



UNIVERSITY OF
BIRMINGHAM

Hydrogen as a component of City Development

The business case for city
hydrogen deployment with
Tyseley Energy Park an
exemplar case study

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Executive summary

Rapid urbanisation and the constant acceleration in demand for energy are putting an increasing strain on energy systems worldwide and leading to significant increases in emissions of Green House Gases. These emissions, particularly from transport and heating systems, are resulting in poor air quality in cities, which in turn lead to public health crises. Significant action is demanded, to decarbonise and improve air quality and there is now concerted activity to find ways to achieve this.

Hydrogen has long been seen as a potential answer to decarbonisation. It is a plentiful element and an effective store of energy although its production is itself energy intensive. When produced by steam reformation of methane/natural gas, currently the case for most hydrogen production, it is also carbon intensive. For Hydrogen to be green it has to be produced by electrolysis using renewable electricity. The two key determinants of whether or not this will be cost effective are the cost of the electricity and the utilisation factor of the electrolysis equipment.

As the UK's greatest renewable electricity potential lies in wind and solar, which are inherently variable in output, the utilisation factor will always be below 100%. However, as renewable capacity increases, there will be increasing surpluses of renewable electricity, during which times the cost of electricity will be low (including going negative).

This report estimates that green hydrogen can be competitive with diesel (for transport) at an electrolyser utilisation factor of 50% and at an average cost per megawatt/hour of between £35 and £55 (dependent on electrolysis technology used).

Tyseley Energy Park (TEP) is an energy hub serving Birmingham and the West Midlands and is an example of how energy development can be progressed in the UK. Within the development is a multi-fuel refuelling station that can supply compressed natural gas, electricity, bio-diesel and hydrogen. The hydrogen facility supplied by ITM Power is central to the acquisition of 20 new hydrogen buses to serve Birmingham and is capable of providing enough hydrogen to fuel 60 buses. The study concluded that the provision of hydrogen at a price in the range £5–£6 per kg would be competitive with diesel buses. Further to this are plans to develop a waste to fuel facility that can generate heat, power and hydrogen potentially based on Concord Blue technology.

In parallel, University of Birmingham have co-developed a hydrogen train working with Porterbrook as a proof of concept. Based on a Thameslink stock train, this prototype has shown that hydrogen trains are technically possible although challenges remain in terms of economic viability given the competition is diesel fuel that is not subject to fuel duty. However, should the fuel duty position not change, if hydrogen can be produced for less than £3 per kg viability is possible.

This study examines the levers that drive the business case for hydrogen deployment as a component of low carbon city development. The study focuses on the production of hydrogen and the economics for different uses. In order to reach a price point of £5 per kg it was found that power would need to be supplied at £75 per MWh, with a high electrolyser utilisation factor. This may be possible by using private wire supply arrangements with neighbouring generation facilities. In order to reach £3 per kg of hydrogen the power price would need to be significantly lower at around £35 per MWh – a cost that would be challenging unless excess power was being taken from the grid at times of low demand.

Further to hydrogen there is likely to be a case for green ammonia as a medium to transport hydrogen in significant quantities over longer distances. Green ammonia can be produced through the Haber-Bosch process which combines nitrogen extracted from air and hydrogen electrolysed from water to form the gas. In addition, as well as having a role in transporting hydrogen, the study found that ammonia has potential for use as a fuel in its own right – for maritime, for electricity and heat generation and as a fuel for backup power. The cases for these applications need to be developed but they could form a strong interim retrofit fuel for gas or diesel generators in cities with no carbon emissions output.



In conclusion, this report finds that there could be a strong case for the acceleration of hydrogen based infrastructure in cities. As a zero carbon fuel and with the economics reaching a level that is competitive with the status quo, it is recommended that further research and development into the hydrogen production process is taken on. Waste to fuel shows significant potential as a source of hydrogen and working closely with the power market should enable lower cost hydrogen and thus more economic applications.

Further to this, Tyseley Energy Park could be viewed as an exemplar for future energy development. With a limited amount of land close to Birmingham City centre, much capability has already been delivered and is in the pipeline. Once fully operational, TEP has the potential to fuel up to 300 buses or 75 train carriages. With the total bus and train fleet of Birmingham being significantly more than this, further such energy parks would be required or a further intensification of hydrogen production at TEP would be required – the key to which would be the co-location of generation and conversion technologies and a co-ordinated cross-city approach to development.



Introduction

Around the world there has been much interest in the potential for hydrogen as a zero carbon fuel for the future. This interest has intensified over the last 24 months with mainly localised pockets of activity around the world. Projects such as at Tyseley Energy Park can act as an exemplar for future development but require markets to be created to be viable. Commercial viability is of key importance and it is critical for learnings to be taken from such projects to drive down the cost of hydrogen production so that its viability as an energy store can be fully realised.

2.1 Project Background

There is a growing interest and need for the development of large-scale hydrogen demonstration projects. There are several drivers for hydrogen, but the main ones are linked to decarbonisation of heat and low carbon, low emissions transport. The scale of hydrogen production for the former, which could be potentially through direct injection into the gas grid, is very significant and at present could only realistically be achieved through steam methane reforming. This has the downside of requiring Carbon Capture and Storage (CCS) or Carbon Capture, Utilisation and Storage (CCUS) to capture the CO₂ emissions that result in order to meet the low carbon criterion. The delivery of hydrogen through electrolysis can be green if the power is from renewable sources but comparatively low volume and more expensive at grid price for electricity. On the other hand, the scale of production would seem a good match to the demand from a city scale public transport infrastructure. There are also routes to the production of lower cost hydrogen that obviate the need for relatively expensive grid electricity, which could offset the cost of the production of hydrogen by electrolysis. The opportunity is to target energy from waste activities and focus them on delivering affordable, city scale, hydrogen production.

Developing the rationale and business case for a comprehensive Hydrogen based approach to city infrastructure development

Urbanisation globally continues to gather pace as an increasing proportion of the world's population live in Cities. This growth means increased demand for power, heat, coolth, clean water, transportation, healthcare, education and social services.

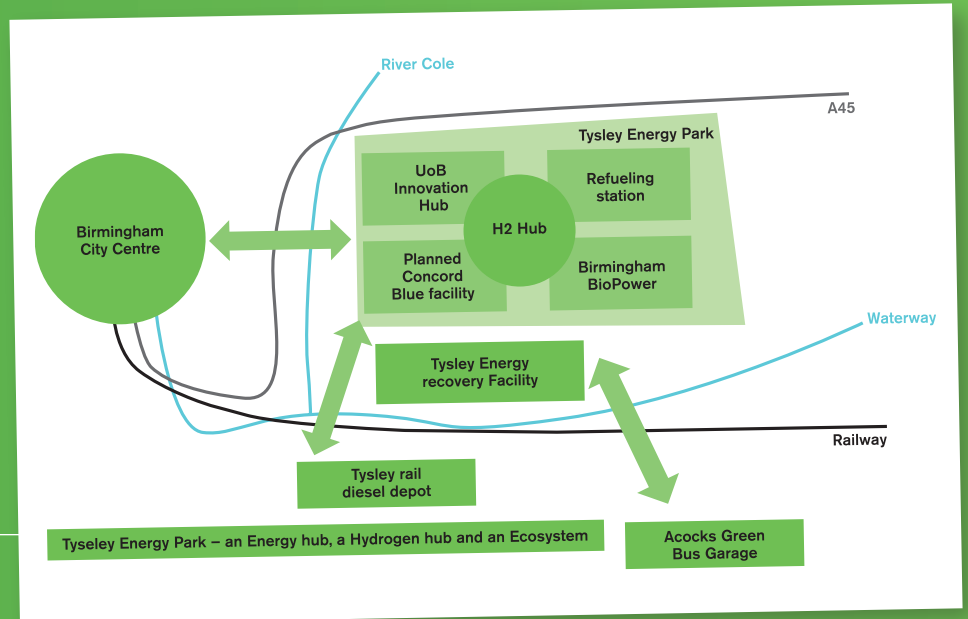
Traditional means of providing critical services predominantly rely on fossil fuels. This is not compatible with the Net Zero targets recently set by UK Government, or the general trend towards cleaner energy alongside the Climate Emergency declarations made by UK Central government and many UK Local Authorities in 2019.

Hydrogen as a plentiful element is seen as a significant opportunity to support the decarbonisation of the world in which we live. The use of hydrogen as a fuel for transportation, as a feedstock for power and heat generation and as a storage medium for energy should be critically important to the future energy mix.

Given the legacy systems in place across the developed world, often relying on natural gas, the transition to hydrogen as a primary source of energy will take time, investment and a significant change in technology and skill sets.

There are both opportunities and threats in the Birmingham area. Air quality has become a critical problem with a resultant public health emergency. Housing stock is in all classes with a significant number being of an age that is not compatible with modern day building regulations. There are pioneering technologies and commercial innovations that may pave the way to a low carbon future and for example, University of Birmingham have recently co-developed a hydrogen powered train – which could help to address the emissions problem caused by diesel trains around New Street Station. Birmingham City Council are at the centre of a scheme to put hydrogen buses on the streets.

Alongside this is Tyseley Energy Park ('TEP') – a locally owned development of a number of schemes focused on a low carbon future. A multi-fuel refuelling station is in the process of opening – hydrogen, biodiesel and EV charging being some of the re-fuelling options. There are further plans to develop energy from waste facilities that can generate hydrogen for use in the city.



Tyseley Energy Park

There is a concentration of world class academic and commercial expertise intelligence and know how in the field of energy within Birmingham;

- The Birmingham Energy Institute and Aston and Warwick Universities are the academic backbone and main drivers behind the formation of the Energy Research Accelerator (a multi-million pound collaboration with Cranfield, Keele, Loughborough, Leicester, Nottingham Universities and the British Geological Society under the aegis of Innovate UK) to address the major energy challenges facing the UK.
- Birmingham District Energy Company (BDEC)/ENGIE facilitated New Street Stations connection to the district energy scheme generating significant carbon savings and is now the prototype for low carbon investment by Network Rail.
- The Local Development Order at Tyseley Environmental Enterprise District (TEED) has paved the way for significant private sector investment – most recently by Birmingham Biopower in the Biomass Facility located within the TEED.
- Webster and Horsfall (Birmingham's oldest continuously operating manufacturing business) is now transforming its business base and site, working to bring forward Tyseley Energy Park as the energy and waste nexus for the city of Birmingham.
- Energy Systems Catapult – an Innovate UK funded think tank – has been located in Birmingham.

Tyseley Energy Park has the opportunity to galvanise and catalyse low carbon energy for the city and has the potential to set the standard for future city energy system development. Hydrogen is already forming a part of the output of the energy park and hydrogen is already forming a significant part of the future development of the city and is a focus for energy development.

2.2. Purpose of report

A business case is needed to support the hypothesis that hydrogen can form a significant part of the energy mix for cities as they seek to decarbonise and set sights on 'net zero'.

There are a significant number of initiatives in the Birmingham area centred around Hydrogen and the first step is to understand and explore the direct and indirect opportunities that may emerge.

In continuing the Climate KIC Connected clusters work to date there is further development required to gain understanding of the existing schemes and programmes in operation to set out a case for large scale adoption. Tyseley Energy Park is a clear example of where there is an opportunity to centre around a single development to become a hub for hydrogen production, distribution and use and become a case study for broader adoption.

The University of Birmingham commissioned Kingscote Enterprises Limited (KEL) to bring together a high level business case for Hydrogen adoption in city development. Given the progress of Tyseley Energy Park the business case is supported by a case study of Tyseley as an exemplar.

2.3. Approach

Initial work was focused on understanding the broader hydrogen value chain through a desktop research exercise and engagement with the industry. Market and economic research can be summarised as:

- Assessment of market initiatives in execution/operation – UK and International
- Engagement with actors in the UK hydrogen industry – both current and planned
- Examination of the hydrogen value chain
 - Production
 - Storage
 - Transmission
 - Usage
- Commercial City scale applications
 - Transportation (vehicle use, refuelling)
 - Power generation
 - Heat generation

Upon reporting the value chain this report then sets out the business case for hydrogen deployment:

- Benefits
 - Emissions
 - Efficiency
- Challenges
 - Infrastructure requirements
 - Volatility in transit and mitigants
 - Contractual considerations
- Economics
 - Setting out the business case for different market uses
- Tyseley Energy Park as an exemplar

Interviews

Interviews were requested and conducted with the following entities and personnel. Highlighted in bold are the contacts that were formally interviewed for this commission.

University of Birmingham

Martin Freer, David Boardman, **Rex Harris**, **Robert Steinberger-Wilckens**, Stuart Hillmansen, **Stephen Kent**

Cogen

Peter Lawrence

Tyseley Energy Park

David Horsfall

Siemens

Steve Aughton, Elaine Trimble, **Matthew Knight**, **Matthias Huber**

Engie

Melanie Biddle, Andy Davey

ITM Power

Rachel Smith

Ecuity

Clare Jackson





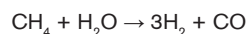
Hydrogen Value chain

The full benefits of hydrogen as a zero carbon fuel will be unlocked by innovation and adaption to the industrial value chain. Optimum green hydrogen methods need to be developed alongside economic technical solutions for CCUS. As hydrogen becomes increasingly mainstream, economic and environmental pressure will drive lower costs and emissions.

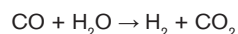
3.1 Hydrogen Production

3.1.1 Steam reformation of methane

Globally, in 2018, circa 70 million tonnes of hydrogen was produced and consumed¹. Most hydrogen (circa 96%) used in the UK is produced by steam reformation of methane. This results in a molecule of methane and a molecule of water (steam) being converted into three molecules of hydrogen and one of carbon monoxide.



