum-based cathode, commonly used in fuel cell designs, with a mix of liquid chemicals that are not only significantly cheaper but also reduce the amount of maintenance the fuel cell requires. Platinum is an expensive precious metal and can account for up to 20% of the cost of the entire fuel cell system.

Hydrogen-powered fuel cell cars use electric drivetrains powered by a fuel cell. ACAL Energy's design is potentially very well-suited to the automotive industry.

Dr Byron McCormick, former Executive Director of General Motors' fuel cell car development team and Non-Executive Director of ACAL Energy, explains: "The human lung and bloodstream is incredibly efficient at what it does, transferring oxygen around the body to generate energy. I had been looking for many, many years to find a comparable fuel cell design."

Charles Stone, former VP of R&D at fuel cell developer Ballard Power Systems, gives his verdict: "Reducing the amount of platinum used in a fuel cell is a very direct way of reducing its cost. ACAL Energy's solution is highly innovative and provides a very plausible route to cheaper fuel cells."

Having recognised the potential of this disruptive technology, the Carbon Trust's Polymer Fuel Cells Challenge is helping ACAL Energy to access the automotive market. Carbon Trust experts and a series of major sector players, including a Japanese car producer, have helped ACAL Energy develop a set of key performance criteria that the fuel cell must now meet. These criteria cover everything from the power output to the size of the entire system, and ACAL Energy is currently focussed on proving its technology can be transferred from the lab to under the bonnet of a car.

About ACAL Energy

- Founded in 2004
- Technology invented by Dr Andrew Creeth
- Based in Runcorn in the UK
- £13m investment raised
- Employs 32 people
- 20 patents relating to fuel cells filed

How it works

While many companies around the world have developed fuel cells, ACAL Energy's approach is unique. It eliminates the need for at least two thirds of the expensive platinum that is commonly used as a chemical catalyst to react oxygen and hydrogen as part of the fuel cell process that generates electricity.

The system architecture, developed by ACAL's co-founder Andy Creeth, takes inspiration from the human lung and bloodstream. On the cathode side, a specially designed liquid polymer solution absorbs the electrons and protons coming across the membrane. This catholyte continuously flows from the stack to an external regeneration vessel (the lungs). Here, the catholyte comes into contact with air and the electron, proton and oxygen from the air react to form water, which exits the regenerator as vapour. The regenerated catholyte then flows back to the fuel cell to absorb more electrons and protons.

How the technology can reduce costs – the science

The ACAL Energy fuel cell design can save costs in a number of ways (see Figure 18), producing an overall cost reduction of 25% compared to current leading fuel cell technology.

Besides reducing the upfront capital cost of systems by eliminating the need for expensive platinum at the cathode, ACAL Energy's FlowCath system also has a number of other benefits:

- The system can take oxygen from the air at atmospheric pressure so extra pressurising equipment is not required.
- The design has an inherent ability to effectively recover heat, and the temperatures of the regenerator and stack can be managed independently to optimise power output, heat removal and carbon monoxide susceptibility.
- Using a liquid catholyte avoids the need for humidification of the membrane, anode and fuel.
- With no drying of the membrane, and reduced corrosion or oxygenation of the membrane, catalysts and bipolar plates, the design also significantly improves durability.

The main technical improvements that ACAL Energy is currently working on are:

- Identifying higher voltage catalysts to increase higher overall fuel efficiency.
- Improving the cathode design to generate faster reactions.
- Reducing the thickness of each cell.
- Improving the regenerator kinetics for faster regeneration.
- Reformulating the catholyte 'chemical soup' so it works even in cold temperatures.
- Scaling up and pilot testing, with ongoing cell component optimisation from parallel project collaborations

