NewStatesman

Supporting the hydrogen economy

How fuel cell technologies can shape the UK's future

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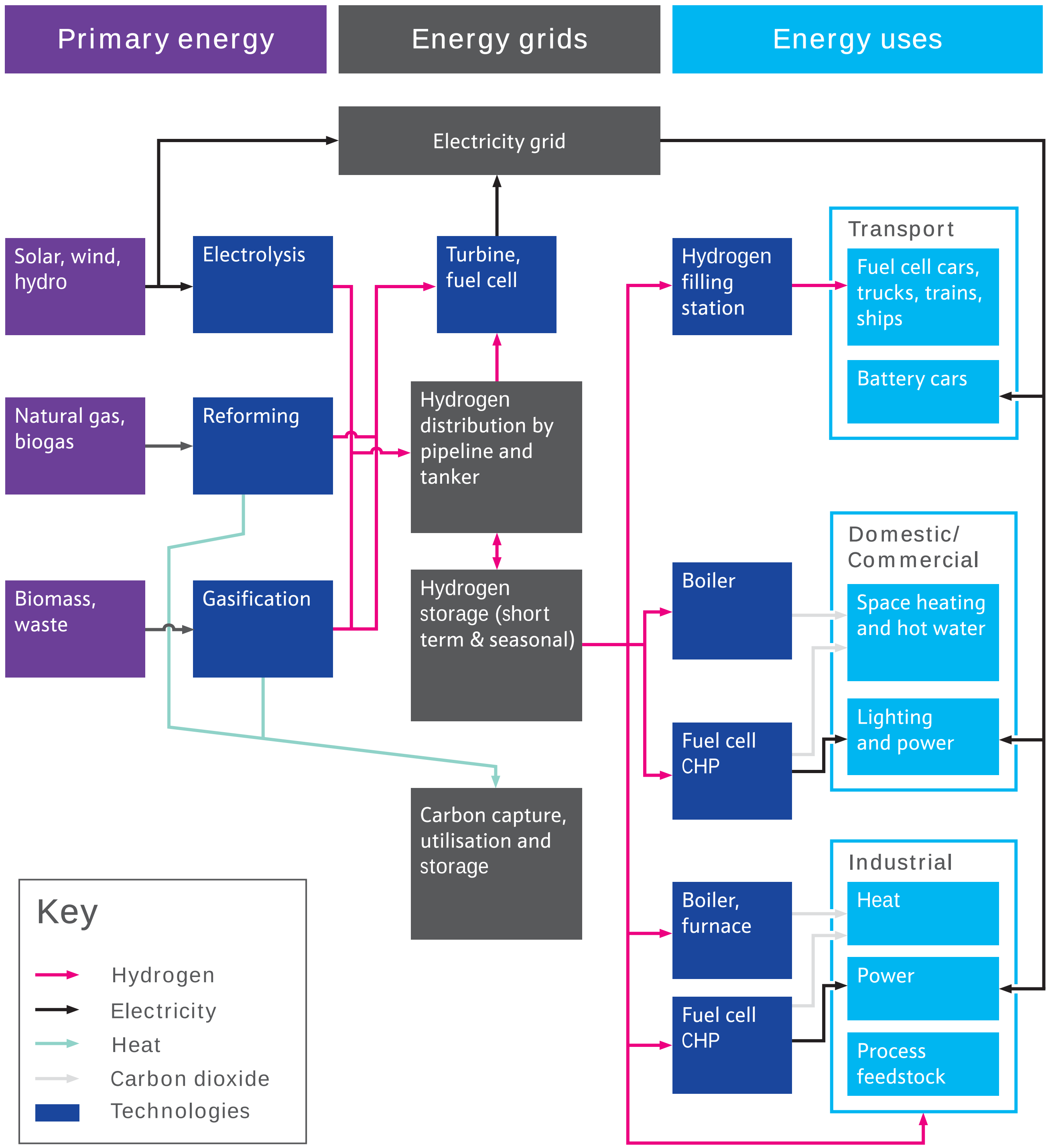
Hydrogen in the energy system