In a second stage (water shift reaction) the molecule of carbon monoxide is reacted with another molecule of water to produce a further molecule of hydrogen and molecule of carbon dioxide.



Overall, one molecule of methane and two of water will produce four molecules of hydrogen and one of carbon dioxide.

As the overall process is endothermic, it requires heat, usually provided by burning additional methane, which in turn results in further emissions of carbon dioxide. Thus, hydrogen produced in this way has a high carbon emissions factor and will continue to do so unless the carbon dioxide can be captured and put into storage in disused oil and gas wells ('Carbon Capture and Storage' or CCS). Given the distance of Birmingham from the oil and gas fields, and the fact that CCS is as yet unproven at scale, this production methodology is unlikely to be suitable at Tyseley.

3.1.2 Steam reformation of biomass

Production of hydrogen by steam reformation has been the subject of research over the last 20 years. Basically, two pathways have been followed:

- Pyrolysis of biomass to produce a pyrolysis oil that is then subjected to steam reformation, followed by use of the water shift reaction to produce hydrogen from the char from the pyrolysis process.
- Gasification of biomass with the resultant syngas subjected to steam reformation.

Most of the research projects encountered problems with carbonisation within the process, in particular reduction in catalytic activity, and hydrogen yields were relatively low due to the relatively low hydrogen content of biomass. One project² found that by adding iron oxide to the fluidised bed being used increased hydrogen production as a result of a reduction reaction with the iron oxide.

No commercial scale processes using steam reformation of biomass to produce hydrogen were identified in this study.

3.1.3 Pyrolysis/lean gasification of wastes

Considerable research into and experimentation with pyrolysis³ and lean gasification⁴ of waste materials has taken place in recent decades. Originally this effort was directed at finding a cleaner way to recover energy from waste, but more recently attention has turned to the potential of these technologies to produce utile hydrogen.

Whilst gasification of waste wood and woody biomass has become widespread for the production of electricity, most technologies for the gasification of waste⁵ have failed to find commercial success⁶.

The Energos gasification technology has been successfully deployed at seven sites in continental Europe, but the parent company went into administration in 2016. Subsequently, two projects (in Glasgow and Derby) using the technology have failed to commission. This makes the technology unfinanceable, although a Norwegian offshoot Energos A/S continues to market it. The similar KIV technology has also been deployed at a number of sites in continental Europe, but the company no longer appears active. Both the Energos and KIV technologies are regarded by many as not being true gasification: whilst they met the UK's definition of Advanced Conversion Technology, in reality they were close coupled gasification and combustion units where the syngas produced in the gasification phase was burnt in an immediately adjacent (less than 3 metres separation) combustion chamber to raise steam. As such their conversion efficiencies⁷ were only 16% to 17% (as much of the radiative heat in the gasification chamber was not used to raise steam), compared to the 23% to 24% conversion efficiency typical of conventional EfW plant. As such they have no potential to produce hydrogen unless the technology is modified, which is unlikely to happen now.

Pyrolysis of MSW/RDF has found even less commercial success; most have failed technically with common causes of failure being tar blinding, incomplete pyrolysis, slagging (particularly with waste with high percentages of silica rich biomass materials), chlorine corrosion of metal and poor overall efficiency (compared to conventional EfW). However, a small number of technologies have shown considerable promise at the pilot stage.

One such technology, the German KUG technology⁸, showed in its 1 tonne per hour pilot plant that it could convert plastic rich waste into a mixture of light fuel oil substitute (LFOS), ash and a syngas rich in hydrogen and methane⁹. This technology was technically successful because it:

- used a counter rotating screw within a tapered reaction chamber to press the waste against the heated walls of the reaction chamber;
- ensured solid to solid rapid transfer of heat to the material being pyrolysed, resulting in complete pyrolysis¹⁰;
- used highly corrosion resistant Molybdenum steel that could withstand the presence of chlorine radicals under sub-stoichiometric conditions;
- recirculated syngas through the system that included a 7 stage cracker, which cracked long hydrocarbon chains and enabled the system to run at a relatively cool 540°C (giving a relatively high conversion efficiency of 22.5% when the syngas and LFOS were used to generate electricity via a spark ignition engine);
- used carbon in the pyrolysis char to produce hydrogen and CO₂ in a water shift reaction within a secondary chamber of the unit; and
- contained a scrubbing stage that scrubbed chlorine and other contaminants from the syngas.

The design of the process was such that it could accept waste with a moisture content ranging from 8% to 40%, meaning that it was capable of accepting a broad range of wastes without need to dry the waste first. The LFOS was stored on site. It was used to run a diesel generator and diesel vehicles, and to preheat the unit prior to the introduction of waste. Once the unit was operating, the temperature of the unit was maintained by either syngas or LFOS. Syngas was preferred for this, as the LFOS was more valuable, but by altering the recirculation rate of the syngas, the amount of LFOS produced could be reduced and the amount of hydrogen in the syngas could be increased.

Within the UK, PowerHouse Energy has designed its Distributed Modular Generation (DMG) unit. Whilst descriptions of this technology are limited, it appears to be high temperature (1,000°C) pyrolysis within a rotating pyrolysis chamber. Its stated aim is to produce/extract hydrogen from the pyrolysis syngas. It has a 1 to 3 tonnes per day demonstration unit located at the Thornton Science Park on Merseyside. Full scale units are projected to be 25 tonnes per day generating up to 2,000 kg of hydrogen or circa 1.6MW electricity¹¹, with the first unit projected to be built on the Peel Group's Protos site near Ellesmere Port. Work on the demonstration unit has shown that hydrogen (up to 50% of the syngas by volume) could be extracted by pressure swing adsorption (PSA).

Whilst this technology is yet unproven, it appears to share similarity with the KUG technology. Consequently, this technology could, in the future, be suitable for TEP.



Already proposed at TEP is the Concord Blue technology. This is described as thermolysis (thermal decomposition) rather than pyrolysis. It comprises of three chambers arranged vertically:

- the lower or thermolysis chamber into which waste with a moisture content of 20% or less is pushed;
- the middle chamber or reformer, where gaseous outputs from the lower chamber are converted into syngas; and
- the heat carrier vessel where ceramic balls are heated before flowing through the reformer into the thermolysis chamber.

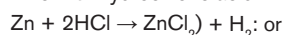
Decomposition of the waste occurs by solid to solid transfer of heat from the ceramic beads when they are mixed with the waste in the thermolysis chamber. The temperature of the beads when they enter the waste is not stated, but this results in the waste being heated to 400°C+ and volatilising it. The gaseous products then pass to the reformer, where steam is injected to raise the temperature to 1,050°C and break long hydrocarbon chains, thereby producing a syngas composed of hydrogen, CO₂, CO and CH₄. In this regard it is similar to the steam reformation of hydrogen described above. It is unclear what happens to the solid residue from the process, although one source¹² indicates that this is burnt to provide the heat for heating the ceramic beads.

As with both the KUG and PowerHouse Energy technologies, this technology uses solid to solid transfer of heat. Unlike the other two, Concord Blue has some plants already operational¹³ and it is backed by Lockheed Martin who provide engineering, procurement, and construction services for Concord Blue facilities. Various sizes of module are indicated on the company's website ranging from 250 kW/10 tonnes per day to 3MWe/230–330 tonnes per day. This suggests an overall conversion efficiency that

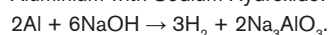
is less than that of a conventional EfW plant, however this cannot be stated definitively without access to detailed information about the process.

3.1.4 Other chemical reactions

Hydrogen can be produced by various other chemical reactions for example, by reacting Zinc with hydrochloric acid:



Aluminium with Sodium Hydroxide:



These reactions are best considered in the context of hydrogen storage rather than the production of hydrogen per se and are dealt with below.

3.1.5 Electrolysis of water

Hydrogen can be produced by passing a direct current through water between electrodes to split water molecules into hydrogen and oxygen: $2\text{H}_2\text{O} \rightarrow 2\text{H}_2 + \text{O}_2$

Hydrogen gas forms at the negatively charged cathode (a reduction reaction), and oxygen gas at the positively charged anode (an oxidation reaction).

The resistivity of water is high, so electrolytes are used to permit the current to flow. Within this general description there are a multitude of processes, most of which either employ a liquid electrolyte or a solid polymer-electrolyte membrane (also called a proton exchange membrane or PEM). Solid Oxide Cells have also been developed that carry out high temperature electrolysis of steam¹⁴, which use less electricity per kg of Hydrogen produced than low temperature electrolysis. However, their viability depends on a cheap source of heat for steam production and realistically the technology is still in development.

Electrolytes typically contain soluble salts (particularly lithium and sodium salts), acids (frequently sulphuric acid) or alkalis (frequently potassium and sodium hydroxides).

The electrodes used are typically made of catalytic materials, usually platinum group metals or nickel. Other materials can be used for electrodes, depending on the nature of the electrolyte, the required purity of the hydrogen and the acceptability of electrode dissolution.

Whilst many modern electrolyzers (such as the ITM electrolyser already deployed at TEP) employ PEMs, many liquid electrolyzers are used, particularly alkaline ones. Pure Energy Centre is an example of a UK company that manufactures both types¹⁵. Within the limits of existing technology, alkaline electrolyzers are promoted by some manufacturers as being better suited to large scale (1MW+) electrolysis (noting that evidence to support this assertion is limited).

It is clear that high capital costs of electrolysis equipment mean that the cost per kilogramme of hydrogen produced varies proportionately with utilisation: the higher the utilisation, the lower the cost. At the same time, given that it takes approximately 43 to 51 kWh¹⁶ of electricity to produce 1 kilogramme of hydrogen, the cost of electricity is the other major influence on cost. A considerable amount of research is currently focussed on electrolysis using surplus renewable electricity ie, electricity that otherwise be constrained off¹⁷ and which in theory is less than the average cost of wholesale electricity. The cost of hydrogen produced this way will therefore be a function of this lower electricity cost and a higher capital cost per kilogramme of hydrogen produced.

3.2 Hydrogen Storage

Hydrogen is relatively difficult to store. It boils at roughly 20.3 K (−252.9°C) and is the smallest molecule of any element, meaning leakage is always an issue. The flammable limits of hydrogen are 4% to 75% in air and it has a low minimum energy of ignition of 0.016 millijoules¹⁸. Hydrogen can cause embrittlement of metals in which it is in contact.

There are three methods of storage:

- cryogenic, where hydrogen is liquified. This requires highly insulated containers and significant energy input to chill the hydrogen. However, even with the best insulated containers, some 'boil-off' will occur resulting in losses;
- pressure, where the gaseous hydrogen is pressurised and stored in a tank, or underground cavern or depleted gas field; and
- chemical, where the hydrogen is chemically combined with other elements to form stable compounds such as ammonia.

For the purpose of this study, cryogenic storage is discounted as this is mainly directed at applications such as fuelling rockets and use in industry (for example as a coolant in power generation) and for transport of hydrogen. Similarly, the use of underground storage is discounted here as there do not appear to be any suitable existing underground structures in the vicinity of Tyseley.

The choice of pressure and/or chemical storage at Tyseley is primarily to do with how and where the hydrogen will be used, how it will be transported there, and how long it is required to be stored.

3.2.1 Pressure storage

Currently, most applications of hydrogen outside the chemicals and petrochemicals industries require relatively small quantities. Consequently the most common form of hydrogen storage is storage in pressurised containers. The containers are themselves graded:

- Type 1, limited to between 175 bar (Aluminium) and 200 bar (Steel) pressure;
- Type 2 260 bar (Aluminium tank overwrapped with a structural material or materials such as fibreglass or fibre reinforced polymers) to approximately 300 bar (steel tank similarly overwrapped) pressure;
- Type 3 are tanks made from composite materials with a metal liner – Maximum pressure approximately from 300 bar (Aluminium/glass) to 700 bar (steel/carbon)
- Type 4 are composite tanks with a polymer liner – Maximum pressure approximately 700 bar.
- Type 5 are all composite liner-less tanks with maximum pressures up to 900 bar (but so far appear to have only been used for specialised applications and not necessarily for Hydrogen).

Type 4 storage would appear to be appropriate at TEP. Of note is the Linde tube trailer which consists of 100 Type 4 composite storage tanks mounted on a 13.5m long Trailer. The containers have a charged pressure of 500 bar, and each trailer can carry 1,100 kg hydrogen. They were developed as a cost effective alternative to cryogenic tankers for the transport of hydrogen, however they can also double as mobile storage tanks. This could be useful for TEP in the future: 1,100 kg is enough to power

55 fuel cell buses per day and is only slightly less than the daily production of the existing ITM Power electrolyser. This would enable hydrogen produced at Tyseley to be taken to a remote bus depot to charge buses there, rather than have buses travel to Tyseley.

3.2.2 Chemical storage

Chemical storage can take many forms and is the subject of much research. Of principal interest to Tyseley are:

- compounds of hydrogen, particularly ammonia;
- metal hydrides;
- Aluminium.

Hydrogen binds strongly with other elements/molecules, and all methods require an energy input to release the stored hydrogen. Consequently, choice of chemical storage requires consideration of both the hydrogen content (expressed as hydrogen as a percentage of the weight ('wt.%') of the compound or carrier) and the round-trip energy efficiency.

Ammonia shows particular promise and is under active consideration at Tyseley. Hydrogen produced by electrolysis is combined with Nitrogen in a Haber-Bosch reactor. This process is mature and the storage of ammonia is safe and well understood. When hydrogen is required, the ammonia is passed through a reformer.

