

**The Hydrogen Hub Initiative:**

A Vision for the Hydrogen Economy

September 2015



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**Overview**

**Hydrogen technologies offer the UK a long-term opportunity to cost-effectively deliver secure high quality energy services whilst significantly reducing greenhouse gas (GHG) emissions and local pollution. The development of local Hydrogen Hubs that service multiple end-users can deliver affordable, low emission and secure energy to local communities across the UK. Collaborative schemes will reduce the costs of the development of infrastructure needed for lasting clean energy that will benefit local enterprise, public bodies and people for decades to come.**

**This paper will consider:**

* ***What is a Hydrogen Hub?***
* ***What are the benefits of Hydrogen Hubs?***

**The value of hydrogen-based energy systems lies in their flexibility. Hydrogen is able to connect and satisfy differing energy domains from electricity generation to building level heat, to transport. In this sense one energy carrier can deliver mutually beneficial efficiencies between previously distinct domains of generation, heating and transport.**

**Prepared for:**

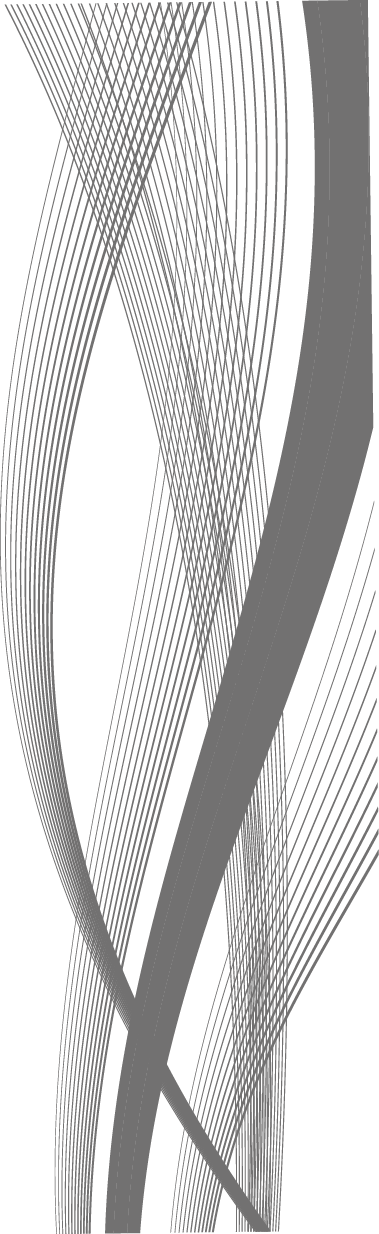
**Johnson Matthey Fuel Cells**

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**Prepared by:**

**Ecuity Consulting LLP - Ilias Vazaios, James Higgins and Robert Honeyman**

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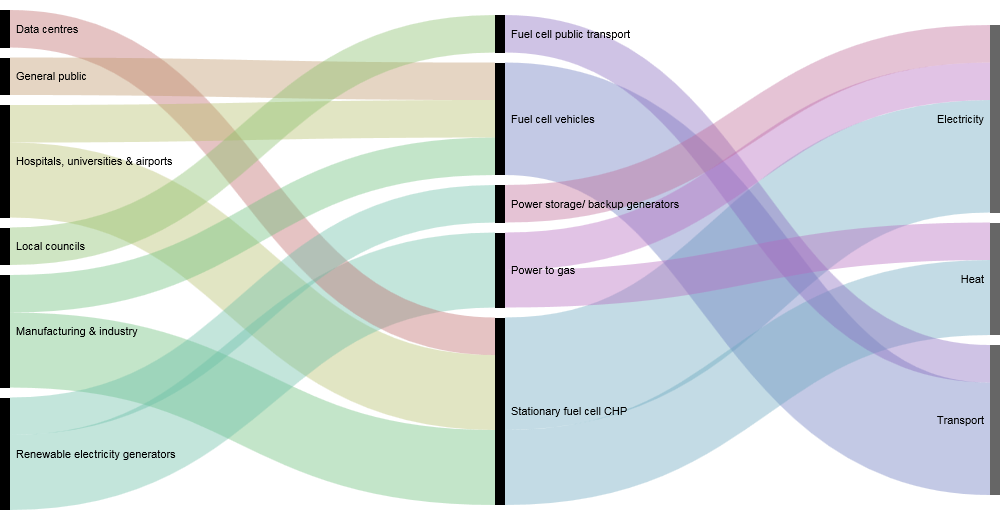
**What is a Hydrogen Hub?**