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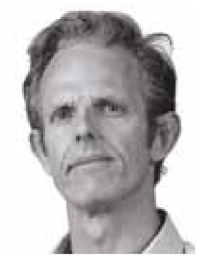

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Matthew Harwood, chief strategy officer at Johnson Matthey, explains how the UK can become a world leader in developing hydrogen energy systems and markets

How hydrogen represents a necessity and an opportunity

Transport and electricity generation each account for a quarter of UK carbon emissions. Business and residential sectors – predominantly heating – represent a further third. Meeting our binding carbon budgets will require a shift from fossil fuels to renewables and other low-carbon energy sources in each of these sectors: road fuels, electricity and heat. We can achieve this transition most efficiently with hydrogen as part of the solution.

Hydrogen is a partner to electricity in a zero-carbon energy system. We can produce electricity from hydrogen and hydrogen from electricity. As with electricity, we make it from many primary energy sources so its potential availability is limitless; as with electricity, we can use it to power vehicles, homes, offices and factories; as with electricity, it produces no carbon emissions or other pollution at point of use and can be generated in carbon-free ways. Hydrogen is complementary to electricity because, unlike electricity, it can be stored without loss in large quantities and over long periods. Most significantly, hydrogen is better suited than electricity in sectors that are hardest to decarbonise: heat, heavy transport and energy-intensive industries.

Natural gas is the UK's most important source of primary energy, representing 40 per cent of the energy used nationally. Nearly all our heat and 40 per cent of our electricity comes from burning gas. The least disruptive means to decarbonise these sectors is by reforming the natural gas to make hydrogen and carbon dioxide. We can use hydrogen as we do natural gas – in turbines, boilers and fuel cells – to make electricity and heat. The carbon dioxide needs to be captured and stored (carbon capture, utilisation and storage – CCUS). Hydrogen made

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from natural gas with CCUS can be supplemented with hydrogen made from biomass and waste and, with CCUS, these sources are carbon-negative.

Hydrogen can assist the integration of wind and solar power into the network by balancing the grid, both when there is too much demand and when there is too much generation. Hydrogen-fuelled generation is dispatchable; that is, it can be turned on and off rapidly to cover periods of low renewables generation and high demand. When there is surplus electricity from wind and solar farms that the grid cannot absorb, it can be used to produce hydrogen by water electrolysis.

Transport is the one sector of the UK economy in which carbon emissions are growing. Battery electric vehicles (BEVs) are part of the answer. But a third of UK road fuel is used by lorries, vans and busses. These vehicles need long-range and fast refuelling and these cannot be practically achieved with batteries. The answer is fuel cell electric vehicles running on hydrogen, which have the fuelling times and range of diesel vehicles while having zero emissions.

UK technology leadership

The UK's heritage in making hydrogen by reforming gas goes back to ICI in the 1920s and we've been reforming natural gas in the UK for fertiliser production and oil refining since North Sea gas came ashore in the 1970s. The UK has the world's best advanced reforming technology for use with CCUS.

The UK also has a leading industrial and academic position in fuel cell and electrolyser technologies. Fuel cells are devices that combine hydrogen with oxygen (from the air) to produce electricity and water, first demonstrated by the Welshman, William Grove, in 1842. They are used to power both vehicles and buildings; in the case of buildings providing heat as well as electricity. Electrolysers work like fuel cells in reverse, taking electricity and using it to split water into hydrogen and oxygen.

Hydrogen is already produced and handled in large volumes in the UK, with a quarter of a million tonnes produced annually. We have used hydrogen as an energy carrier before: prior to the switch to North Sea gas in the 1970s, the gas grid contained a significant proportion of hydrogen. Hydrogen is stored and distributed nationally.

A national opportunity

Beyond meeting the national carbon emissions targets, there are two pressing reasons for the UK to build hydrogen into the energy system now: improved public health and economic rewards. The public health benefits derive from improved air quality. In fuel cells, hydrogen is reacted chemically and not burnt, so there are no harmful emissions. When hydrogen is combusted, as in boilers and turbines, it produces no particulate and oxides of nitrogen (NOx) can be controlled to very low levels. These benefits apply equally to vehicles and stationary sources of pollution.