Metal hydride storage is commercially available but typically has a high cost: for example H2Planet's MYH2 3000 cylinder that can store 3,000 litres (0.270kg) costs approximately £6,700. This is primarily due to the use of platinum group metals. Research into other hydrides, in particular Aluminium, Lithium, Magnesium and Boron, and alloys and compounds of these metals, is on-going. In all cases, heat is required to release hydrogen in the reforming process.

Aluminium is not strictly a hydrogen store, but it can be reacted with water to release hydrogen and form Aluminium hydroxide. This can then be reformed to Aluminium. Research is driven primarily by favourable round-trip efficiency, however it has a low carrying capacity of 3.7% wt.%

3.3 Transmission

Hydrogen can be moved by cryogenic tanker, pressurised containers (such as the Linde tube trailer mentioned in 3.1) or pipeline. If hydrogen is stored in ammonia, the ammonia can be moved by tanker or possibly by pipeline.

In the case of TEP, onward transmission of hydrogen is not envisaged for the first phase: hydrogen produced by the ITM electrolyser will be used at the multi-fuel fuelling station to fill fuel cell buses. However, in the next and subsequent phases there is likely to be a need to move hydrogen to other locations. In considering this, the means of storage, the means and scale of hydrogen production, the use and the relative costs will need to be taken into account in an iterative manner. For example, if in the next phase hydrogen production capacity is installed in modules of 1,000 to 1,200 kg per day, two trailers¹⁹ per module could allow hydrogen to be stored at TEP as it is produced, then transported to a location remote to TEP and then stored there for use²⁰.

Pressurised tube trailers will enable hydrogen to be taken to other parts of the city. However, this will depend on individual locations having either their own storage or the space to park a trailer. In the case of buses based at depots elsewhere in the city, it is likely to be more practical and economic to take the hydrogen to them in trailers rather than bringing the buses to TEP to refuel²¹. Based on a projected 20 kg of hydrogen per bus per day, one trailer should be sufficient for 55 buses per day.

To be economically viable, pipelines generally need a relatively high throughput²². However, they generally obviate the need for the end user to have on-site storage²³, which means that existing facilities (such as city centre CHP energy centres) without storage ability would be able to convert to hydrogen. In the short term, TEP is unlikely to produce enough hydrogen to be able to justify the cost of pipelines. However, it is well placed to consider them in the future, as it is located close to both the railway and the canal along which it should be relatively easy to install lines. If future hydrogen production is dedicated to powering hydrogen trains, a pipeline from TEP to Tyseley rail maintenance yard should be considered. It could be relatively easy to run a pipeline from TEP to the yard via the James Rd bridge across the canal and alongside the railway track. This would have a distance of approximately 1,300m. It could also be possible to extend this pipeline along the railway line to the Acocks Green bus station (an additional 1,200m) if there is sufficient hydrogen production in the future.

In the case where ammonia is used as a hydrogen store and there is a requirement to transport it to an end user, movement will almost certainly be by tanker as pressurised liquid ammonia: the volume is much less than that of pressurised hydrogen gas (17.5 wt.%, compared to 5 wt.% for pressurised hydrogen). However, the demand for ammonia transport will be dependent the number of end user's with the ability to:

- store ammonia on site;
- reform ammonia to hydrogen on site; or
- use the ammonia directly as a fuel²⁴.

In the short to medium term there are likely to be relatively few such users. However, as it is much easier and cheaper to store ammonia than pressurised hydrogen, and as it can be used directly as a fuel (for example in a modified CHP engine), it is possible that demand will grow. There are safety issues to consider when handling, storing and using ammonia, however these are well understood and materials and procedures for doing so are highly developed.

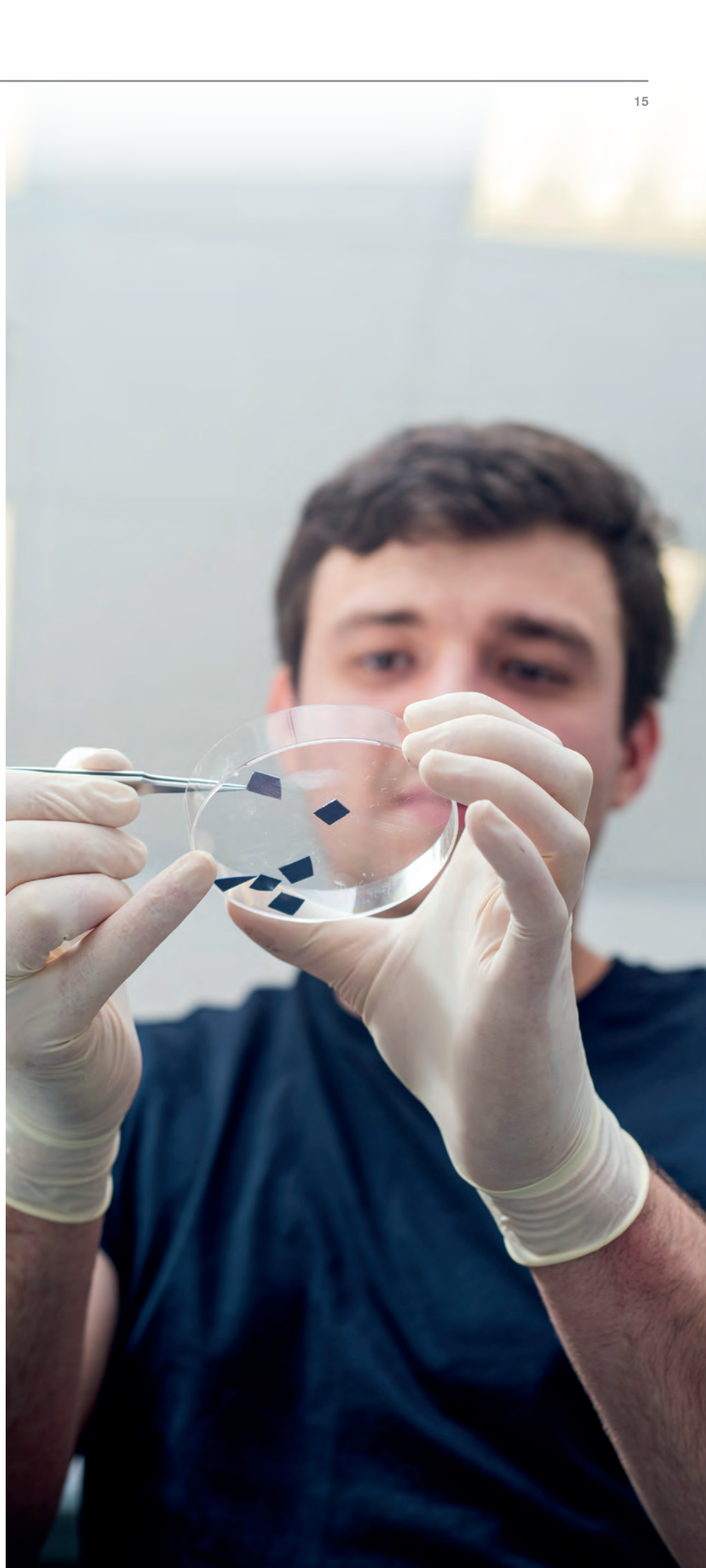
An alternative consideration for TEP is the transport of ammonia produced elsewhere to TEP. The TEP site is limited in size and ultimately this will limit the amount of hydrogen that can be produced there by on-site energy generation and/or pyrolysis (noting that electrolyzers powered by grid electricity will not have the same limitation). Ammonia reformation requires a small footprint and therefore using 'off-site' ammonia could enable TEP to increase hydrogen production beyond that which would otherwise be the limit. In this scenario, a pipeline to transport hydrogen into the city (and/or the Tyseley rail maintenance sheds) could be viable. To avoid the carbon emissions associated with conventional ammonia production, such ammonia would have to be produced elsewhere using renewable energy and brought to TEP by road tanker, rail tanker or barge.

3.4 Hydrogen usage (markets)

Key to the successful implementation of a hydrogen economy will be the creation of a market for hydrogen. A hydrogen market exists predominantly within industry in a variety of applications – ranging from the production of carbon steels, special metals and semiconductors, raw material for the chemical industry and a key component in the manufacture of ammonia, methanol and many polymers. Around 55% of the hydrogen produced globally is for ammonia synthesis, 25% in refineries and 10% for methanol production with other applications making up the remainder²⁵. Whilst hydrogen in industry is significant it is not for discussion in this report although some of the principles and processes are important – most notably with the role of hydrogen in ammonia production.

Increasingly as outlined in the introduction to this report there is the desire to seek opportunities to deploy hydrogen to the market for non-industrial applications. Whilst hydrogen is a plentiful element it requires energy hungry processes for production. Given the efficiency of these processes, this means that hydrogen should be perhaps best regarded as a means of storing energy which can then be released in a variety of applications to serve the market.

The context of this report is for City based application of hydrogen and this is considered in section 4.



Commercial City Scale Application

Cities are faced with many conflicting imperatives in maintaining and improving competitiveness in the domestic and international markets. Given the demand for growth, which means attracting new employers and residents, there is a critical requirement for new physical and digital infrastructure – all of which increases demand on the energy system.

Given further that the energy system remains largely fed by fossil fuels, this means an increase in emissions within cities. This is in conflict with the Climate Emergency that many cities have declared and in turn puts greater pressure on the healthcare system. Whilst the links between poor air quality and public health are understood the economic impact is unclear. What is clear though is that an improvement in air quality will have a positive impact on the health of the city, thus relieving some of the strain on the healthcare system.

Poor air quality is a function of harmful emissions, which can be summarised as originating from transportation, heat and power generation. Thus, consideration has been put to how hydrogen as a fuel or energy store can be deployed to reduce poor air quality and the impact of individual cities on climate change. The role of the municipality could also be argued to be significant in creating and facilitating a hydrogen market – this role could potentially be multi-faceted – possibly including:

- Building the hydrogen infrastructure (production, transmission, storage and distribution)
- Creation of demand – through buses, trains, refuse trucks, owned fleet, heat and power generation in buildings/district schemes through the city
- Power generation (through renewables) for hydrogen generation
- Underwriting offtake agreements to power hydrogen generation
- Supporting the built environment shift towards hydrogen for backup power

The business case for hydrogen deployment to transportation, heat and power generation is considered in the following sections.

4.1 Transportation

The clearest case for deployment of hydrogen and for the development of a hydrogen market is within transportation. Fossil fuels – diesel, petrol – have significant duties applied to them at purchase so the absence of these for hydrogen mean the economics can look reasonably favourable. Duties are applied differently across different modes of transport so this also needs to be considered. Further to this, the assumed competitor in terms of low/zero carbon transportation is electric vehicles although the lower emissions of LNG/CNG should also be considered although perhaps as an interim step. Comparison between hydrogen and electricity as competing feedstocks to transportation have not been considered in this study.

Buses

There have been a number of instances around the UK where local authorities have backed the deployment of hydrogen buses (notably in operation in Aberdeen, London, and Brighton, and planned in other UK cities including Birmingham). The hydrogen bus initiative in Birmingham is focused on the refuelling station at Tyseley Energy Park which lays the groundwork for further hydrogen bus development in the city.

At TEP the electrolyser in the refuelling station has the capability to deliver up to 1,200kg of hydrogen per day. This would be enough to fuel up to sixty hydrogen buses – a fraction of the 2,000+ buses that are in operation in

the City of Birmingham. This in turn points to a distribution or distributed requirement for Birmingham should hydrogen be chosen as the fuel of choice to reduce the impact of emissions from buses.

Newer fuel cell buses use 8–9kg of hydrogen per 100km whilst comparable diesel units will use circa 40 litres of diesel over the same distance. At current diesel prices of circa £1.36 per litre, 40 litres consumption gives a fuel cost of roughly £54 per 100km. At 9kg per 100km, the cost of hydrogen would need to be £6 per kg or less to be comparable (including costs of storage and refuelling equipment). This would suggest that a suitable cost per kg for hydrogen would need to be approximately £5 to be competitive. Actual consumption will vary based on type of operation – whether urban, sub-urban, rural or inter-city.

Trains

University of Birmingham recently delivered a Hydroflex (ex-Thameslink) stock hydrogen train intended for development of the local rail services within Birmingham. This has great potential for the city of Birmingham where air quality is at its worst around Birmingham New Street Station. Thus any move towards hydrogen for local trains on a larger scale would significantly reduce emissions and assist in the improvement of air quality.

Working against the widescale adoption of hydrogen for train travel is the fact that there is no fuel duty on diesel for train transportation. The resultant low fuel cost makes the economic case for hydrogen trains more difficult to justify.



Further to this, the amount of hydrogen required to drive trains over the distances they need to between refuelling is significant. This will mean that either the carrying capacity of trains will need to be reduced for hydrogen storage or trains will have to refuel more frequently.

A single car train travelling approximately 350km a day would require up to 70 kg of hydrogen. This means that the current installation at TEP would be able to fuel 17 train cars. A typical metro train would comprise 2–4 cars so on average the TEP installation could fulfil the needs of almost six metro trains. Were the full hydrogen capacity assessed in this study to be available (ie, 5,400 kg, this would support 77 train cars or 25 three car trains.

At this point it is worth highlighting the potential role of ammonia as a fuel for trains. Ammonia as a combustible gas can be used as a direct fuel for engines. Initial exploration suggests that current diesel stock trains could be modified to burn Ammonia instead of diesel. In which case and given the much higher density of ammonia over hydrogen it may be possible to switch across to ammonia fuelled trains with less modification than a switch to hydrogen fuelled trains. It should be highlighted that this requires significant further investigation.

Important to note in the context of Birmingham and TEP is the proximity of the diesel refuelling depot for rail stock near to Tyseley station. Just a short distance – less than 1km – from TEP the diesel refuelling depot could be an ideal location for a hydrogen refuelling station. It is understood that the Hydroflex train has a storage capacity of 20kg of hydrogen although as noted, an operational capable train would require 70kg per car.