**The Hydrogen Hub is an infrastructure project which integrates a number of hydrogen-based energy services. These services match supply and demand for energy to meet our needs for heat, power and transport.**

**Hydrogen and fuel cell technologies are flexible to many applications and energy requirements from fuel cell vehicles, to stationary fuel cell CHP units and grid balancing services (see examples in figure 1).**

**A centralised Hub can allow for the sharing of technology and infrastructure. As demonstrated in the appendix of this paper, this clustering creates economies of scale and lower unit costs of energy for each service that shares the infrastructure.**

*End - users*



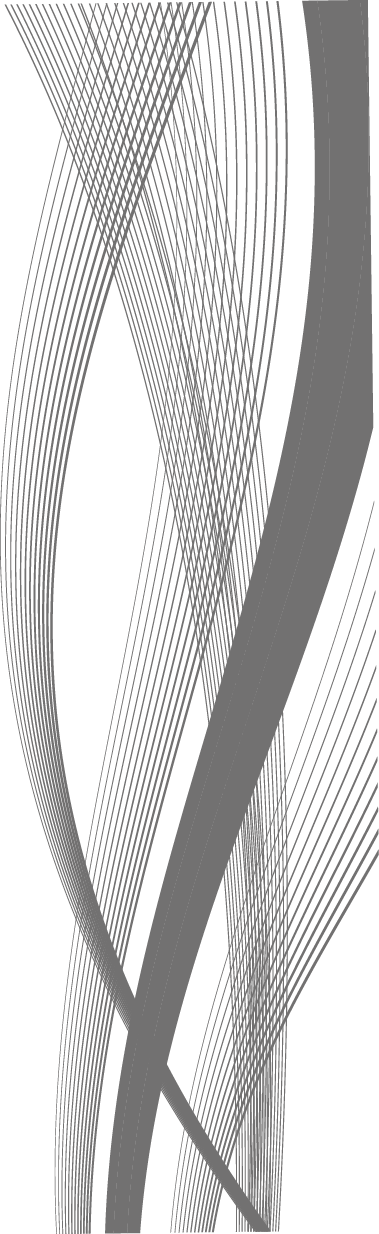
*Services / technology*

***Figure 1 – Examples of hydrogen-based energy services***

**The hydrogen based economy has the potential to displace fossil fuel and fully capitalise on the potential for renewable energy technologies, however widespread uptake cannot be achieved overnight. Hydrogen utilisation is not viable without supporting infrastructure, and this infrastructure is not viable without appropriate demand. The high capital costs of infrastructure warrant targeted approaches initially, where projects are focused in locations of suitable demand. These initial infrastructure projects can be described as Hydrogen Hubs.**

**Ultimately the goal is to demonstrate a viable Hydrogen Hub model that can be scaled to numerous locations across the UK, lowering production costs and creating the infrastructure needed for a larger hydrogen economy**

*Energy domains*

**Benefits of Hydrogen Hub**

**Hydrogen as an energy carrier and solution has been shown to be versatile and able to satisfy numerous demands. Thus one of the principle benefits of such local initiatives is their ability to meet time, place and service variant demands. From an energy system perspective, this flexibility is a notable strength. Additionally this allows for the clustering of a number of services and end-user demands around a centralised Hub, which lowers cost.**

**Broadly speaking the benefits of adopting fuel cell technologies and utilising hydrogen-based energy services can be sub-divided under three categories**

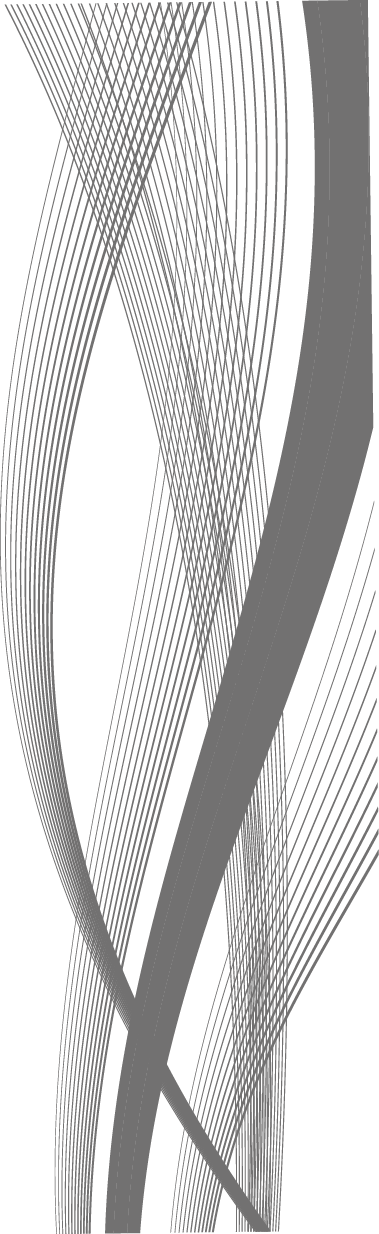
Note that these categories are not mutually exclusive, and any project can have a number of benefits which apply to each category.