Economic benefits will come from the creation of a UK-based industry to build hydrogen energy systems at home and abroad. As noted, the UK has the core technologies required. By creating an early market in the UK, we will give UK industry an advantage in developing and demonstrating the engineering skills and supporting technologies needed to make them apply them at scale. Further benefits come from giving British industry access to decarbonised energy so that they will be best positioned to compete in global markets in a low-carbon future.

The other great economic benefit will be reduced reliance on imported oil and gas and more stable domestic energy prices. The required investments are great, but so are the benefits. The UK H2Mobility project showed how fuel cell vehicles with hydrogen will be cost-competitive with conventional vehicles.

Building on the UK's advantages

The UK's starting point is auspicious. As well as the strong technology base that we have, the UK is already committed to decarbonisation and the adoption of renewable energy. Our market is large but, as an island, contained. We have world-class engineers with a worldwide reputation. We have a well-developed gas grid that can be adapted to take increasing amounts of hydrogen, and projects such as H21 in Leeds have already assessed the viability of converting parts of the UK gas network to pure hydrogen.

But other countries share our ambition to be leaders in hydrogen energy, particularly those in northern Europe and East Asia. To make the most of its opportunity, the UK needs concerted effort and purpose across government, the energy market and industry. The two key ingredients for success are early opportunities to demonstrate technologies that have the potential to make a dramatic difference and long-term certainty on public policy. Hydrogen, then, is an essential part of the transition to a zero-carbon economy.

For more information, please visit: www.matthey.com/fuel-cells

Is hydrogen the new horsepower?

Claire Perry, Minister of State for Business, Energy and Industrial Strategy, outlines the government's plans for safe and sustainable energy

Since the domestication of horses and the invention of the wheel, transport has developed in sudden fits and starts, revolution rather than evolution, and with each change society and the economy have found new ways to flourish. The Romans linked Europe in a vast trading empire with new techniques in surveying and construction for roads, and the Victorians shrunk the world with steam power.

Indeed, many of the rapid changes in the last century have been driven, at least in part, by the extraordinary adoption of the internal combustion engine, freeing people up to travel and trade at their own pace. Today, another seismic change is underway in the way we live, travel and work. We are finding ways to develop technologies to transform the way that we travel and the air that we breathe.

A few weeks ago, I had a peek into this exciting new world of discovery, on a visit to Swindon's Hydrogen Hub. Not only did I get to hear about the potential hydrogen and fuel cell technologies offer the UK in securing cost-effective, clean and secure energy for power, heat and transportation; I also heard about the world-leading innovation taking place in my local area. Johnson Matthey, and Swindon in its own right, are pioneering developments in fuel cell technology – bringing forward products that are now on the brink of commercial viability.

Not that long ago, horsepower was the relied-upon means of transport for most people in the UK. Now I find myself touring a hydrogen refuelling station and having the opportunity to refuel a hydrogen fuel cell vehicle. So, what are these hydrogen fuel cell cars like? Well, the one I had the pleasure of refuelling looks like a regular petrol or diesel car, drives like a regular car, and filling up is no more burdensome than refuelling my own car. Yet it has a secret. Instead of CO_2 at the tailpipe, it emits only harmless water vapour; instead of a battery, hydrogen and a fuel cell produce

Claire Perry (centre, right) visited the Swindon Hydrogen Hub.

the electricity to power its motors. It's clean, it's efficient and it's difficult not to get excited by this new technology.

And this is just a snapshot of the ground-breaking innovation under way across the UK. Developing and deploying hydrogen fuel cell electric vehicles will help us meet our ambition that all new cars and vans should be zero-emission by 2040, as fuel cell technology could offer a longer-term solution in the harder to decarbonise bus and freight sectors.