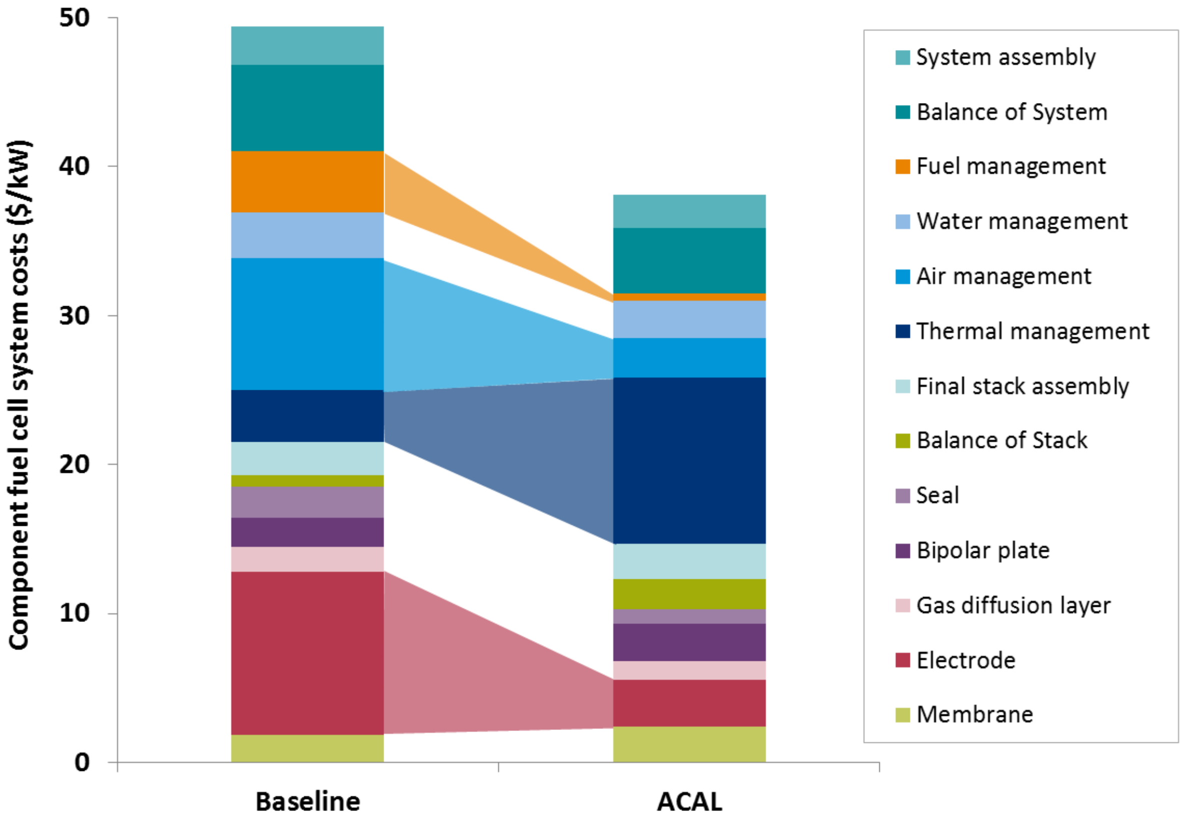


Figure 18: How ACAL Energy's fuel cell design reduces cost compared to current industry-leading technology. The increase in thermal management costs is due to ACAL's catholyte regenerator

Annex B: ITM Power Case Study

ITM Power's unique technology offers punchy performance for future fuel cell cars

A critical factor for bringing down the cost of a fuel cell is its power density – the amount of power produced for the size of the fuel cell. ITM Power has recorded the highest ever published polymer fuel cell power density using hydrogen as the fuel and ordinary air, rather than pure oxygen. The more power you can generate per cm^2, the smaller the fuel cell can be, and the power to weight ratio is of paramount importance in cars.

Simon Bourne, CTO of ITM Power, explains: "we are basically squeezing more power out of the fuel cell than anyone else. That means we can cut the size of the fuel cells needed to power the car and so reduce the cost of the overall system."

Charles Stone, Former VP of R&D at fuel cell developer Ballard Power Systems, gives his verdict: "ITM Power's membrane technology has the flexibility to work with a variety of fuel cell designs. It's a front-runner on the all-important measure of power density and could make a considerable performance improvement to future mass produced fuel cell cars."

ITM Power is now aiming for its technology to be included in the second generation of hydrogen-powered cars expected to be launched in 2017-2018. The Carbon Trust, through its Polymer Fuel Cells Challenge, identified ITM Power's membrane as one of three breakthrough technologies that could make fuel cell vehicles cost competitive with their internal combustion engine counterparts. Having selected ITM Power, the Carbon Trust commissioned further research to demonstrate the technology's performance and is now providing high level introductions to key players in the automotive sector.