1. **Financial benefits**

**Many of the hydrogen and fuel cell technologies are nascent and haven’t achieved the mass-market deployment necessary to reduce upfront capital costs to the levels of other solutions, in particular compared to fossil fuels. However the structure of the Hubs clustering around multiple users creates the opportunity for increased volumes, economies of scale and lower energy costs.**

**In addition certain regulations and commercial conditions require specific energy solutions on a technical level that can be met by fuel cells and hydrogen. Take for example material handling vehicles (MHVs) which often operate in warehouses. Employers have an incentive to invest in MHVs that produce no pollutants given that their workers will be indoors with the vehicles. This leaves two options, the first being battery-powered vehicles and also fuel cell powered MHVs. Despite requiring a higher upfront fee, the fuel cell option gives the opportunity for lower running costs over time as described in detail in box 1.**

**Similarly for a local council considering investing in a low-carbon bus fleet, the fuel cell option allows for reduced refuelling times, greater range and ultimately lower costs over their lifetime**





Box 1: Area of opportunity – material handling vehicles (MHVs)

Material handling vehicles (MHVs) are currently powered by either electric motors or internal combustion engines. For many indoor applications electric MHVs are preferred because of the potential for lower running costs and zero exhaust emissions. Though currently more expensive in relation to the upfront cost of capital, fuel cell MHVs can be considered a more attractive alternative to electric MHVs for a number of reasons.

Firstly unlike batteries fuel cells operate consistently and deliver the required power level at temperature extremes and in particular cold conditions (such as in refrigeration units perhaps). In addition figure 3 illustrates graphically the reduced refuelling times that a fuel cell powered MHV (6 minutes per day) enjoys over an electric alternative (closer to 50 minutes per day). Consider also that batteries require up to 8 hours cooling time in between change overs, and the potential for improved productivity per vehicle (and battery) when operating fuel cell MHVs is clear.

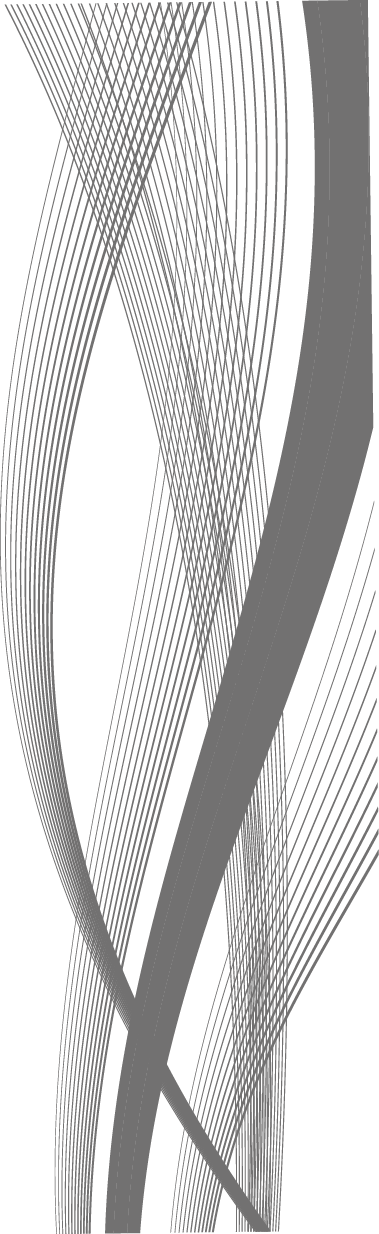


This improved productivity has a financial bearing on the operation costs associated with running a fuel cell MHV. Figure 3 utilises data from a US Department of Energy study on the comparative costs of MHVs to demonstrate the cost savings that can be obtained when investing in the fuel cell option rather than an electric alternative over the lifetime of the investment.



Note that the economics for other *back-to-base* fleet vehicles such as buses appears to be similar in regard to the efficiency and operating cost savings that can be made over EVs as a result of quicker refuelling times (and no need for additional batteries/vehicles if operations run throughout the day).