We are revolutionising our energy sources across all walks of life. Last year, through our modern Industrial Strategy, we launched the Faraday Research Challenge with £246m of investment to establish the UK as the go-to destination for innovation in battery technology. We are also providing £23m to grow the hydrogen for transport sector, supporting customers to buy these low-emission vehicles and increasing the number of refuelling stations, so that low-emission vehicles are an established part of the travel infrastructure.

We will leave a legacy of clean energy

Not only will this help us meet our emissions reduction targets, it will also lead to cleaner air to breathe, and a natural environment that is more pleasant and more sustainable. But hydrogen has the potential to transform more than just the way we travel. Last year, we published the Clean Growth Strategy, our blueprint for decarbonising the UK's economy throughout the 2020s. Here we set out our commitment to exploring a wide range of clean energies, including hydrogen, to heat our homes and businesses across the country.

Let's be honest – hydrogen is expensive as an energy alternative. We are aware that for this to be a sustainable and realistic option, we need to bring these costs down. And that is why we have announced a series of investments in research and development for hydrogen technology – including a £20m boost to look at how we can significantly reduce these high costs of producing large volumes of low-carbon hydrogen.

There is an upswing of interest in hydrogen as some of the technological barriers are diminishing – fuel cell life is extending, and hydrogen vehicles are already on our roads. It is clear to me that hydrogen has the potential to provide clean, reliable and flexible energy for families and businesses, while creating a new innovative sector in the UK.

Just six years ago, dirty coal power stations accounted for 40 per cent of our electricity. Now this figure stands at seven per cent. An unprecedented level of investment in renewables means that we have the biggest installed offshore wind capacity in the world.

For too long we have been reliant on dirty fuels. Now, around 50 per cent of our electricity comes from clean sources. There's a reason why the world is looking to the UK as a model for how you can grow the economy in a clean, green way. I am proud that we continue to lead the world in tackling climate change – since 1990 we have cut our emissions by more than 40 per cent while growing our economy by over two thirds.

Innovation and world-leading research has been the key to this success. By 2021 we will have invested more than £2.5bn in low-carbon innovation. Our unwavering commitment to tackling climate change and desire for the UK to benefit from the multi-billion pound investment opportunity presented by the transition to a low-carbon economy, means that we have invested the most amount of public money in science and research in almost 40 years.

One thing that struck me on my visit to Swindon is that the UK starts from a position of strength when it comes to growing a world-leading hydrogen economy. We have the right skills and infrastructure. We already have a successful hydrogen economy based around the chemicals industry and engineering strengths in fuel cells, electrolysis and boiler manufacture.

We are poised to seize the economic opportunities of hydrogen. Our low-carbon economy employs more than 200,000 people – and scaling up hydrogen technologies is one of the many ways we can maximise UK businesses' share of new and growing global markets in clean technologies.

The Prime Minister has been clear that we will leave the world a better place for future generations, and I am committed to this vision. We are on track to meet or over-deliver against our first three carbon budgets. If we get decarbonisation right and take clean energy sources even further, we will not just deliver against the Paris Agreement – we will have cleaner air, lower energy bills, and fantastic employment opportunities. If we get it right, the low-carbon future looks bright, and hydrogen looks to be an exciting part of it.

HYDROGEN HUB

Change is in the air: a hybrid future for hydrogen

The UK's energy mix should ally the role of hydrogen with the production of green gases, says Alan Whitehead, Shadow Minister for Energy and Climate Change

There have been several episodes of "hydrogen economy" thinking over the last 100 years, with the central proposition being that hydrogen, as a fuel, could be at the centre of our energy mix. A prominent question of the past was: if oil was about to run out, could hydrogen take over as a prime transport fuel? This question has lingered since the 1970s, but hydrogen fuel cells as alternative vehicle propellants did not make the progress anticipated. Attention on alternatives to the internal combustion engine has switched to the real prospect now of a substantially electric vehicle fleet, despite oil not running out in the way then envisaged.