About ITM Power

ITM Power plc was founded in Sheffield in 2000. They were admitted to the AIM market of the London Stock Exchange in 2004, with £10m raised in its IPO. A further funding round of £28.5m was completed in 2006. ITM Power has recently completed another fund raise which generated £5.5m. ITM Power has now made the transition from a R&D company to a product manufacturer and technology provider, with 66 employees. They have both a strong base of intellectual property and engineering expertise for providing complete hydrogen solutions, with a suite of CE-marked electrolyser products for industrial, domestic and vehicle refuelling applications.

How it works

All polymer fuel cells contain a membrane which sits between the oxygen and hydrogen sides. ITM Power is a leading provider of electrolysers (devices for generating hydrogen from water and electricity) and originally developed their membrane technology for that purpose. As an electrolyser is effectively doing the reverse of a fuel cell, the ITM Power team identified that their membrane technology could have huge potential benefits if also used in a fuel cell. The membrane allows the transfer of ions (but not electrons) directly from the hydrogen to the oxygen side, forcing electricity to flow round an external circuit. ITM Power has developed an ultra-high performance membrane which enables more electrical power to be generated per cm^2 than any other membrane.

How the technology can reduce costs – the science

The automotive industry is targeting fuel cell technology that can generate one watt of electricity per cm^2 of membrane, using hydrogen and air. Under laboratory conditions, ITM Power's membrane has already achieved 2.1W/cm^2. The average car has a power output of 80kW, equivalent to 80 electric kettles. At

1W/cm^2 you still need to fit 8m^2 of membrane into every vehicle – that's a lot of individual fuel cells combined into a large 'stack'. The more power per cm^2, the fewer fuel cells you need and so the cheaper the overall system.

ITM Power's membrane technology is also made from less costly hydrocarbons which can be easily mass produced. Incumbent fuel cell membranes are commonly made from fluorocarbons using expensive chemicals in their manufacture. ITM's new membranes give rise to several mechanical, hydration, conductivity and manufacturing differences compared to the membrane in a conventional PEM fuel cell, hence new benefits and challenges arise. Optimisation of the surrounding stack and system components can therefore further improve fuel cell power densities, cost and durability.

ITM are currently looking to further improve material durability, optimise the operation of the catalyst, improve their catalyst deposition and recovery techniques, along with testing new cell and stack geometries.

Figure 19 shows how ITM's technology could reduce the mass manufacture cost of a fuel cell system to \$35/kilowatt compared with a projected global baseline of current state-of-the-art fuel cell technology at mass produced volumes of \$49/kilowatt.