1. **Strategic benefits**
2. **Energy storage (and grid balancing)**

The UK’s centralised power generation system is undergoing a radical overhaul with a significant proportion of intermittent (wind and solar) generation already online, alongside plans for tidal energy and uncertainties over new fossil fuel plant construction as older plants are decommissioned.

The Government’s current approach to managing intermittent demand is the development of a Capacity Market, which procures spare capacity. This approach is both expensive and potentially damaging environmentally as many of the generating plants providing this capacity are diesel or other fossil fuel plant. The Capacity Market approach also fails to provide sensible options for utilising excess electricity from intermittent generation when demand is low.

Progressively it is expected that as supply becomes more variable (i.e. the wind does not always blow equally) it will become more difficult to marry generation with demand without storage. An energy system with the ability to store excess energy creates the flexibility for consumption to take place at different times places. More tangibly there is a technical need to better utilise our existing electricity generation resources, and with this need should follow commercial opportunities.

Many opportunities involve the creation of hydrogen using excess electricity through the process of electrolysis (see box 2 for an example). Instead of dumping or not generating this additional energy it can usefully be stored as hydrogen.

A number of different commercial models have been trailed which involve the storage of hydrogen created from electricity. Germany has been at the forefront of the commercialisation of power-to-gas, which involves electrolysers powered by excess electricity (often renewable/intermittent) producing hydrogen which is injected into the natural gas grid (either as hydrogen or as methane). This injection effectively stores the energy, which can then be utilised at a later date and in another location for heating, power generation or as a transport fuel. Indeed the German utility company RWE AG has installed an operational power-to-gas 150 kW plant in Germany in 2015.

Another promising avenue for hydrogen-based energy storage is to utilise underground gas storage facilities. A study by the Energy Technologies Institute (2015)[[1]](#footnote-1) detailed the potential for salt caverns to provide storage for hydrogen, which would be flexibly utilised to power turbines and provide tens of GW’s of electricity at times of need.

1. **Energy security**

From an energy systems perspective, security of supply is significantly benefitted by the ability to store energy and consume during times of insufficient supply. The increased proliferation of companies providing backup generators in the UK is testament to the need for energy security. This provides commercial opportunities. Hydrogen-based storage technologies could provide low-carbon solutions enabling supply to adapt to variable demand especially during peak usage hours.

Additionally, hydrogen is an energy carrier which can be generated using resources native to the UK. Given that currently 45% of energy is imported[[2]](#footnote-2), there is a value to being self-sufficient and the domestic production of hydrogen would help the UK move towards a more secure energy system.

Security of energy supply is of particular importance for certain businesses and buildings including data centres and hospitals which require constant, dependable power. The installation of stationary fuel cells which are powered by natural gas can provide reliable baseload power for buildings. As they operate independently of the national grid the risk of power outages, surges and other centralised power issues are mitigated. In addition some stationary fuel cell modes are able to generate useful heat and operate with little noise pollution and low carbon emissions (see box 3 for analysis).

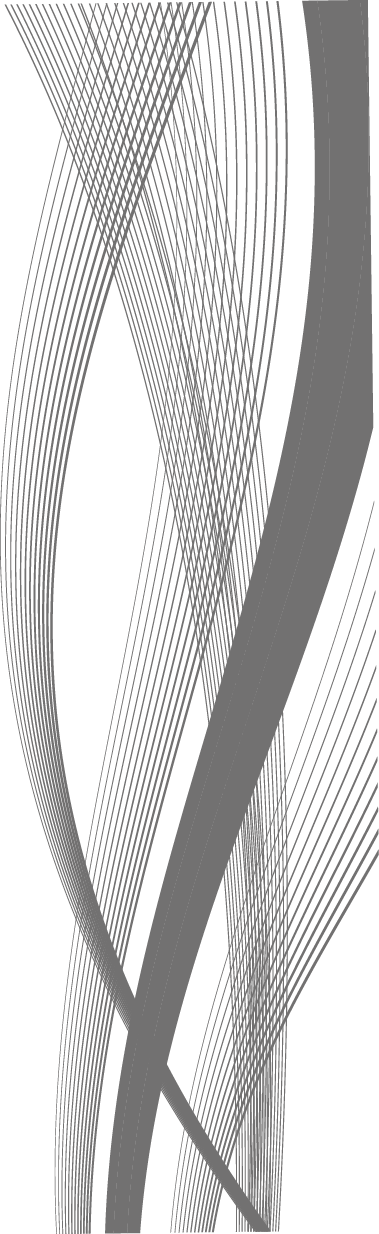
Box 2: Area of opportunity – grid balancing services

The production of hydrogen can assist with the difficult task of balancing an ageing and geographically disparate grid network. When power supply exceeds demand, as part of the settlement process the National Grid will bid to generators to stop supplying electricity in exchange for a balancing payment. At these times energy (often wind) can be thought of as having a negative resource cost. It thus follows that there is an opportunity for this excess electricity to be utilised more efficiently if powering water electrolysers and the production of *green* hydrogen.