It is unlikely that we will ever have a full "hydrogen economy" but that should not mean that we throw hydrogen out entirely. Particularly in the context of climate change, it has a clear prospect of bridging the gaps in energy economy decarbonisation. This is aided by a number of circumstances not present in the 1970s, by the development of technological changes in energy generation, by our resolute failure so far to decarbonise heat and by the emergence of consequent concerns over energy use such as air quality.

The air quality issue, rising up the political agenda, seems to be very difficult to progress on present assumptions in transport, industry and heating. We are seeing the positive and welcome initial stages of a revolution in transport which will radically reduce the effect of vehicles on air quality in cities by electrifying our vehicle fleets and developing hydrogen solutions in larger vehicles. Progress in this transition should be faster than the government's proposed phase-out of new internal combustion engine sales by 2040.

We still have heavy loads of sulphur, nitrous oxides and particulates from old modes of energy production. Despite some progress, energy-intensive industries continue to contribute to air pollution and the less harmful, but still significant production of particulates and NOx from the millions of gas boilers almost 90 per cent of us use as the main means of domestic heating. It is in these areas that hydrogen is perhaps now starting to become relevant. It is, after all, the cleanest fuel imaginable: burn

hydrogen in oxygen and you've got water vapour as a by-product, and that is it. So we can and probably should tackle decarbonisation and air quality long-term in our heating economy by using hydrogen as one substitute for gas in our heating.

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An alternative, of ripping out all our boilers and electrifying our heating has the disadvantage of having to do just that; junk an entire delivery system for heat and start again, perhaps with ground source or air source heat pumps. These solutions are only as low-carbon as the electricity they use, and would anyway lead to such a hike in demand for electricity, (heat representing 80 per cent of energy demand) that it would be difficult to envisage how it could be done. Perhaps it is better to focus then on substituting the methane that goes through the system with hydrogen, which, after all, used to be about 40 per cent of the content of original town gas.

It so happens that our gas distribution systems have now largely been "sleeved" with polyurethane pipes, making it suitable for carrying hydrogen molecules with little or no leakage. Once the transmission system was also updated all that you might need to do is to adjust the burner jets on the nation's boilers. Even before that becomes necessary, injecting hydrogen into the current system to the limit of tolerance of present equipment (it is up to about 10 per cent of the mix, since you ask) would itself make considerable strides towards both decarbonisation and better air quality for the combustion process.

That sounds quite easy, and indeed there are a number of pilot experiments currently under way run by distribution companies doing just that within particular communities. But it isn't easy. There are and will be problems of price (at the moment hydrogen is far more expensive per kWh of heat than natural gas is) and calorific value.

The overwhelming bulk of hydrogen produced at the moment is through the process of steam methane reformation, and the source fuel is natural gas; which doesn't take us very much further along the decarbonisation road and worryingly, would tie us into continuing to import gas for the foreseeable future.

There is, of course, an alternative – electrolysis – the process simply of passing a current through water and hey presto, oxygen and hydrogen emerge. Hitherto electrolysis has largely been dismissed as a method of making large amounts of hydrogen because the electricity would need to be produced in equally large amounts to do it, which would involve relatively high-carbon processes to work and would place a substantial additional burden on generation of electricity for daily use.

However, with the emergence of a large load of variable power onto the system it may be that this "surplus" electricity is becoming available without additional power plants being required. That is, wind and solar do not produce when required, and often produce potentially a lot of electricity when not required. The current solution to preventing surplus power arriving on the system is to pay such plants not to produce, but this surplus power not needed by the electricity system could be harnessed, and would essentially be free. What would be needed at that point is the ability of plants to convert that electricity to hydrogen, which could either be stored for reconversion to power when needed, or drawn off for injection into the gas grid. This potentially produces a storage option which may be more efficient than current battery storage solutions.

It is possible to envisage, then, holistic renewable power plants that integrate power production, power storage and the production of hydrogen, predominantly for heat, all at the same time. Perhaps that is the way we should go with our next generations of wind and field solar, with the advantage that the more renewables that are installed, the more reliable and low-carbon the whole system becomes.