Fuel for rail transport is not subject to fuel duty which puts significant pressure on the cost of hydrogen in order to be competitive with diesel. Thus, in order to be comparable with rail it is estimated that the cost of hydrogen would need to be in the range £2.50 to £3 per kg.

Refuse vehicles

Refuse collection vehicles ('RCVs') are in constant use on the streets of cities and as such these generally diesel fuelled vehicles are contributing significantly to emissions and poor air quality. As is the case with buses there is a potential for Cities to take a lead in the switch to hydrogen for refuse trucks on some form of timed replacement programme. Such a replacement programme could provide added impetus to the business case for a City to deploy the infrastructure to support hydrogen for transportation. There are a number of examples of hydrogen fuelled RCV's in the UK and Europe²⁶.

Further to this – and in a similar vein to that outlined for trains, ammonia could also potentially be the fuel for RCVs – possibly retrofitted. Further investigation is needed here into the viability of an ammonia conversion but initial feedback has been positive.

It is assumed for the purposes of this report that the characteristics of a refuse truck – in terms of storage and consumption of hydrogen – is similar to that of buses.

Automobiles

It is broadly believed that the case for hydrogen in automobiles is less well established and that electric vehicles are the likely winner. Certainly there is some substance to this belief when it comes to low mileage vehicles although for greater range the case for hydrogen re-emerges.

The economics for hydrogen in automobiles are broadly similar to that of a diesel or petrol fuelled car whereas the cost of power for an electric vehicle is significantly lower.

Hydrogen for automobiles has not been considered further within this study.

Shipping

This segment is significant in terms of emissions and air quality. However, it is considered to be outside of scope for this study.

One potential area for further investigation would be the utilisation of the canal system within Birmingham as a means of moving goods and fuel around the city.

Aviation

Hydrogen has potential as the fuel of the future for aviation. Should TEP be developed out to be a significantly sized hydrogen production centre it is possible that hydrogen could be exported to Birmingham Airport although it is likely that more suitable local applications will be more economically advantageous. However, aviation is considered to be out of scope for this study.

4.2 Power Generation

The production of hydrogen is a process that is on average 70%–85% efficient depending on the process used and the relative advancement of the technology used. This is covered in section 2 of this document.

The efficiency of converting hydrogen back to power is 40%–50% again dependent on the technology deployed – predominantly via fuel cells or hydrogen engines.

Given the efficiencies noted it would not be possible to use hydrogen as the main source of power generation. However, since the largest single cost of hydrogen production is power, where there is excess or cheap power there is an opportunity to arbitrage power generation into the market through the use of hydrogen as an energy store. In essence, this means using low cost/excess electricity that would otherwise have been wasted to produce hydrogen which is then processed back into power when needed and more expensive. The variability of renewable power will require increasing energy storage as renewable capacity expands. The use of hydrogen as an energy store is an ideal potential partner to the advancing battery market.

The built environment presents a potential opportunity in terms of decentralised generation. Behind the meter power – such as on site generation and backup power – is not subject to the same industry levies as buying power from the grid so could see an advantage over grid based power. Historically, gas-fired CHP has been deployed for on-site power but the emissions profile of such generating assets means that they are now being discouraged. With suitable hydrogen infrastructure and a

secure supply of hydrogen this could present a significant opportunity for a sector of the market that is particularly difficult to decarbonise.

Technologies for power generation have been considered as:

Hydrogen engine/turbine

The gas turbine power generation market is mature with the use of natural gas as the fuel. As hydrogen is an explosive gas it is possible that it could be used as an alternative fuel for this market with modifications to design as required. In the case of Siemens, there has been a company commitment that all gas turbines will be hydrogen capable by 2030 and indeed many of their turbines already can operate in this way.

Reciprocating gas engine – modified

Hydrogen should be able to be used within reciprocating gas engines (for example CHP engines) with some modification. The Jenbacher engine – formerly a GE product, now owned by Innio has a defined plan²⁷ to be able to operate with hydrogen the fuel.

Further to this reciprocating gas engines should be able to operate using ammonia without modification²⁸. With the rapid advancement of distributed generation and in particular CHP over the last few years ammonia could have significant potential in terms of retrofitting to existing assets and infrastructure – thus helping to maximise investment in existing assets.

Diesel engine – modified

Diesel is a fuel of choice for backup generation, plant power and event power. It is relatively cheap, mature and easy to utilise. However, increasingly the emissions of diesel generators are being recognised as unacceptable, with the built environment, real estate and construction industries becoming increasingly focused on low carbon / low emissions solutions.

With modification, diesel generators should be able to run with hydrogen or ammonia the fuel. The potential for such a shift is enormous. However, the economics will be challenging without some form of regulatory or incentive based support in the short term.

Fuel cell

Fuel cells are the most commonly understood use of hydrogen for power generation and are the technology generally deployed to transportation environments as well as buildings. The capital cost of hydrogen fuel cells, however, is high within the market so when compared to alternative generation technologies they do not stack up without some form of incentive (or disincentive) for alternatives. It is likely that the cost of fuel cells will decrease as the market increasingly looks for hydrogen solutions.



4.3 Heat Generation

Heat generation can either be as a bi-product of power generation (thermal or fuel cell CHP) or through direct combustion of hydrogen within a boiler. Thermal or fuel cell CHP generation is covered in the previous section.

Hydrogen injection to the gas grid is a further route to heat generation. This is possible and seen as an interim route to the decarbonisation of the gas grid. However, at the current cost of hydrogen it is not economic to inject hydrogen to the gas grid – unless there is spare capacity that cannot be stored in any other way.

There is much discussion around the conversion of the gas grid to be a hydrogen grid. This is technically problematic given the effect that hydrogen has on plastic and metal pipes. The required upgrade to the gas grid could be seen to be uneconomic by current standards. Given that hydrogen would be used for any other purpose before being injected to the grid it has not been covered within this report any further.



Economics and Business Case

The market for hydrogen will be driven by economic pressure to reduce costs and carbon emissions in order to compete across vectors with hydrocarbon fuels. With power the main component of green hydrogen production, taking a systems approach should enable reductions in costs. However, carbon pricing is also likely to be key in establishing the business case for hydrogen – particularly in City development where air quality is a key policy issue.

To produce additional hydrogen at TEP, there are a number of possibilities:

- electrolysis using onsite generation;
 - from Birmingham Bio Power;
 - from future generation located on site
- electrolysis using grid electricity;
- pyrolysis of waste (using Concord Blue or similar technology);
- reforming of ammonia brought to site from elsewhere

£5 per kilogramme using Concord Blue technology: this will not be confirmed until the plant has planning permission, a construction contract, waste supply contracts and funding; and

- the cost of hydrogen from reforming off-site ammonia is as yet unknown: it will depend on the cost of production of hydrogen from renewable energy and the costs of transport to TEP, consequently they are not considered further here, but should certainly be considered in more detailed studies/once better information is available.

In considering electrolysis, a review of literature has been carried out and a number of equipment manufacturers have been approached to try to determine energy consumption, hydrogen production rates, capital costs and operating costs. Whilst technical information has been made available (to varying degrees), cost information has not been forthcoming. Consequently we have relied on data in a study in the International Journal of Hydrogen Energy²⁹ and work done by the US Department of Energy³⁰, taking into account cost inflation since the studies were published and converting values into pounds sterling at current exchange rates.

For the purposes of this study:

- the cost of hydrogen from pyrolysis has been stated as being circa

Using this data, five technologies were considered as set out in the table below:

	Sunfire Hylink HL40	NEL 3880	NEL M4000	HyStat 60 – 10	ITM Power
Design Type	Alkaline (KOH) with inorganic membrane	Alkaline (KOH)	PEM	SOEC using saturated steam at 40 kg/h @ 150°C and bar	PEM
Design Output	40 Nm ³ /h	3880 Nm ³ /h	4000 Nm ³ /h	60 Nm ³ /h	
	3.60 Kg/h	348.73 Kg/h	359.52 Kg/h	5.39 Kg/h	50.00 Kg/h



The assumptions used were as follows:

Assumption/Variable	Value	Notes
Hydrogen Density Kg/Nm3	0.08988	Standard scientific data
Discount Rate	8%	Used to account for finance costs and profit
Plant Life	15 years	Working assumption, in reality would be determined by reference to existing plant and OEM guarantees
Electrolyser Utilisation	95%	Based on OEM literature, assuming 100% availability of electricity
Capital Costs per electrolyser kVA		
Alkaline – Low	£1,035	Calculated from literature
Alkaline – High	£1,240	Ditto
PEM – Low	£1,925	Ditto
PEM – High	£2,400	Ditto
SOEC	£3,700	Ditto
Electricity Cost per MWh	£75	Based on on-site electricity supply
Other operating Costs	16.90%	Represents uplift on capital and electricity costs, from DoE study

Using the technical data, the costs data and the assumptions, the following table was produced:

	Sunfire Hylink HL40	NEL 3880	NEL M4000	HyStat 60 – 10	ITM Power
Output Nm3/h	40	3880	4000	60	
Output Kg/h	3.60	348.73	359.52	5.39	50.00
kWh/Nm3 Low	3.75	3.80	4.53	5.20	
kWh/Nm3 High	3.75	4.40	4.53	5.40	
kWh/kg Low	41.72	42.28	50.40	57.85	60.00
kWh/kg High	41.72	48.95	50.40	60.08	
Electrolysis KVA (Max)	150	17,072	18,120	324	3,000
Kg per year	29,919	2,902,168	2,991,925	44,879	416,100
Electricity Costs Low	£93,623	£9,202,468	£11,309,598	£194,735	£1,872,450
Electricity Costs High	£93,623	£10,655,489	£11,309,598	£202,225	£5,500,000 ³¹
Capital Cost Low	£155,250	£17,669,520	£34,881,000	£623,700	£5,500,000
Capital Cost High	£186,000	£21,169,280	£34,881,000		
Annual Cost of Capital – Low	£18,138	£2,064,322	£4,075,131	£72,867	£642,562
Annual Cost of Capital – High	£21,730	£2,473,197	£4,075,131		
Other operating cost uplift	16.90%	16.90%	16.90%	16.90%	16.90%
Cost per kg Low	£4.37	£4.54	£6.01	£6.97	£7.07
Cost per kg High	£4.51	£5.29	£6.40		

5.1 Sensitivities

Given the lack of firm manufacturers' data, sensitivities were run to examine the impact of varying availability, electricity costs, capital costs and life of plant. Given the dominance of capital and electricity costs, operating costs were not sensitised. However, these would be sensitised in a more detailed study once specific OEM information is available (including the costs of periodic refurbishment).



5.1.1 Base Case

	Hylink HL40	NEL 3880	NEL M4000	HyStat 60 – 10	ITM Power
Cost per kg Low	£4.37	£4.54	£6.01	£6.97	£7.07
Cost per kg High	£4.51	£5.29	£6.40		

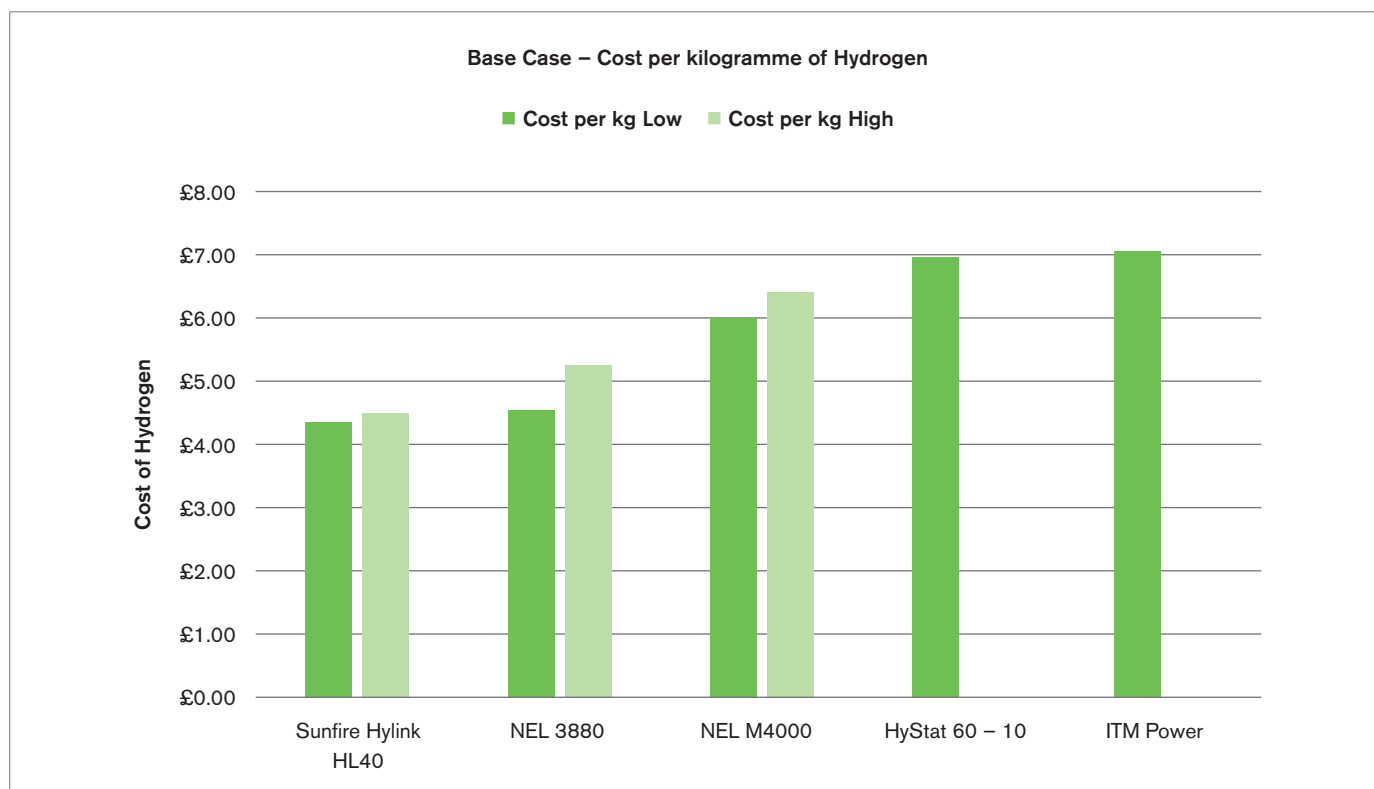


Chart 1: Base Case Cost per Kilogramme

5.1.2 Utilisation

These sensitivities assume all other parameters are unchanged from the base case, ie, electricity price is £75 per MWh etc.