Ecuity modelled the cost price of hydrogen given an electrolytic hydrogen production and refuelling station configuration. Figure 4 considers how a reduced price of power could significantly reduce the cost of producing and distributing hydrogen to end-users. Every £10 reduction in the price of electricity (£/MWh) results in a 70p reduction in the cost of hydrogen (£/kg), and given a £40/MWh price of electricity the cost-price of renewable *green* hydrogen reaches parity with SMR-produced gas. Conceptually if electrolysers provide a grid balancing service, this excess electricity could be offered for free leaving a hydrogen price that is 64% lower.



Equally back-up generation is needed when demand exceeds supply. Hydrogen-based solutions are again available with the storage of the gas in pressurised containers, or even on a greater scale stored in the UK’s unused salt beds. Then when power is needed the gas can either be utilised to run combustion turbines or smaller-scale fuel cells – which are particularly efficient if the excess heat is also used (box 3).

**3. Environmental benefits**

Hydrogen and fuel cells offer a zero particulate, lower carbon emission alternative to fossil fuel heat, power and transport technologies. The development of the hydrogen economy has potentially far-reaching environmental benefits, from the reduction of noise pollution (stationary fuel cell – silent power generation) to supporting the grid integration of intermittent renewables. Broadly speaking the most significant impacts can be characterised as improving air quality and reducing greenhouse gas (GHG) emissions.

1. **Air Quality**

The impact of particulate and NOx emissions from energy sources are becoming a crucially important issue globally and locally. Public Health England estimated that 3-5% of deaths in the UK in 2010 were attributable to long-term exposure to air pollution, and the World Health Organization estimate that these deaths cost the UK economy £54 billion or 3.7% of GDP[[3]](#footnote-3). Indeed in 2014 the European Commission Supreme Court began legal proceedings against the UK for its failure to cut levels of nitrogen oxide (NOx) which have been shown to be dangerously high[[4]](#footnote-4).

For NOx in particular transport is the most significant source of pollution with diesel vehicles being most problematic. When considering this issue many think of our motorway network and long journeys as a culprit. However, the majority of journeys are local, with the majority of personal travel trips (67%) being less than 5 miles[[5]](#footnote-5). It therefore stands to reason that local actors such as public authorities or fleet owners could make a big impact on air quality in urban or other localised areas through action to deliver low or zero emission vehicles.

FCEV technology only produces a small amount of water vapour from tailpipes, and a hydrogen-ran public transport system, coupled with FCEV taxis and goods vehicles promises to deliver the air pollution reductions that local authorities and the UK government need to achieve. Indeed these initiatives are already forming in the UK with Aberdeen Council delivering Europe’s largest fleet of hydrogen-ran buses and the Levenmouth Community Energy Project hoping to deliver the world’s first fuel cell refuse collection vehicles[[6]](#footnote-6).

1. **Reducing Greenhouse Gas (GHG) Emissions**

A movement away from traditional fossil-fuel energy sources towards hydrogen alternatives will have a significant impact on the UK’s efforts to lower GHG emissions. The shift in transport infrastructure described above is one such element, as is the use of stationary fuel cells which can provide secure heat and power to buildings – especially and most economically to those that have reasonably high energy demands for sustained periods (see box 3 for hospital example).

Hydrogen is inherently a zero carbon energy carrier; combustion or conversion to electrical energy in a fuel cell produces no carbon emissions. The total emissions associated with using hydrogen as an energy carrier or fuel depends on the method of production. Given an electrolysis process powered by renewable electricity, this can be done with no emissions at all. However steam reforming (where hydrocarbons are reacted with high temperature steam) is currently the dominant form of hydrogen production, and results in carbon emissions as a result of the combustion of fossil fuels. Yet this process is still more environmentally friendly, and emits about one tenth of the emissions produced from gas-combusting technologies per kWh of fuel input.