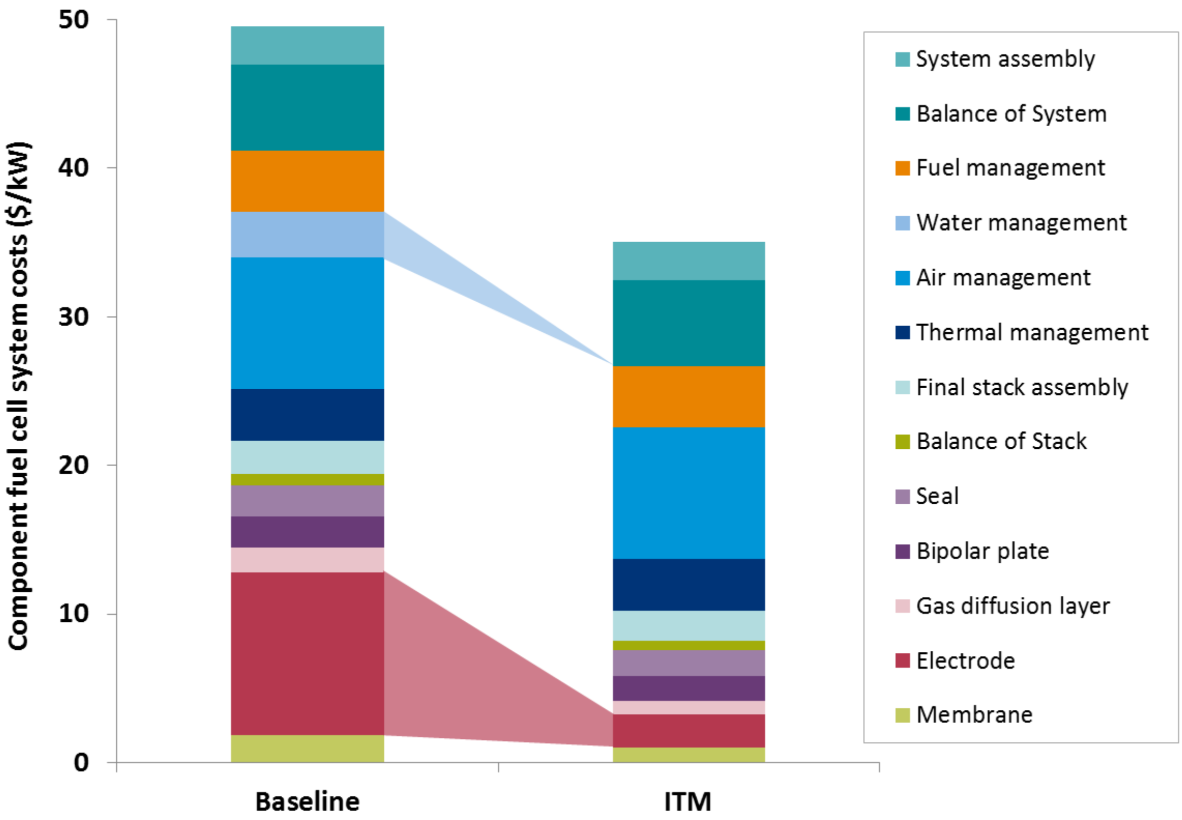


Figure 19: How ITM Power's fuel cell technology reduces cost compared to current industry-leading technology

Annex C: Imperial College London and University College London Case Study

A UK design seeks to create cheaper fuel cells by using well established printed circuit board mass production techniques

By adapting printed circuit boards (PCBs) commonly found in computers, scientists at Imperial College London and University College London are developing an entirely new way of building a fuel cell that is also significantly cheaper. The PCB industry is well established and has developed ultra-efficient manufacturing techniques. The new design could make use of this existing cost-effective production capability while also benefitting from PCB's low material costs and ease of assembly into larger structures.

Fuel cells are commonly arranged into 'stacks' to generate the level of power output required. Normally they are arranged in "two dimensions" so if one unit fails, the whole system fails. The PCB design eliminates this problem allowing malfunctioning individual fuel cells to be bypassed creating a more reliable system. Individual boards can also be easily 'switched out' and replaced.

Charles Stone, former VP of R&D at fuel cell developer Ballard Power Systems, explains: "By building on an existing manufacturing technique the novel approach from the Imperial and UCL team could offer a cheaper way of making fuel cells with the added benefit of improved reliability thanks to the innate properties of printed circuit boards."

The Carbon Trust, through its Polymer Fuel Cell Challenge, identified the PCB technology as one of three breakthrough designs that could make fuel cells cost competitive with the internal combustion engine. For automotive applications, the PCBs can be easily arranged to fit around the shape of the car's chassis. The design could also be used for stationary electricity generation such as combined heat and power (CHP).

With support from the Carbon Trust, Imperial College and UCL will now develop the technology, building a series of scaled models to demonstrate the concept.

Generic commercially-available fuel cell components will be used to build complete power-generation systems – one of the benefits of the technology being that it is potentially capable of being used in any fuel cell design. An early-stage prototype will then be constructed.

Alongside the technical development, Carbon Trust is also helping the project team to engage with potential partners in the automotive and CHP industries to better understand their specific requirements.

About the project

The technology was invented by two of the UK's leading fuel cell scientists: Anthony Kucernak (Imperial College) and Dan Brett (University College London)

How it works

The 'Flexi-Planar' design uses a layered arrangement of laminated printed circuit boards, bonded on top of each other, to create a stack with internal fuel, water and air channels. These channels, cut into the circuit boards, provide an efficient way of distributing the fuel cell reactants (oxygen from air and a fuel such as hydrogen). Once the fuel and oxygen have reacted these grooves then take away the resulting water that is produced from the reaction. PCBs are chemically resistant making them an excellent material for containing the reaction. They are also easy to assemble, and can be made using low-cost, high capacity manufacturing techniques.