A big caveat remains that even then, the "surplus power" now utilised might not be sufficient to release all the hydrogen that would be needed to run a hydrogen heat economy, but we would have come a long way forward. Those techniques allied with the production of green gases, such as biomethane from anaerobic digestion of waste and organic residues, alongside a significant programme of building energy efficiency such as that recently announced by the Labour Party, could in my view do most of the heavy lifting in the decarbonisation of heat.

We would then have not a hydrogen economy as such, but one in which the role of hydrogen in aiding wellbeing through good air quality and effective decarbonisation through a heating revolution really would be centre stage.

Fuelling the future of transport

Matthew Tipper, vice-president for new fuels at Shell, explains why the company is harnessing hydrogen-powered technologies in the transport sector

Hydrogen is the most abundant element in the universe – and one of the most useful. Practically anything that uses energy can be powered by it. It has the potential to play an important part in the transition to a low-carbon world.

Hydrogen's usefulness is probably most obvious in the transport sector. Electric vehicles powered by hydrogen fuel cells can cover long distances between fuel stops and refuel as quickly as petrol or diesel cars. When the fuel is produced at the refuelling stations using renewable power, it creates virtually no greenhouse gas emissions. The vehicles emit only water from their tailpipes. So, as with battery-electric vehicles, they can keep people and goods moving while reducing emissions and the pollution created by traffic in our towns and cities.

The benefits of hydrogen power are starting to be realised here in the UK. For example, London's Metropolitan Police recently rolled out a fleet of hydrogen-powered cars and they are planning to buy more. The quick refuelling time and long range make them ideal zero-emission response vehicles. In line with the Mayor of London's work to improve air quality in the capital, the Met is also trialling seven hydrogen-powered scooters, on loan from Suzuki.

But more needs to be done to establish hydrogen as a practical transport fuel. Collaboration between governments, vehicle manufacturers and energy companies is essential for developing the infrastructure to make any emerging fuel a viable alternative for motorists. Hydrogen is no exception. To fulfil its potential, both the vehicles and refuelling points must be available at the same time. It's not a case of which comes first – we need the chicken and egg to emerge simultaneously. This is biologically impossible, but technically and commercially doable for hydrogen – if there's a will.

Consistent, sustainable government policy is a key element for increasing hydrogen's role in the economy. It was encouraging to hear, at the end of March, that the UK government will help fund a project we are involved in to increase the number of hydrogen refuelling stations and vehicles in Britain. The project – managed by low-carbon consultants

The vehicles emit only water from their tailpipes

SHUTTERSTOCK/METAMORWORKS

Element Energy and combining the expertise of Shell, Toyota, Honda, Hyundai and hydrogen-specialists ITM Power – will enable hydrogen vehicles to travel around the country. The importance of working together across industries and across the world is also why Shell and other companies launched the Hydrogen Council in 2017. This global coalition of energy, technology and automotive company leaders seeks to accelerate the use of hydrogen in the transition to a lower-carbon world.

Although at Shell we see great long-term promise in hydrogen, we also believe that a range of technologies will be needed to help reduce carbon emissions while keeping the world economy moving. Doing so will require a variety of fuels, including petrol and diesel, depending on the needs of the traveller or freight to be transported.

In wealthier countries like the UK, battery-electric vehicles are increasingly popular, despite remaining relatively expensive to buy. We are working to meet the needs of a rising number of drivers who own them across Europe. Over time, we expect battery technologies to become more competitive with combustion engines and for their use to gather pace in parts of Europe, Asia and North America.

Shell began offering fast charging for battery-electric vehicles at some of its retail sites in the UK last year and plans to open more in 2018. We have also recently acquired NewMotion, one of Europe's largest providers of electric vehicle charging points, and we are working with high-powered charging network developer IONITY to offer super-fast chargers across Europe.

But back to the future of hydrogen, and our efforts to build that future. We opened our first UK hydrogen filling station in partnership with ITM Power at the Cobham service station on the M25 in 2017, opened one in Beaconsfield in early 2018, and plan to open another at our Gatwick Airport retail site soon.