Utilisation set to 25%

	Hylink HL40	NEL 3880	NEL M4000	HyStat 60 – 10	ITM Power
Cost per kg Low	£6.35	£6.87	£10.47	£12.28	£12.12
Cost per kg High	£6.88	£8.08	£11.96	£0.00	£0.00

Utilisation set to 50%

	Hylink HL40	NEL 3880	NEL M4000	HyStat 60 – 10	ITM Power
Cost per kg Low	£5.00	£5.29	£7.44	£8.68	£8.69
Cost per kg High	£5.27	£6.18	£8.19	£0.00	£0.00

Utilisation set to 75%

	Hylink HL40	NEL 3880	NEL M4000	HyStat 60 – 10	ITM Power
Cost per kg Low	£4.56	£4.76	£6.44	£7.48	£7.55
Cost per kg High	£4.73	£5.55	£6.93	£0.00	£0.00

Utilisation set to 95% (Base Case)

	Hylink HL40	NEL 3880	NEL M4000	HyStat 60 – 10	ITM Power
Cost per kg Low	£4.37	£4.54	£6.01	£6.97	£7.07
Cost per kg High	£4.51	£5.29	£6.40	£0.00	£0.00



Commentary:

- lower utilisation gives a 9% to 29% variance in the cost of Hydrogen for every 25% change in utilisation. This is significant. It is not linear due to the high, fixed cost of capital;
- within the caveat that capital costs are estimates and not based on OEM information, it would appear that if new hydrogen production is to be based at TEP using on-site generation, it will require a continuous supply of electricity in order to maximise electrolyser utilisation and minimise costs of production;
- the danger of using generic information rather than manufacturer's information is highlighted by the Hystat SOEC technology: even under the base case, its estimated cost of production is £6.97 per kg. This is at variance with a claim to be able to produce hydrogen at less than £5 per kg.
- notwithstanding the above caveats, utilisation of 50% or more is required (at an electricity price of £75 per MWh) to obtain hydrogen at £5 per kilogramme, as illustrated in Chart 2 below:

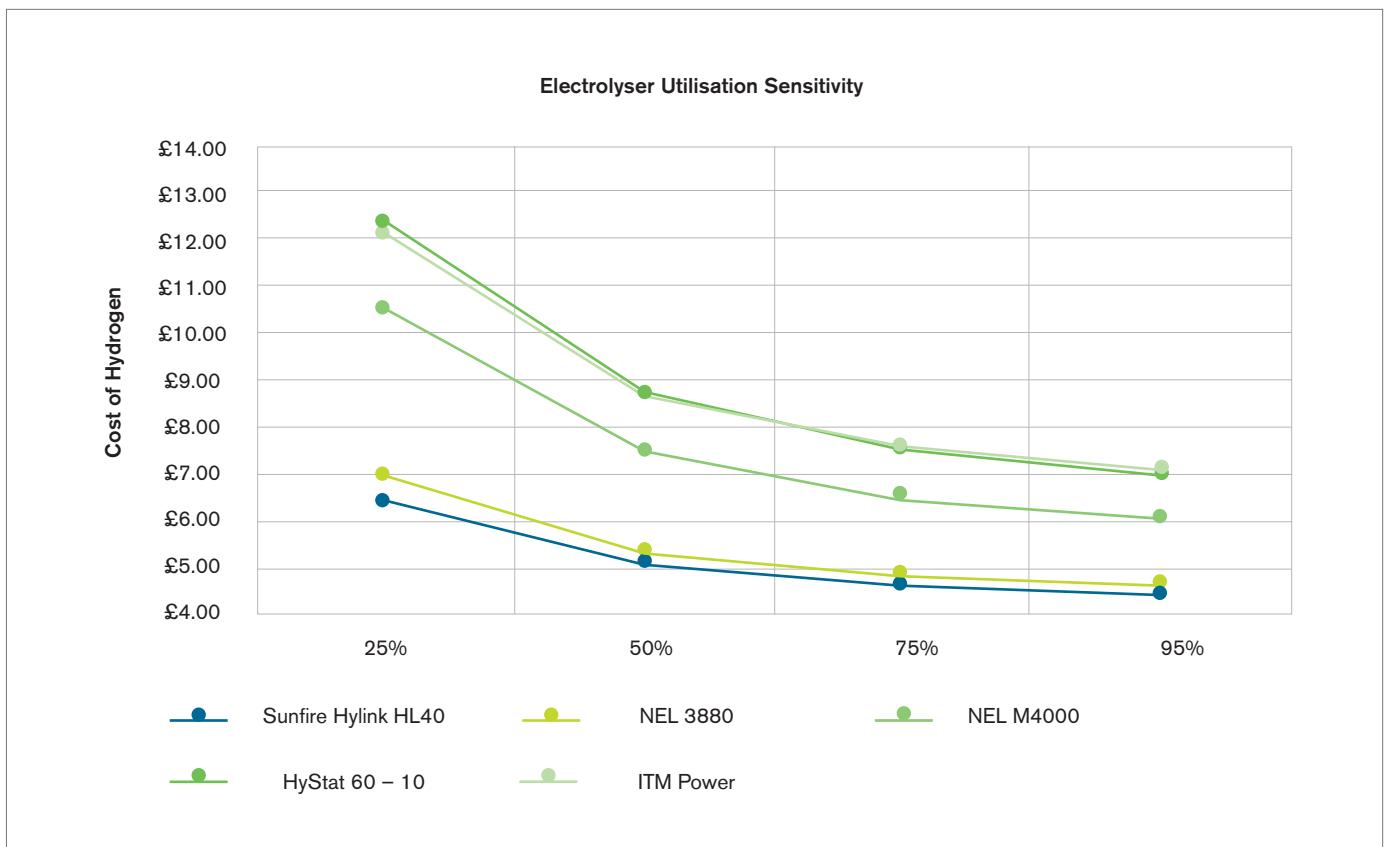


Chart 2: Electrolyser Utilisation Sensitivity showing cost of Hydrogen varying with utilisation (assuming an electricity price of £75 per MWh)

5.1.3 Electricity Price

The sensitivity of the production cost of Hydrogen to the price of electricity used for electrolysis was examined over an electricity price range from £35/MWh to £95/MWh:

- in the current market, overnight power can be supplied as low as £35 per MWh from the grid;

- at other times grid prices will be higher, but beyond £95 per MWh electrolysis appears to become non-viable;

- given the sensitivity of electrolysis to availability, rates between £35 and £95 have been considered to allow consideration of running more hours than overnight, which will result in a blended rate of more than £35;

- the cost of electricity supplied from on-site generation at TEP falls within this range.

Electricity cost set to £35 per MWh

	Hylink HL40	NEL 3880	NEL M4000	HyStat 60 - 10	ITM Power
Cost per kg Low	£2.42	£2.56	£3.65	£4.27	£4.26
Cost per kg High	£2.56	£3.00	£4.05	£0.00	£0.00

Electricity cost set to £45 per MWh

	Hylink HL40	NEL 3880	NEL M4000	HyStat 60 - 10	ITM Power
Cost per kg Low	£2.90	£3.06	£4.24	£4.94	£4.96
Cost per kg High	£3.04	£3.57	£4.64	£0.00	£0.00

Electricity cost set to £55 per MWh

	Hylink HL40	NEL 3880	NEL M4000	HyStat 60 - 10	ITM Power
Cost per kg Low	£3.39	£3.55	£4.83	£5.62	£5.66
Cost per kg High	£3.53	£4.14	£5.23	£0.00	£0.00

Electricity cost set to £65 per MWh

	Hylink HL40	NEL 3880	NEL M4000	HyStat 60 - 10	ITM Power
Cost per kg Low	£3.88	£4.04	£5.42	£6.29	£6.36
Cost per kg High	£4.02	£4.72	£5.81	£0.00	£0.00

Electricity cost set to £75 per MWh (Base Case)

	Hylink HL40	NEL 3880	NEL M4000	HyStat 60 - 10	ITM Power
Cost per kg Low	£4.37	£4.54	£6.01	£6.97	£7.07
Cost per kg High	£4.51	£5.29	£6.01	£0.00	£0.00

Electricity cost set to £85 per MWh

	Hylink HL40	NEL 3880	NEL M4000	HyStat 60 - 10	ITM Power
Cost per kg Low	£4.85	£5.03	£6.60	£7.65	£7.77
Cost per kg High	£4.99	£5.86	£6.99	£0.00	£0.00

Electricity cost set to £95 per MWh

	Hylink HL40	NEL 3880	NEL M4000	HyStat 60 - 10	ITM Power
Cost per kg Low	£5.34	£5.53	£7.19	£8.32	£8.47
Cost per kg High	£5.48	£6.43	£7.58	£0.00	£0.00

Commentary:

- A 10% change in the electricity price appears to give approximately 7% change in the cost of production, indicating that the cost of electricity is the single most important factor, as illustrated in Chart 3 below;
- The sensitivity of the electricity price was calculated without knowing the parasitic loads of each of the technologies, or what proportion of parasitic load (if any) is included in other operating costs. The sensitivity must be recalculated when OEM data is available.

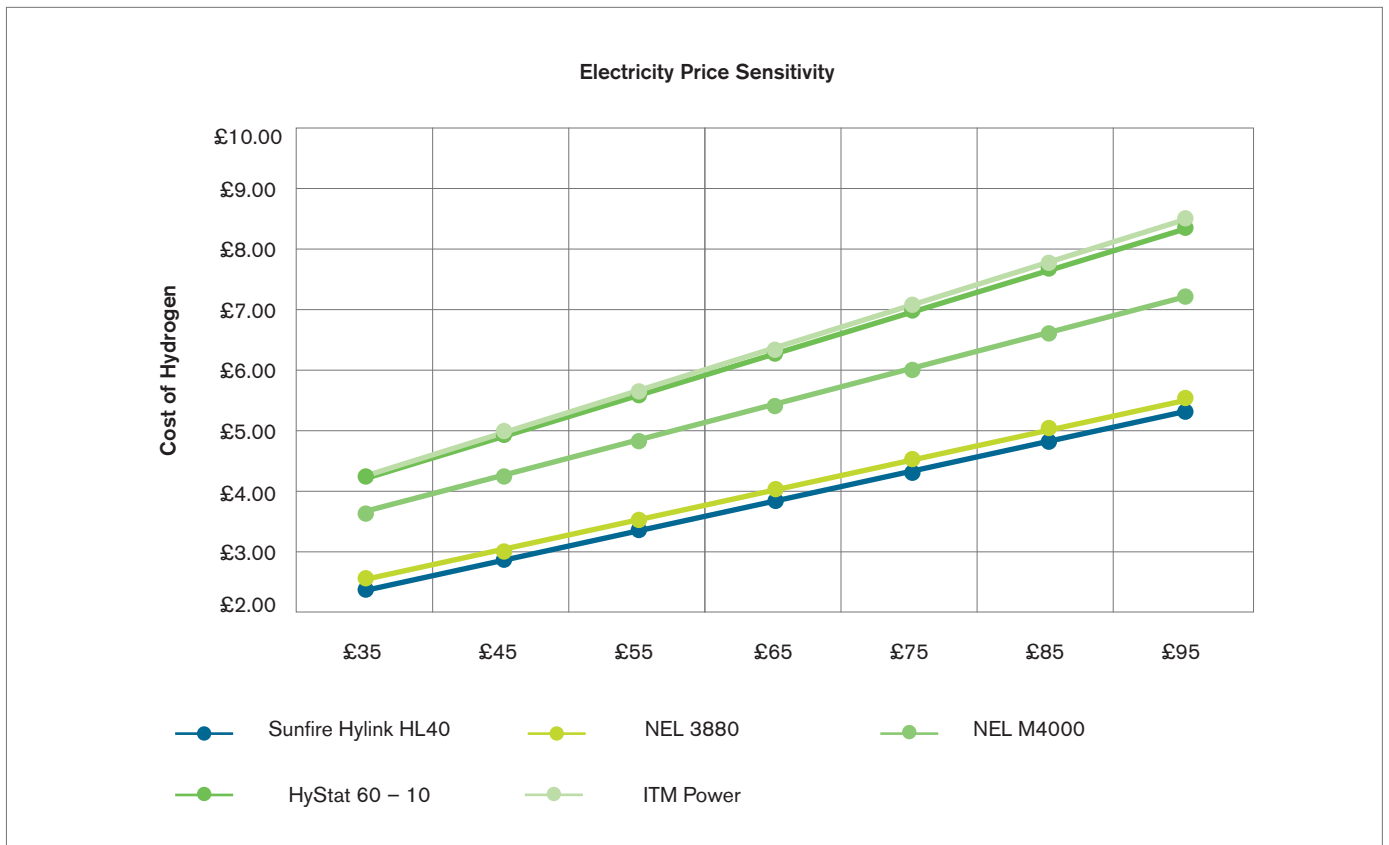


Chart 3: Cost of Hydrogen Electricity Price Sensitivity (using the low cost data)

5.1.4 Capital Costs

As set out in Table 1 above, the capital costs of electrolyzers are estimated to fall in a range from £1,035 per KVA power consumption (lowest cost alkaline electrolyser) to £3,700 per KVA power consumption (Solid Oxide electrolyser). These were sensitised within a range of +/- 10%.