The 'Flexi-Planar' design of the stack brings several technical benefits over the bipolar configuration used in conventional fuel cells. If an individual fuel cell were to fail it can be easily bypassed and potentially replaced and this inherent fault tolerance means less robust, lower cost materials and components can be used. Other benefits include a reduced balance-of-plant, internal humidification and integrated flexible electronic controls on each board. As it could work in any fuel cell design, new advances such as use of alkaline electrodes and high temperature membranes could also be incorporated at a later date.

How the technology can reduce costs – the science

The PCB technology has the potential to reduce the costs of a fuel cell stack by up to 47%. Beyond the use of high-volume, low-cost PCB manufacturing techniques, the design can reduce cost in a number of other key ways:

- Automatic water management within each cell
- Bonding between boards removes the need to use end plates and seals
- Cheaper system components can be used because the power electronics are integrated into the design enabling management of individual cells.

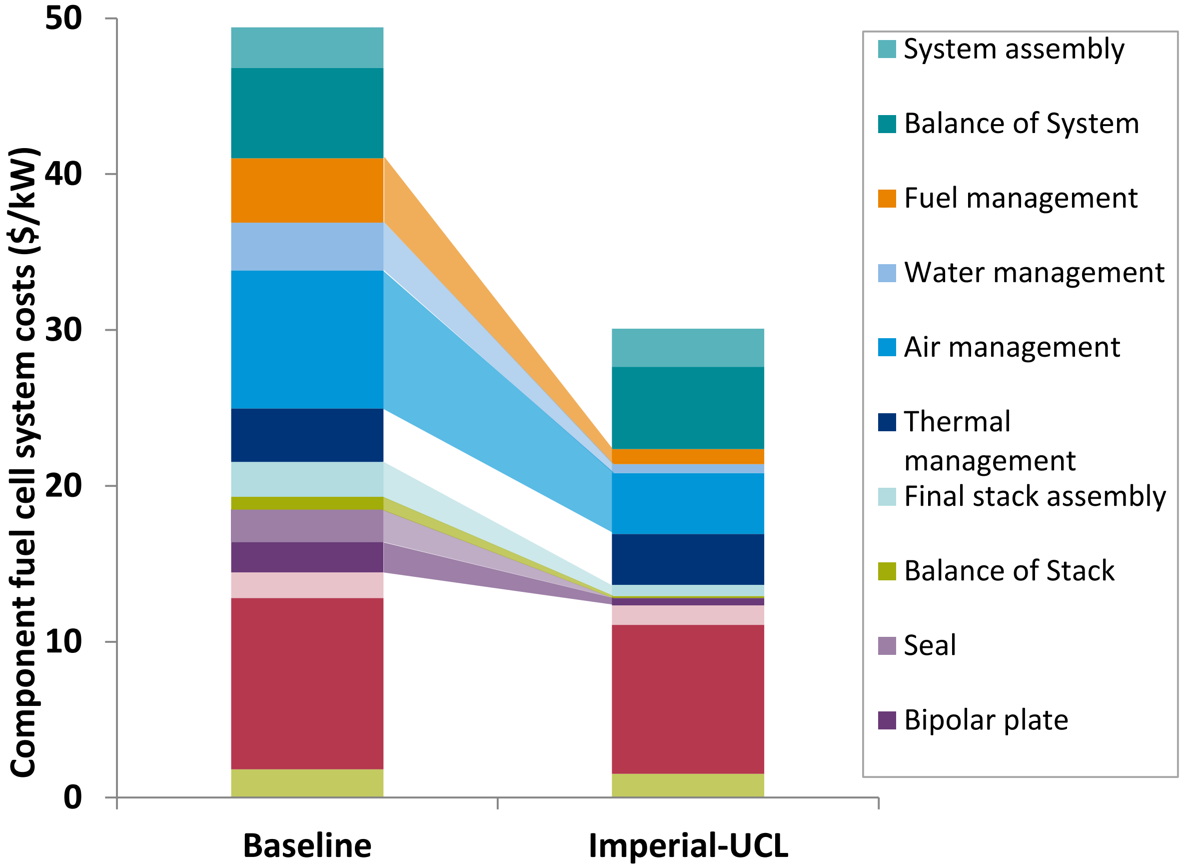


Figure 20: How the Imperial/UCL fuel cell design reduces cost compared to current leading technology

Annex D: Ilika Case Study

Ilika's high-throughput technologies accelerate the search for novel low-cost fuel cell catalysts.