Hydrogen-electric energy initiatives are emerging in other parts of the world, too, where government support allows. For example, the German government is supporting the growth of a national network of around 400 hydrogen fuelling stations across the country by 2023. This is an ambitious project, and we're working on it with partners in a joint venture. We now have 11 hydrogen filling stations at our retail sites in Germany, with more on the way.

We have another two hydrogen stations in Los Angeles, USA, and are working with Honda and Toyota – with the support of the California state government – to build seven hydrogen fuelling stations in Northern California.

Hydrogen cars offered by Toyota, Honda, Hyundai and Daimler provide a glimpse of the future of personal transport. But the commercial vehicle sector may offer the greatest promise for reducing emissions through hydrogen power. For example, buses and trucks are a major source of emissions and their numbers will increase significantly over the next few decades in line with the rise in world population and growth of trade in goods.

The high energy density of hydrogen makes it particularly suitable for carrying heavy goods over long distances. In contrast, it would be hugely technically and economically challenging for battery-powered trucks to do this because of the size and weight of the batteries needed. This is why Shell plans to build a dedicated hydrogen station for trucks in southern California. If supported by the California Energy Commission, we will use it to supply Toyota's fuel-cell truck fleet at the Port of Long Beach, one of the world's largest freight hubs.

The hydrogen for this project will be produced nearby using biogas from agricultural waste. But it can also be captured from industrial processes or by using renewable electricity to split water into hydrogen and oxygen.

For Shell, hydrogen has exciting potential. But its full benefits will only be harnessed, in the UK and across the world, through strong and sustained co-operation between businesses and governments. In the Detroit motor industry of the 1980s they said: "Hydrogen is the fuel of the future – and it always will be." But perhaps now, if we all work together, hydrogen's time really will come, and soon.

How can we solve the energy trilemma?

Zeynep Kurban, H2FC SUPERGEN programme manager at Imperial College London, outlines a strategy to manage energy cost, security and sustainability

The UK government has committed to a clean energy system revolution through the Climate Change Act 2008, which sets out the goal of 80 per cent in CO_2 reductions by 2050 from 1990 levels. Achieving this goal, while simultaneously enabling energy security and universal access to affordable energy, is a formidable challenge for government, industry, and academia. The Hydrogen and Fuel Cell SUPERGEN Hub, funded by the Research Council's UK Energy Programme, works with prominent academics and key industry experts to develop the hydrogen and fuel cell technologies that can support a cost-effective transition to a secure and environmentally sustainable energy system. The Hub's work is not limited to research – it undertakes targeted analysis to inform key stakeholders, and especially policymakers, of the role that hydrogen and fuel cell technologies can play in addressing the energy trilemma (security, cost and environmental sustainability).

Hydrogen and fuel cell technologies are gaining increased attention from global policy and industry actors. The Hub's energy systems modelling work, outlined in the white paper titled *The Role of Hydrogen and Fuel Cells in Future Energy Systems*, sets out that "both hydrogen and fuel cells form part of the least-cost solution to decarbonising the UK economy out to 2050." Even without government intervention, such technologies "offer the best value route to decarbonising heavy goods vehicles, some industries and peak power generation."

Heat

Heat demand peaks in winter and troughs in summer, while electricity demand varies only slightly with the seasons (see Figure 1). The Hub's modelling work shows that it is significantly cheaper to utilise the existing gas grid than to make additional investment in building new power stations and electricity infrastructure to meet the high peak heat demand with electricity. Battery storage currently costs over $200/kWh, but even at the "holy grail" target cost of $100/kWh, batteries will be more expensive than gas storage in salt caverns or depleted oil wells (needing less than €8/kWh to develop) and short-term storage of hydrogen in the gas grid is estimated to be even cheaper.

Electricity

Renewables are becoming an increasing source of electricity, but because Britain's electricity network cannot tolerate excess power when energy supply is greater than demand, it is sometimes necessary to curtail renewable generation. Last year, wind farms were paid over £100m to switch off their turbines. This would not happen if the UK had energy storage to balance supply and demand. While batteries, demand-side response, and interconnectors can help to manage short-term supply and demand dynamics, the UK needs a solution that stores and then releases large volumes of energy when needed at reasonable cost.