Box 3: Area of opportunity - stationary fuel cell applications, hospital example

A valuable feature of fuel cells is their ability to operate efficiently at high load factors and match the load profile of the buildings they’re installed in. They thus represent an effective low-carbon solution to the energy generation demands of hospitals. Financial benefits are available immediately with lower bills arising from higher efficiencies as well as potential eligibility for Feed in Tariff payments.

The UK has over 1,000 hospital sites. Figure 5 below considers the carbon emission savings that could be accrued nationally if only 30 average-sized hospitals installed fuel cells (powered by natural gas from the grid) every year. The exact level of savings depends on the proportion of oil or gas counterfactual fuel heating systems being displaced yet by 2022 cumulatively the UK could have saved between 7-10 Mt CO2e. To put this into the context of national climate change and emission targets, from 2016-2020 the UK needs to cut national emissions by 238 MtCO2e to meet its 3rd carbon budget.



In addition to environmental benefits, financial analysis suggests that for an illustrative hospital (modelled on the Royal Free in Hampstead using data for the Doosan Model 400 fuel cell), the installation of a number of FCs meeting the building’s power demand can lower the hospital’s levelised cost of energy (£/MWh) by 20% whilst also lowering annual carbon emissions by another 35% (compared to an oil boiler counterfactual). With energy bill savings the net present value of this investment is over £3 million, with a rate of return of 6% and a payback period of just over 7 years.



**Next steps**

1. **Strategy development**

The development of Hydrogen Hub infrastructure should allow for and promote growth in supply and demand for energy services. A process of expansion would ideally take place within the existing Hub, but ultimately the aim is to demonstrate a replicable model which can be scaled to other localities and applications. Thereby achieving growth within the Hub and across the UK.

This process will need to develop incrementally with pockets of demand and supply emerging in parallel. Fuel cell technologies (especially FCEV) are not viable without infrastructure, and the infrastructure is not viable without the technologies and users providing demand. A strategy is needed which concentrates initial development around fuel cell services that can already demonstrate commercial viability. Fuel cell buses in ultra-low emission urban areas, and stationary fuel cells providing secure and low carbon power (and heat) to buildings are two good examples.

This process should operate within a defined geographical area, rather than taking place irregularly over a number of areas. This allows for the sharing of capital and infrastructure, reducing average energy costs and opening up the Hub to other sources of potential demand. This incremental scaling of the Hub cluster will deliver energy more cost-effectively than a distributed solution (see appendix for analysis).

The French *Mobilité Hydrogène* programme offers a good example of a targeted roll-out of clustered refuelling stations centring on “captive fleets” of FCEVs which offer predictable demand to the station operators[[7]](#footnote-7). Indeed this example highlights the merits of securing sources of demand in advance, with fleets of vehicles with regular, back-to-base routes (buses, taxis and material handling)

being successfully targeted by the French programme.

1. **Collaboration**

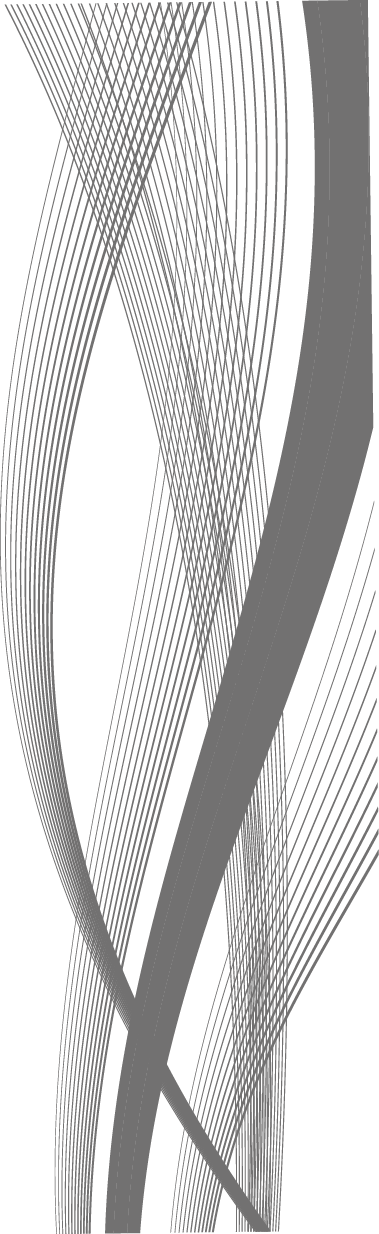
Integral to the development of a Hydrogen Hub, is the collaboration that must take place between elements of the supply chain, civic champions (such as local authorities) and potential end-users. As alluded in this paper the Hub is best delivered when targeted towards pre-determined sources of demand, with clustering of many services and end-users lowering average energy costs. This sharing of common resources and infrastructure of course requires collaboration between relevant parties.