The most significant cost within a fuel cell is the precious metal catalyst. Ilika's aim has been to address this potential obstacle to the early deployment of fuel cell vehicles by developing new low-cost catalysts. Ilika uses a unique, patented process – which is up to ten times quicker and more efficient than traditional materials discovery processes – and has applied this technique to the discovery and optimization of novel alloy catalysts for fuel cells. Once Ilika has identified novel compositions which have a high activity and low-cost, they join forces with synthesis partners to scale-up this material for larger scale testing. Through this methodology Ilika has developed a catalyst material which enables a 70% cost reduction for an equivalent power output versus the current precious metal standard.

Ilika's catalyst can be considered a 'drop-in' technology, in that it can be combined with existing FCEV stack designs and supply chain, without any architectural changes. It could also potentially be combined with other innovations being developed as part of the PFCC.

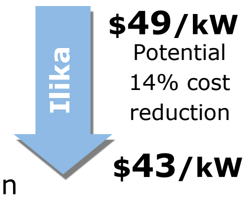
About Ilika Technologies

- Founded in 2004
- Floated on the AIM stock exchange in May 2010
- 35 employees
- Based in Southampton, UK
- Applies proprietary high-throughput techniques to accelerate the discovery of materials

Graeme Purdy, CEO of Ilika Technologies, explains: "Ilika's high-throughput technologies make it possible to fast-track the discovery of next generation fuel cell catalysts. This has enabled us to develop novel materials with a potentially significant cost benefit over current industry standards."

Ilika is now aiming to scale-up its catalyst technology and undertake pre-commercialization trials with automotive companies in 2012-2013. To help accelerate the development of innovative low carbon technologies, and as part of its Polymer Fuel Cell Challenge, the Carbon Trust is supporting Ilika to develop its technology and intends to provide high level introductions to key players in the automotive sector.

How the technology can reduce costs - the science



The cost of the electrodes makes up 51% of the total stack cost for the Proton Exchange Membrane Fuel Cells used in automotive applications. Due to the current high loadings required for the cathode reaction, this electrode makes up two thirds of the total electrode costs. Ilika have identified a fuel cell catalyst made of a palladium ternary alloy, which offers the potential for at least a 70% cost reduction of the cathode vs. the expensive platinum catalysts commonly used in polymer fuel cells, and with similar competitive performance. These catalysts have undergone independent testing to determine their activity and stability under standard test conditions.

About the Project

Previous funding enabled Ilika to test a large number of alloys that could replace platinum; the work resulted in development of a palladium ternary alloy catalyst that can be substituted for platinum in fuel cells. The alloy promises to be 70% cheaper than platinum on a cost/performance basis. The latest investment will initiate a project that will run for 21 months while Ilika works with a partner to scale-up production. Manufacturing larger quantities of the material will enable them to perform tests with car companies and to confirm the stability of the material at higher voltages.

Annex E: Glossary

BEV – Battery Electric Vehicle

CHP – Combined Heat and Power

DECC – Department of Energy and Climate Change

FCEV – Fuel Cell Electric Vehicle

IC – Imperial College

ICE – Internal Combustion Engine

IEA – International Energy Agency

LPG – Liquid Petroleum Gas

OECD – Organisation for Economic Co-operation and Development

OEM – Original Equipment Manufacturer

PEM – Polymer Electrolyte Membrane

PEMFC – Polymer Electrolyte Membrane Fuel Cell

PFCC – Polymer Fuel Cells Challenge

PHEV – Plug-in Hybrid Electric Vehicle

Pt - Platinum

TCO – Total Cost of Ownership

UCL – University College London

WBCSD – World Business Council for Sustainable Development

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