Commentary:

- Capital costs were varied within a range of +/- 10%, which produced variances in production costs of between 0.06% and 0.3% per percentage point of capital cost.
- In most energy plant, capital costs rarely vary more than 10% around the base cost, however given the unavailability of OEM information, these sensitivities should be remodelled once OEM information is received.

Capital cost set to 90%

	Hylink HL40	NEL 3880	NEL M4000	HyStat 60 - 10	ITM Power
Cost per kg Low	£4.30	£4.46	£5.85	£6.78	£6.89
Cost per kg High	£4.42	£5.19	£6.21	£0.00	£0.00

Capital cost set to 95%

	Hylink HL40	NEL 3880	NEL M4000	HyStat 60 - 10	ITM Power
Cost per kg Low	£4.33	£4.50	£5.93	£6.88	£6.98
Cost per kg High	£4.46	£5.24	£6.30	£0.00	£0.00

Capital cost set to 100% (Base Case)

	Hylink HL40	NEL 3880	NEL M4000	HyStat 60 - 10	ITM Power
Cost per kg Low	£4.37	£4.54	£6.01	£6.97	£7.07
Cost per kg High	£4.51	£5.29	£6.40	£0.00	£0.00

Capital cost set to 105%

	Hylink HL40	NEL 3880	NEL M4000	HyStat 60 - 10	ITM Power
Cost per kg Low	£4.40	£4.58	£6.09	£7.07	£7.16
Cost per kg High	£4.55	£5.34	£6.50	£0.00	£0.00

Capital cost set to 110%

	Hylink HL40	NEL 3880	NEL M4000	HyStat 60 - 10	ITM Power
Cost per kg Low	£4.44	£4.62	£6.17	£7.16	£7.25
Cost per kg High	£4.59	£5.39	£6.60	£0.00	£0.00



5.1.5 Life of Plant

Life of Plant set to 10 years

	Hylink HL40	NEL 3880	NEL M4000	HyStat 60 – 10	ITM Power
Cost per kg Low	£4.56	£4.77	£6.45	£7.49	£7.56
Cost per kg High	£4.74	£5.56	£6.95	£0.00	£0.00

Life of Plant set to 15 years (Base Case)

	Hylink HL40	NEL 3880	NEL M4000	HyStat 60 – 10	ITM Power
Cost per kg Low	£4.37	£4.54	£6.01	£6.97	£7.07
Cost per kg High	£4.51	£5.29	£6.40	£0.00	£0.00

Life of Plant set to 20 years

	Hylink HL40	NEL 3880	NEL M4000	HyStat 60 – 10	ITM Power
Cost per kg Low	£4.28	£4.43	£5.81	£6.73	£6.83
Cost per kg High	£4.40	£5.16	£6.15	£0.00	£0.00

Commentary:

- Variation in life of plant is essentially a variation in the cost of capital. Unsurprisingly, it is showing a similar sensitivity to that of capital costs.
- If the life of plant is significantly less than 10 years, or major periodic replacement costs are high or have a short interval, the significance of plant life could change significantly.
- These sensitivities will need to be re-run once better information is received.



5.1.6 Combined sensitivities

Notwithstanding the uncertainty around capital and operating cost data, it is clear (even using the generic data) that electricity cost and plant utilisation are most significant.

Initially two combined sensitivities were run (illustrated in Chart 4 below):

Utilisation 25%, price of electricity £35/MWh

	Hylink HL40	NEL 3880	NEL M4000	HyStat 60 – 10	ITM Power
Cost per kg Low	£4.40	£4.89	£8.11	£9.58	£9.31
Cost per kg High	£4.93	£5.79	£9.61	£0.00	£0.00

Utilisation 47.5%, price of electricity £35/MWh

	Hylink HL40	NEL 3880	NEL M4000	HyStat 60 – 10	ITM Power
Cost per kg Low	£3.12	£3.39	£5.25	£6.16	£6.07
Cost per kg High	£3.41	£4.00	£6.03	£0.00	£0.00

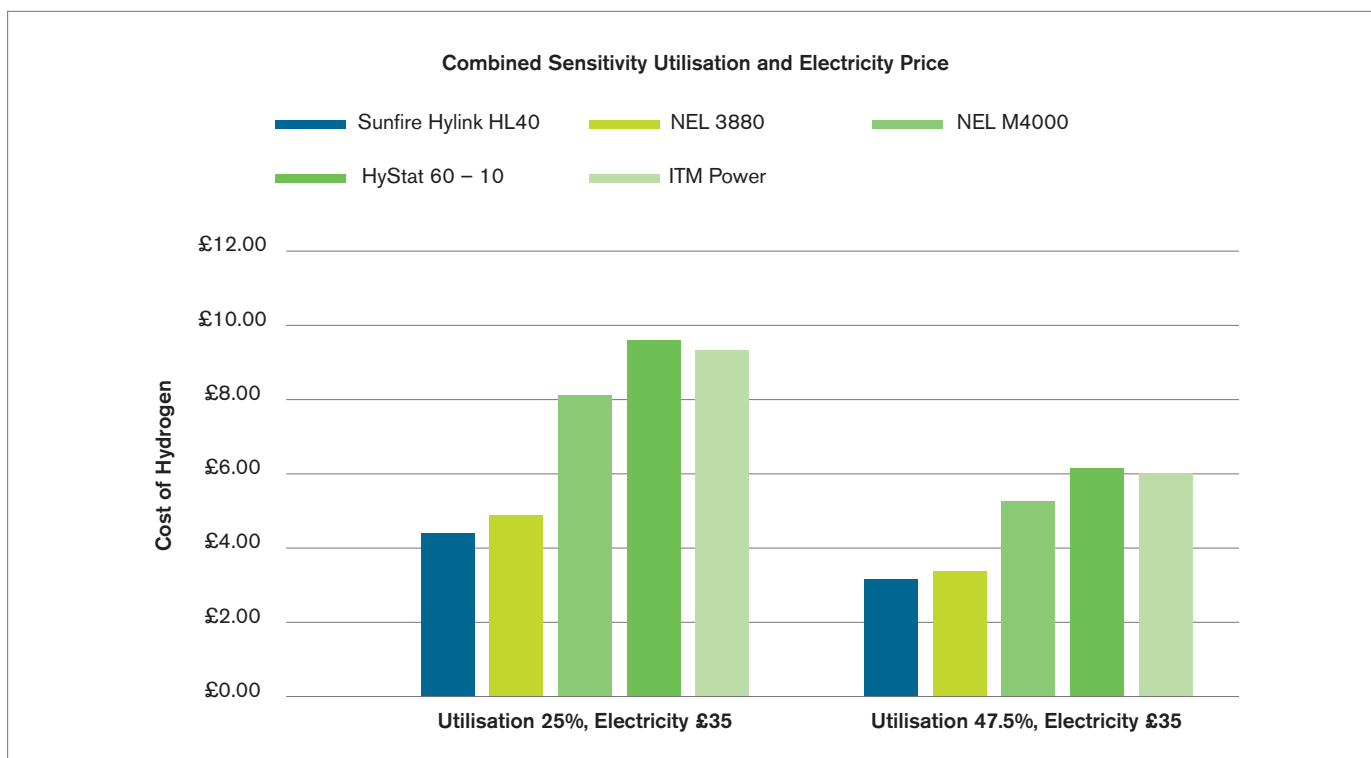


Chart 4: Cost of Hydrogen Combined Utilisation and Electricity Price Sensitivity (using the low cost data)

Commentary:

5.1.6 Combined sensitivities (continued)

Further sensitivities were then run against various parameters before running a sensitivity, for each technology, where the utilisation was set to achieve a target production cost of Hydrogen at £5 per kilogramme. Hydrogen of £5 per kilogramme over a range of electricity prices. Where utilisation needed to be 100% or greater to achieve the target, it was not used. These are presented in Chart 5 below:

All previous caveats about the generic nature of the equipment costs apply. Once detailed OEM data is available, these sensitivities should be re-run. Notwithstanding the caveats, it would appear that:

- The price of electricity is the single most important consideration: at £35 per MWh, the alkaline electrolysis plant can produce hydrogen for less than £5 per kilogramme with utilisations as low as 20%.
- The relationship between electricity price and utilisation is non-linear; this should be borne in mind when electricity price risk is considered in further detailed feasibility

studies, and when considering any particular electrolysis technology.

- The sensitivity curves for alkaline electrolyzers appear to indicate that they have greater price resilience than PEM or Solid Oxide electrolyzers.
- Overnight and weekend power tends to be lower priced. If an alkaline electrolyser fed by the grid only runs for 8 hours per week day (11.00pm to 7.00am) and 20 hours per Saturday and Sunday to take advantage of lower prices, it will be competitive with the same electrolyser running at 95% utilisation with an electricity price of £75 per MWh.

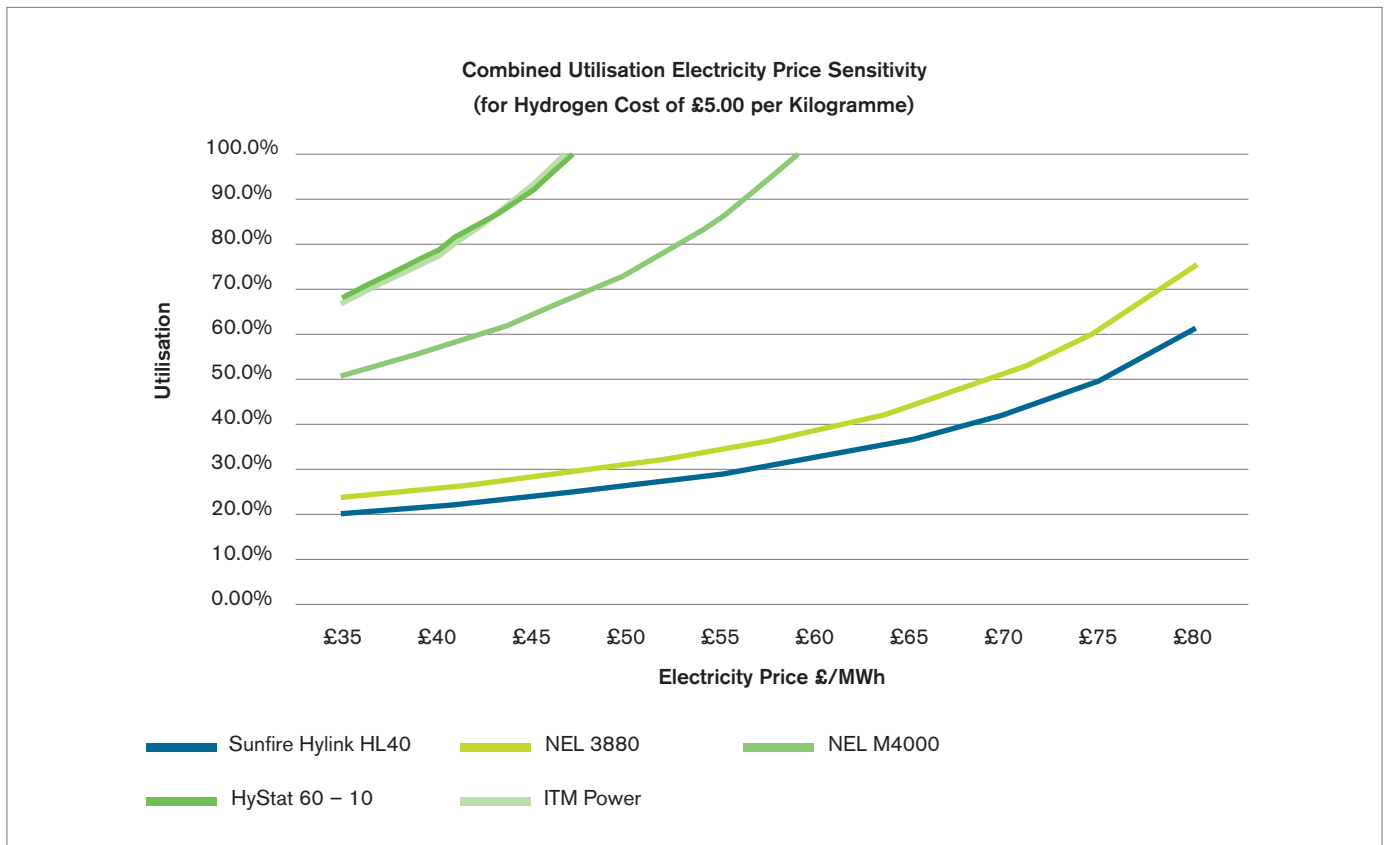


Chart 5: Combined Utilisation and Electricity Price Sensitivity for a £5 target production cost of Hydrogen