In addition the delivery of a Hydrogen Hub will require technical and financial collaboration between different elements of the supply chain. To give a specific example, the development of a FCEV refuelling station may involve input from private companies that produce electrolysers, buffer tanks, compressors and other refuelling equipment, hydrogen transportation, forecourt station operators and vehicle manufactures.

From a technical perspective, collaboration is important to deliver reliable infrastructure and solve any operational issues if they arise. Each company also has a commercial interest in the development of a hydrogen economy, and this development would benefit from positive collaboration between stakeholders.

1. **Efficient market design – role for government policy**

To allow for the development of a dynamic and competitive market for hydrogen and fuel cells, policy has a role to play. As discussed hydrogen is a particularly valuable energy carrier with attractive attributes for energy storage. Though hydrogen has a lower volumetric energy density than hydrocarbons, it has a higher density than other large-scale storage solutions such as pumped hydro plants. In addition hydrogen storage prevents any substantial loss of energy over time unlike batteries, and it can be relatively easily transported from one location to another and utilised to meet a wide variety of energy needs.

Opponents will argue that this process requires costly investment in the infrastructure and technologies needed to convert electricity to hydrogen, and then back to power or heat. In addition there are inefficiencies involved with conversion processes.

Despite this hydrogen storage can play an invaluable role in enabling the efficient deployment of renewable electricity. Increasingly the UK generation mix includes more intermittent sources, and with further investment in renewables and inflexible nuclear power, the task of balancing grid supply and demand is becoming more complex.

At times of excess electricity supply the National Grid utilises settlement pricing to reduce generation. For conventional fossil fuel ran plants such as CCGTs, the opportunity cost to generating electricity is equal to the price of inputs, and thus when operations are stopped, costs are saved. For renewable plants there is effectively no opportunity cost to generating and any directive to stop producing electricity will result in lost revenue with no benefit of saved fuel consumption.

Large wind farms in particular have received capacity payments from the National Grid to compensate for this lost revenue at times of over supply on the grid. This is a clear inefficiency, with plants able to generate valuable energy being paid not to do so. The government could correct this failure and provide the conditions for the development of the hydrogen and fuel cell market, by adjusting policy to incentivise the conversion of excess renewable electricity to hydrogen. This act would both reduce the National Grid’s expenditure in the form of capacity payments, whilst also increasing the efficiency of the power generating infrastructure in the UK and providing the impetus for hydrogen industry growth. The task is for both industry and the government to develop this storage market.

**Appendix**

**Benefits of Hubs**

The Hub configuration can be thought of as a cluster of hydrogen-energy services meeting captive and dependable sources of demand. This considered and planned localised development model will be an important element of delivering commercially viable and scalable Hydrogen Hub projects. Especially initially with many of the technologies, services and supply chains being in their infancy the clustering of related energy systems allows for the co-development of infrastructure at a lower average cost.

To tangibly demonstrate the benefits of this initial clustering, analysis was conducted to compare the cost price of hydrogen for FCEV refuelling stations produced under a *Hub* model and a *distributed* alternative. Both economic analysis and field evidence demonstrates that the Hub is best clustered, with a large station producing the hydrogen and supplying smaller refuelling stations. This model of distribution has been termed the mother and daughter model and has been demonstrated by Tokyo Gas in Japan[[8]](#footnote-8).

Note that though the following analysis is specific to transport and FCEVs, the principle of clustering demand around a smaller number of large production facilities, enables economies of scale and delivers energy at a lower cost.

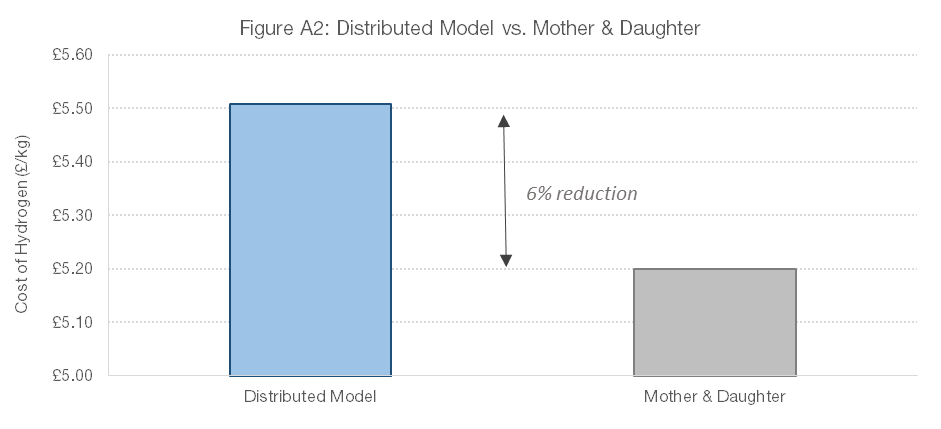
**Illustrative analysis – Mother and Daughter versus distributed model**