5.2 Business Case

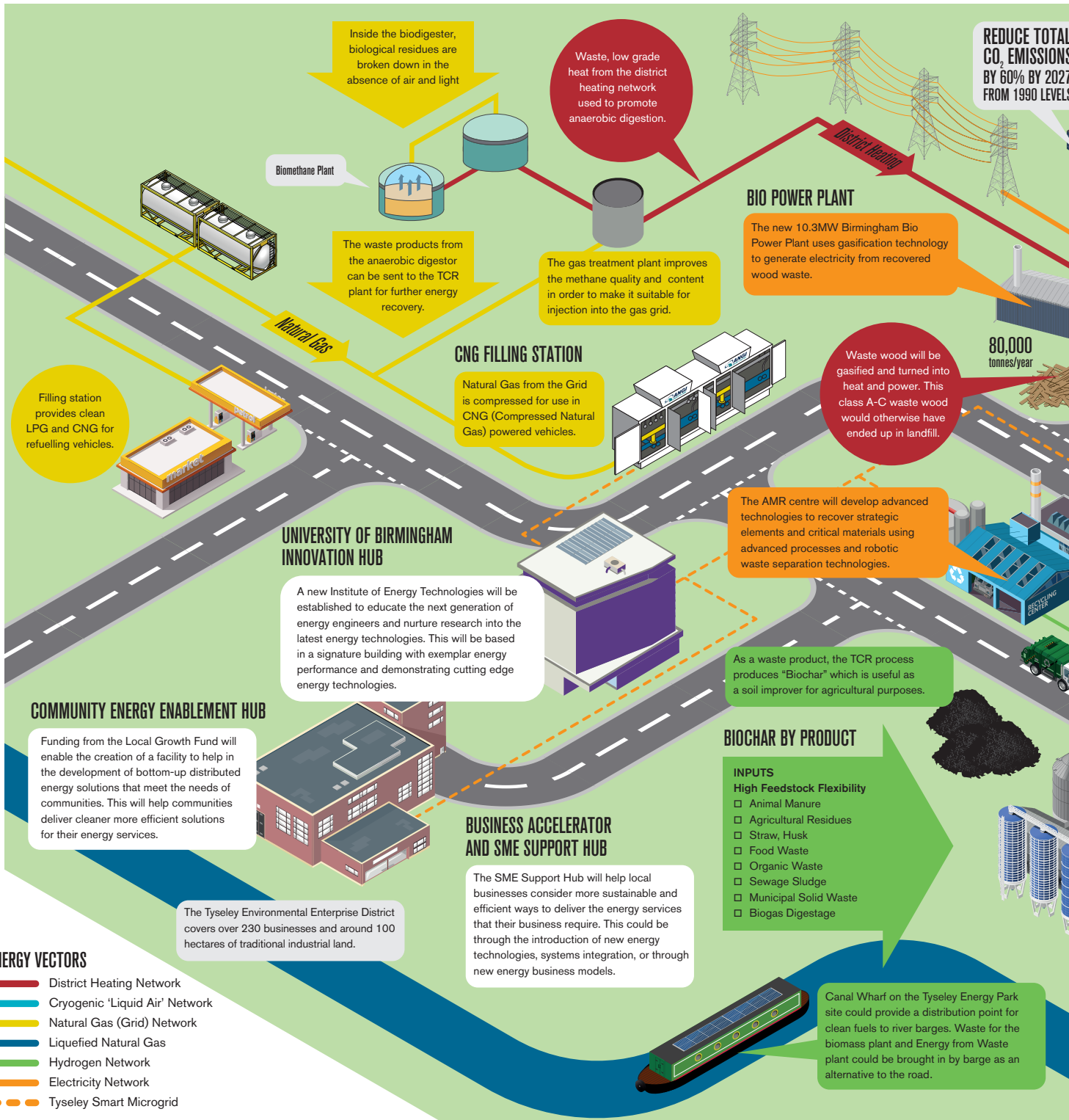
Throughout this study, the assumption used is that hydrogen priced at £5 per kg can be used to run buses economically. Using OEM technical data and generic cost data, it would appear that alkaline electrolyzers can deliver sub-£5 hydrogen either using on-site generation at £75 per MWh, or using overnight low-cost grid electricity. The case for PEM electrolyzers is less certain and will need better information before a definitive conclusion can be reached.

Space at TEP is limited, however there is sufficient space for a circa 4,000 Nm³/h alkaline electrolyser – the foot print required would be circa 1,000 m² (0.25 acres) excluding hydrogen storage.

Running overnight/weekends using grid electricity at an average cost of £35 per MWh, this could produce 3,975 kg of hydrogen per day at an estimated cost of £3.40 to £4.00 per kilogramme. This would be enough to power 220 buses.

- The same electrolyser running with 95% utilisation and an electricity cost of £75, would produce 7,950 kg at an estimated cost of £4.50 to £5.30 per kilogramme. This would be enough to power 440 buses.



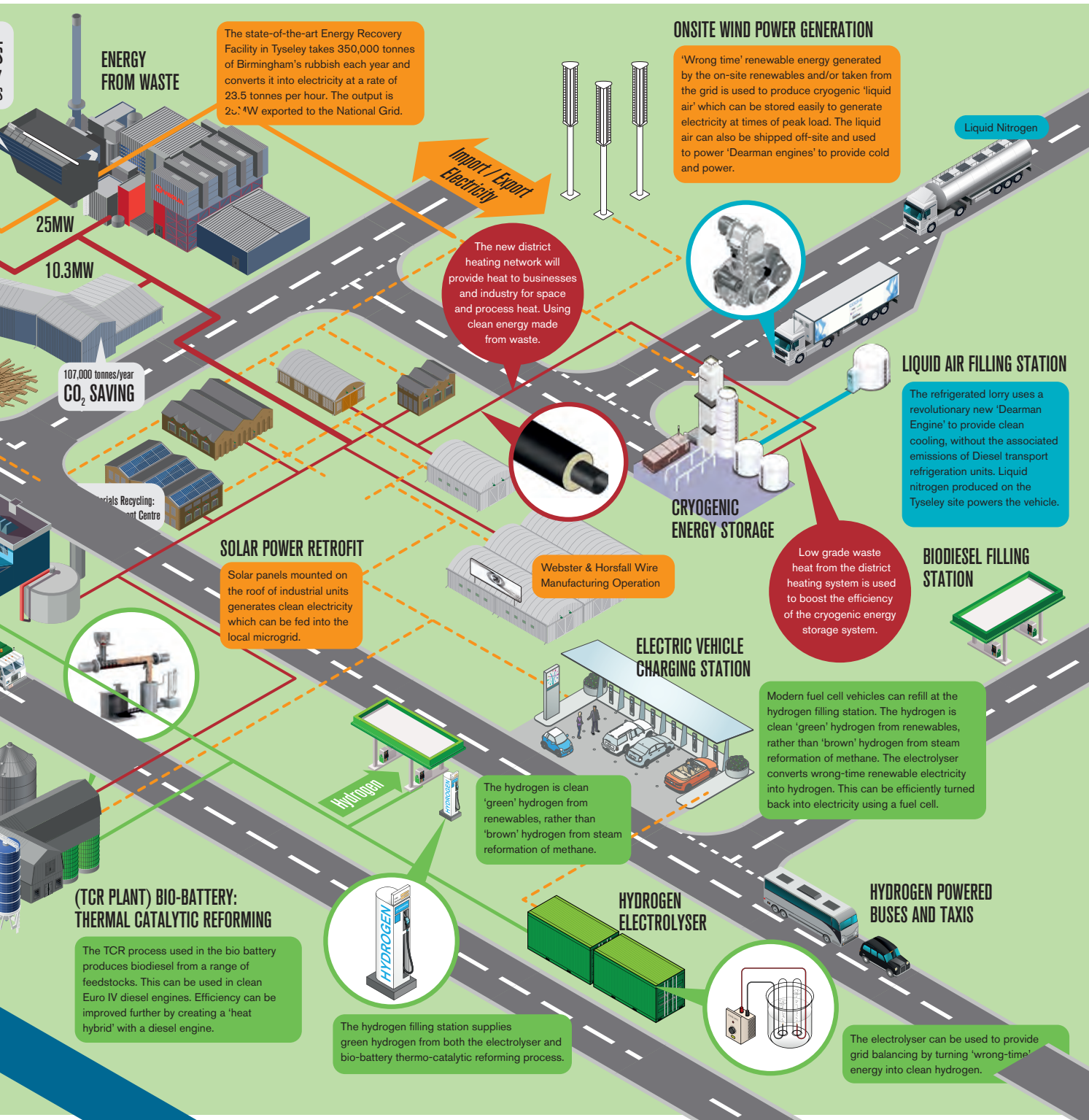


The Birmingham and Tyseley Energy Innovation Zone

In 2018, a Policy Commission chaired by Sir David King was established by Energy Capital and key partners.

The report places the government's policy drivers and ambition for clean growth within a local framework and advocates a requirement for system change with the development of Energy Innovation Zones (EIZs) to act as a stimulus to local action and system change.

EIZs are significant geographic areas where energy market regulations might be varied to encourage investment in infrastructure to meet specific local needs. There are five proposed pilot areas in the West Midlands – including Central Birmingham and Tyseley, which provide the opportunity to attract significant external investment in energy infrastructure to meet the needs of local people and industry.



TEP is the most developed of the five EIZs and is striving to help Birmingham overcome severe energy, business and social challenges. These include electricity grid constraints, poor air quality, unemployment and having one of the worst rates of energy poverty in the UK. The ambition for the TEP EIZ is to reduce emissions and stimulate growth by creating a platform to test and demonstrate new technologies.

It will integrate low carbon technologies to develop the business models and infrastructure needed to support new approaches to clean energy.

Conclusions

As a component of city development and given its zero carbon credentials, hydrogen has a strong position that will only be strengthened as technology matures to bring down the costs of production. Add to that the increasing pressure on fossil fuels and the likelihood of increasing carbon taxes and the case for hydrogen will improve further.

As to be expected given the high cost of fuel duties within the transportation sector, the first case for hydrogen is within the transportation sector. Investigations have shown that at a cost of £5 per kilogram of hydrogen usage in buses is economic. Further investigations show that to achieve this cost of hydrogen, power would need to be sourced at £75/MWh – significantly below the retail cost of power. Train operation would require hydrogen to be supplied at £2.50–£3 per kg to be competitive due to diesel for rail transport not being subject to fuel duty. This points to the need for different approaches to producing hydrogen at scale to achieve economies or some form of carbon/air quality tax to redress the balance.

On TEP there is the opportunity to link the generation of Birmingham Biopower to the ITM Power refuelling station. Were it to be able to supply power approaching the target of £65 to £85 per MWh the target of £5 (plus VAT) per kilogramme of hydrogen may be achievable assuming a high level of electrolyser utilisation.

Further hydrogen is intended to be supplied via the Concord Blue facility. The stated cost of hydrogen from this facility is in the £4 to £5 range – in line with the cost demand for bus transportation. However it has not been possible to verify the purity of hydrogen that is achievable from Concord Blue at this stage. It is expected that a clean-up process would be required which will increase the cost of hydrogen. The cost of clean-up will depend on the concentration of hydrogen and the composition of the syngas from which it is extracted.

The current capacity output of the ITM Power facility of 1,200kg per day is enough hydrogen to fuel up to 60 buses or up to 6 three car trains. This facility utilises 3.4MW of power. The available on-site power is 10MW from Biopower which if all utilised for hydrogen production could triple the potential output to 3,600kg – enough to supply 180 buses or 18 trains.

The next potential source of hydrogen at TEP is from the Ecuity/Siemens/Engie initiative to deliver an ammonia cracker which will process shipped in ammonia and produce hydrogen. The intent behind this is to deliver hydrogen at £5 per kilogram.

The total expected daily hydrogen output of TEP is 1,200kg (ITM Power), 4,000kg (Concord Blue) and 200kg (Ecuity/Siemens/Engie) totalling 5,400kg. Given the capacity of buses (18kg) and trains (210kg) this overall capacity could supply 300 buses or 25 trains (or some combination). However, it should again be noted that the purity of hydrogen from Concord Blue is an unknown at this stage.

If for any reason Concorde Blue cannot be delivered at TEP, the land could be used to site a 17MW alkaline electrolyser. This could either run over night and at weekends using cheap grid electricity to produce 3,975 Kg per day, or it could run at 95% utilisation to produce 7,950 kg per day, at an estimated cost of £3.40 to £5.30 per kg. The footprint of such an installation would be in the region of 1,000 square metres. Capital costs are understood to be in the range £17–£34 million.

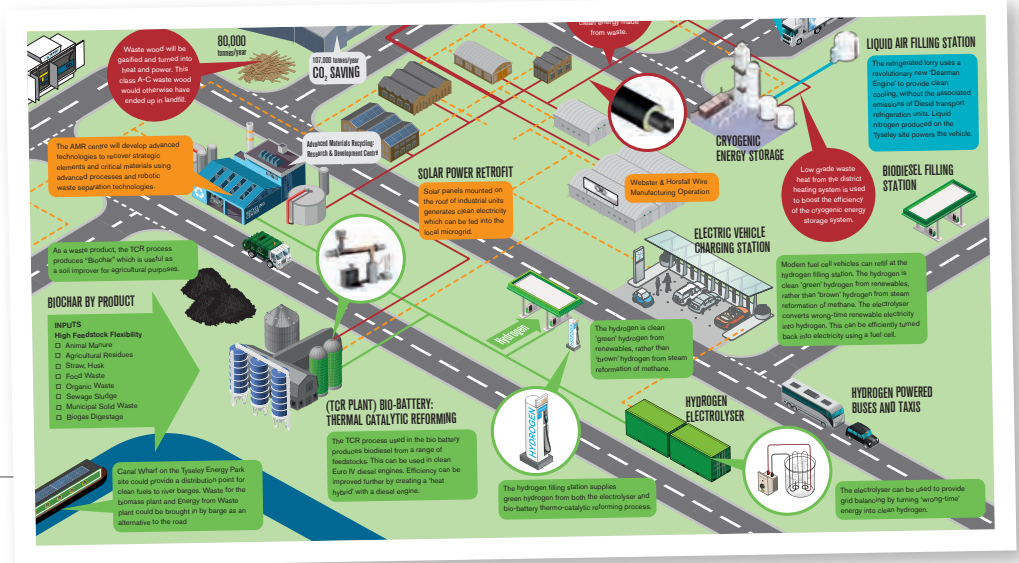


Figure 1: Hydrogen refuelling schematic at Tyseley Energy Park

Exploring the options, it would seem unlikely that the City of Birmingham or the bus operators would re-route that number of buses to refuel at TEP from their existing bus depot infrastructure so alternatives should be considered. These can be summarised as:

Transport hydrogen to other existing bus/train depots for refuelling buses/trains

Rather than bringing buses in there could be opportunities to transport the hydrogen out to depots for refuelling – either by tanker or pipeline. This could also take the form of conversion to ammonia for decentralised ammonia cracking in line with the Ecuity / Siemens / Engie initiative. This presents an opportunity for TEP to become the defacto hydrogen hub for Birmingham and, through increased demand, increase the opportunity for hydrogen production at the site far beyond the current anticipated capacity.

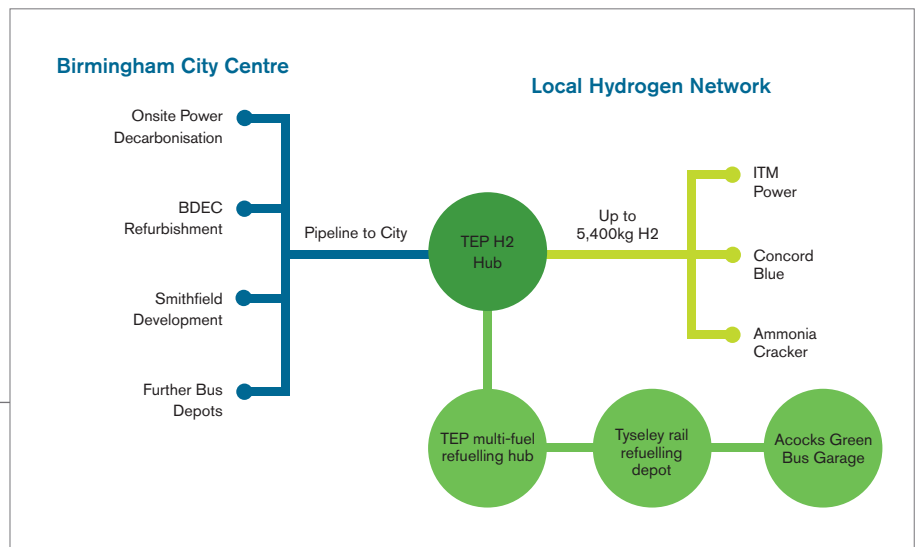
In the case of trains, the diesel refuelling depot at Tyseley would seem a relatively simple development to perform in the case that hydrogen trains are to be taken forward as a long term proposition.

Further to this there is the potential to start developing a hydrogen and/or ammonia network radiating from TEP as a hydrogen hub. Key to this is likely to be the buy in of the City in facilitating the infrastructure and playing a leading role in creating the hydrogen market – as has been done to some degree with the hydrogen bus initiative.

TEP has a unique position in the city due to its proximity to the local rail refuelling depot, to the Tyseley Energy Recovery Facility, the canal and road networks and the Acock’s bus depot – so its connectivity to the city is excellent. Further to this there is renewable energy generated on site and an ethos of decarbonisation alongside the existing recently opened refuelling station which presents TEP as an ideal location to be the first hydrogen hub for the city and an exemplar model for the country.

It is notable also the difference to other schemes that are being developed in the UK – for example Hynet and H21. Hynet – supported by Cadent NW – is focused on traditional means of hydrogen production and the capture and storage of CO₂. H21 is the Leeds based project seeking to refurbish the existing gas grid to carry hydrogen for fairly traditional use in households. Both schemes have their merit, one focuses on hydrogen production, the other on leveraging existing infrastructure and the market. TEP differs in that it is leveraging electrolyser technology fuelled by renewable power to generate green hydrogen. The market for the hydrogen in the short term is for transportation but there are as discussed opportunities for use within the gas network and in refuelling existing onsite power installations around the city. All three schemes when fully developed may benefit each other but for now, TEP has a unique approach to a market ripe to be developed and expanded.

Figure 2: Developing a hydrogen hub from Tyseley Energy Park as a base





Start conversion of refuse collection vehicles to hydrogen fuel

Birmingham City Council own and operate the refuse collection service in the City and as such own the 300 refuse collection vehicles (RCVs) in the city. These are on a staggered replacement programme and many of the vehicles collect waste which is then transferred to the Tyseley Energy Recovery Facility (TERF) adjacent to TEP. Thus it would seem a relatively simple process to mandate the refuelling of RCVs to be hydrogen from TEP. Since the dynamics of hydrogen powered RCVs have not been investigated in this study it has been assumed that they share similar characteristics to buses³².

Should such a route be taken, this would reinforce the need to decentralise hydrogen refuelling of buses to depots around the City. Given the production and ambition of TEP it would be sensible to retain TEP as the central hub for hydrogen production and distribution.

Conversion of hydrogen to ammonia for usage within the city

It has been identified that ammonia could be a suitable interim replacement fuel for onsite power and CHP around the city. Thus, hydrogen that isn't being directly used for

hydrogen refuelling could be converted to ammonia for transport around the city – either via trucks or a pipeline. Given the drive towards decarbonisation within the city there could be significant market opportunity for conversion of natural gas CHP around the city – in particular the Engie operated Birmingham District Energy Company.

Further to this, Lendlease, who is developing the Smithfield site in Birmingham, has aspirations for zero carbon development. It is actively seeking solutions for heat and power generation that cannot conform to the standards that have been common in recent years. Thus, were an ammonia or hydrogen (or both) pipeline to be built to the centre of Birmingham, this could also distribute the fuel to the centre of the city.

Power to the People

In March 2019 University of Birmingham published the Power to the People report, which set out a systems based approach to developing a low carbon future for the city. The first scenario that was set out highlighted the opportunity to link TERF / TEP to BDEC to share the excess heat from the waste processes of the city – thus delivering circular economy benefits. Whilst this focused on the benefits of transporting heat, this could be

expanded to include the transport of hydrogen and ammonia into the city through parallel pipelines. Should the appropriate commercial contracts be set in place, there would be the opportunity to ramp up the market opportunity for hydrogen at TEP and offer a dramatic opportunity for decarbonisation in the city.

The second scenario set out in the Power to the People report suggested that a local system be developed around TEP to offer benefits to the local community. Whilst again focused mainly on heat, this could also be expanded to include the local distribution of hydrogen to local uses – for example the bus depots and train refuelling depot of Tyseley.

Thus it is suggested that hydrogen deployment is complementary to the energy systems thinking that is already under consideration for the City and presents the opportunity for TEP to be at the centre of a new hydrogen economy for the city.

Recommended next steps

The conclusion to this report suggests that TEP is an ideal location to become a hydrogen hub for the City of Birmingham and an exemplar model that could be packaged and re-deployed across the country. There are two main recommendations that this report contends should be taken forward at this point:

Accelerate the hydrogen hub deployment at TEP

Whilst significant achievements have already been made at TEP – Birmingham Biopower, the refuelling station, plans for the Waste to fuel Concord Blue facility and the UoB Innovation hub – there are obstacles to overcome to complete the development. There also remains additional available land and currently untapped potential, such as access to the canals, the potential integration of TEP to the BDEC system, refuelling for trains, more buses and other vehicles. The potential can be unlocked mainly through the further development of the hydrogen market – whether as pure hydrogen or a mix of hydrogen and ammonia. To develop the market, demand needs to be created or grown from a low base. This will require the commitment of many local stakeholders in order to drive success. These could include: Birmingham City Council, National Express, Transport for West Midlands, the Universities, Commonwealth Games, Veolia, local industrials as well as neighbouring local authorities and the Combined Authority.

Economics will drive the innovation needed to accelerate activity and so it is recommended that the following tasks are considered:

- Further analysis of economics of hydrogen production
- Business case analysis of larger scale electrolysis – alongside fuel from waste tech
- Technical and commercial analysis of the role of ammonia within onsite generation
- Technical and commercial analysis of pipework to carry ammonia or hydrogen
- Business case development for integration of hydrogen hub to other local hubs – for example, BDEC or Acocks bus depot
- Continued stakeholder engagement as is in place with the TEP Co-creation team to develop a long term hydrogen hub business plan, business case and commercial structure
- Create and grow the hydrogen market

Package the TEP model for re-use around the UK

TEP is a very powerful example of a local business and landowner taking the initiative to drive towards a low carbon future. With foundations in land ownership and property development TEP has almost emerged by accident – entirely driven by real estate principles and economics in achieving the right commercial returns for the land on which it sits. Through the process, TEP has worked with many stakeholders and raised Government funds to support activities that might otherwise be uneconomic. At the heart of the development is a vision and ambition from a local business that was navigating towards its fourth century of operation and needed to pivot to the new economy. Such instances are likely to be repeatable around the UK – both with business and landowners such as Webster and Horsfall and with publicly owned land in strategic positions.

Possible actions could include:

- Developing case studies (such as in this report) that highlight the possible routes to funding and development of land for energy purposes
- Develop the commercial models that support energy deployment – including structures, legal documentation and commercial agreements
- Support ongoing BEIS work in establishing Local Energy Markets around local development

References

- ¹ IEA, The Future of Hydrogen, 2019
- ² Steam Reforming of Woody Biomass in a Fluidized Bed of Iron Oxide-Impregnated Porous Alumina, Energy Fuels 20062062727-2731
- ³ Where the material being pyrolysed is heated under anaerobic conditions
- ⁴ Where just enough air is allowed into the gasification chamber to allow sufficient (partial) combustion of the material being gassified to provide heat to pyrolyse the remaining material
- ⁵ Municipal solid waste (MSW), commercial waste similar to MSW and MSW derivatives such as Refuse Derived Fuel (RDF)
- ⁶ www.constructionnews.co.uk/civils/interserves-derby-efw-contract-terminated-04-08-2019/ and www.mrw.co.uk/latest/avonmouth-plant-closed-until-2020/10031688.article
- ⁷ Defined as electrical energy exported divided by chemical energy content (LHV) of the waste
- ⁸ www.kug-forst.de/synthesegasanlagen.html
- ⁹ Typically 40% LFOS, 47%–52% syngas, 3%–8% ash, 5% scrubber residue, but this varied with feedstock composition – source: unpublished due diligence carried out by A. Lloyd then of Envirofinance Ltd
- ¹⁰ This limits the size of any one unit to no more than 2 tonnes per hour
- ¹¹ www.edisongroup.com/publication/fuelling-the-hydrogen-economy/25046/
- ¹² www.globalsyngas.org/uploads/eventLibrary/2013-8-2-Noll-Concord-Blue.pdf
- ¹³ According to the company's website, there are 6 plant operational with a further 3 under construction/development, but this data has not been updated since 2016
- ¹⁴ One such electrolyser is the Sunfire Hylink, which utilises 40kg of saturated steam per hour at 150°C and 3 bar, 150kWh of electricity to produce 40m³ (3.6kg) of hydrogen
- ¹⁵ <https://pureenergycentre.com>
- ¹⁶ Based on the NEL range of electrolysers
- ¹⁷ By reason of lack of demand on the grid, or lack of grid carrying capacity
- ¹⁸ Dow Chemicals published research. http://msdssearch.dow.com/PublishedLiteratureDOWCOM/dh_0959/0901b803809598d5.pdf
- ¹⁹ Depending on rate of use – if not all the hydrogen in a trailer at the point of use is consumed before the second trailer at TEP is full, additional trailers will be required, for example 5 trailers for two hydrogen production modules
- ²⁰ This is mainly technology indifferent – the solution would apply equally to the PowerHouse Energy DMG technology or additional electrolyser units powered by the grid
- ²¹ Taking into account the time taken to get a bus to TEP, refuel and return, and the marginal hourly operating cost of the bus including labour costs
- ²² Pipelines have high capital costs and low operating costs, consequently cost of transmission is inversely proportional to throughput
- ²³ Provided that the pipeline has a high availability factor
- ²⁴ Ammonia has a lower heating value of 18.58 MJ/kg. This enables it to be burnt directly in modified piston engines and turbines. Ammonia holds the potential to decarbonise shipping, including barges on inland water ways.
- ²⁵ Hydrogen in Industry: <https://hydrogeneurope.eu/hydrogen-industry>
- ²⁶ www.smmmt.co.uk/2017/09/hydrogen-powered-bin-truck-enters-service/
www.gasworld.com/first-hydrogen-powered-rubbish-trucks-/2017007.article
www.scania.com/group/en/scania-delivers-fuel-cell-refuse-truck/
<https://airqualitynews.com/2016/05/24/fife-hydrogen-switch/>
- ²⁷ <https://diesलगasturbine.com/innio-lec-working-on-100-hydrogen-methanol-engine-technology/>
- ²⁸ https://arpa-e.energy.gov/sites/default/files/Wittrig_Ammonia_TransportationFuels_Workshop.pdf
- ²⁹ Future cost and performance of water electrolysis: An expert elicitation study. O. Schmidt, A. Gambhir I. Staffell, A. Hawkes, J. Nelson, S. Few, Imperial College Oct 2019
- ³⁰ Hydrogen Production Cost From PEM Electrolysis, C Ainscough, D Peterson, E Miller, DOE Hydrogen and Fuel Cells Program Record July 2014

³¹ Based on a personal communication with TEP

³² Noting that RCVs need a high power demand when operating the container lift and the compactor. In this sense they operate in a similar manner to buses, drawing power from the storage battery when extra power is needed ie, when accelerating with a full passenger complement.



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