***Figure A1 – Hydrogen station configurations: Distributed vs Mother and Daughter***

Analysis prepared for this report compared the cost of hydrogen produced and supplied through a distributed refuelling network of 5 stations with onsite reformers, to a clustered *mother and daughter* model which utilises one station’s large reforming capabilities to supply 4 refuelling stations with hydrogen. Both scenarios are illustrative and envisage a total of 2,000 kg of hydrogen being supplied daily (400 kg from each station).

When distribution is involved, this is done through the operation of compressed gas tube trailers which is demonstrated to be the lowest cost option for delivery from mother to daughter station.

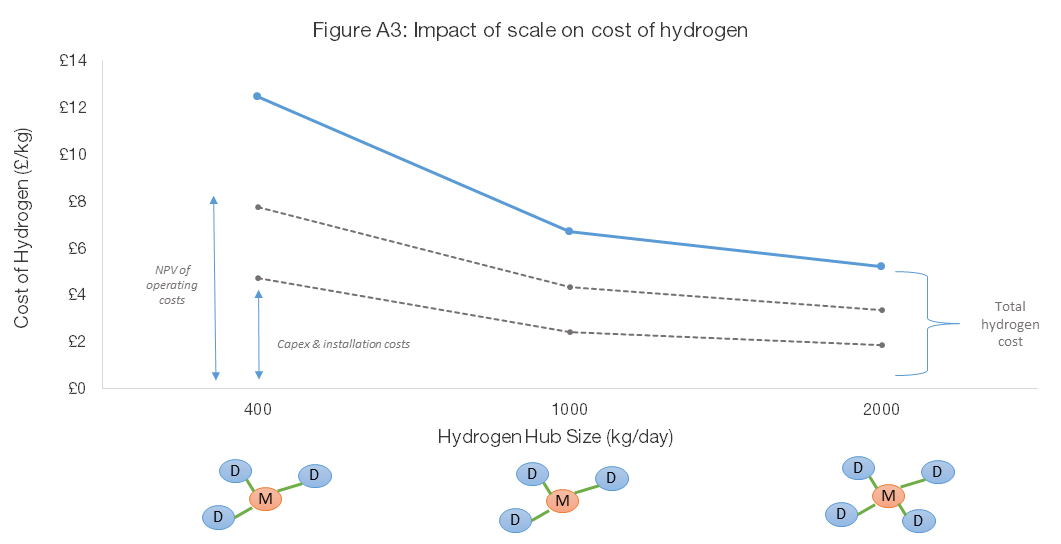
Figure A2 illustrates the cost savings graphically. The distributed model which consists of 5 separate stations producing (through steam methane reforming) and dispensing condensed hydrogen, delivers the gas at a cost-price of £5.51/kg. The introduction of a clustered mother and daughter model – whereby one large station reforms natural gas (at a rate of 2,000 kg/day) and supplies 4 refuelling station – reduces the cost-price of hydrogen at the pump by 31 p/kWh. Given that over the assumed 15 year lifetime (for other modelling assumptions see the appendix) both scenarios have been calibrated to produce and supply over 8.4 million kg of hydrogen, the cost saving is thus sizeable and in the region of £2.5 million.

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*Ecuity Economics*

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| Table 1 – Cost of Hydrogen (*£/kg*) | Distributed Model | Mother & Daughter |
| *Capital & Installation Costs* | ***£2.02*** | ***£1.84*** |
| *NPV of Operating Costs* | ***£3.49*** | ***£3.36*** |
| Total | **£5.51** | **£5.20** |

This modelling exercise also demonstrates the benefit of clustering from a scale perspective. Figure A3 gives a demonstration that as the total volume of hydrogen produced and supplied by Hubs increases and thus the size of the *mother* station is increased, the overall cost-price of hydrogen falls. The argument here being that the clustering of multiple end-users increases the total demand for hydrogen, which reduces the cost per unit.



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