Transport

Fuel cell vehicles have a longer driving range and significantly shorter refuelling time than premium electric vehicles,

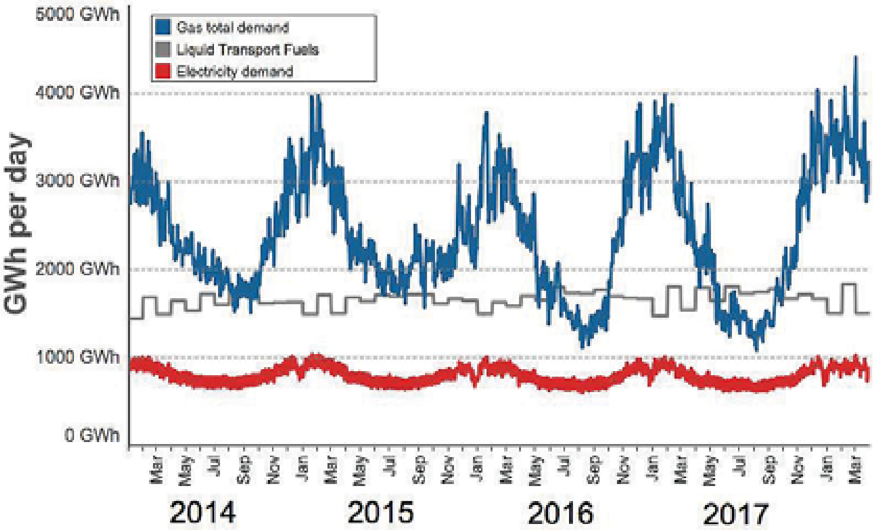


Figure 1: Demand for the major energy vectors in Britain, produced by Dr. Grant Wilson (University of Sheffield)

and are more advantageous as buses, heavy goods, and other highly utilised vehicles. Like battery electric vehicles, fuel cell electric vehicles also improve urban air quality by producing zero local exhaust emissions. Furthermore, macro-economic analysis in the Hub's white paper: *The Economic Impact of Hydrogen and Fuel Cells in the UK*, shows that "a significant move away from current UK use of refined fuels in private transport towards hydrogen can yield a valuable increase in GDP."

Energy security

Hydrogen can be produced from a broad range of feedstocks, including natural gas and water, using different production processes, such as reformation of methane and electrolysis with renewable electricity. Thus, any volatility in prices of primary energy sources or supply disruptions can be ameliorated by switching between sources.

The Hub's white paper *The Role of Hydrogen and Fuel Cells in delivering Energy Security for the UK* shows that "building a diverse portfolio of hydrogen production plants, using a range of feedstocks, and would cost little more than building only the cheapest plant." Furthermore, using fuel cells that can operate on hydrogen and other fuels can enable a high degree of flexibility. In the longer term, fuel cell electric vehicles could greatly reduce oil dependence in the transport sector and fuel cell micro-CHP could reduce gas consumption by generating electricity and heat at high overall efficiencies.

Policy

Despite the industry-led market introduction of fuel cell technologies, their costs are currently too high for most consumers. The steep cost reductions seen for fuel cells in Asia suggest that programmes to support research, development, and deployment can improve the economic viability of hydrogen technologies. Japan's Hydrogen and Fuel Cell Roadmap, the US DOE Hydrogen and Fuel Cells Program, and Europe's Fuel Cells and Hydrogen Joint Undertaking are prominent examples. The UK government expects to invest around £841m by 2021 in innovation in low-carbon transport technology and fuels, of which £246m was recently provided for the development and manufacture of electric batteries.

There is now an opportunity to couple all energy sectors by converting excess electricity supply to hydrogen for non-power applications (heat, transport and industrial processes), as demonstrated in Figure 2. Through this sector coupling, we can ensure the security and affordability of our energy.

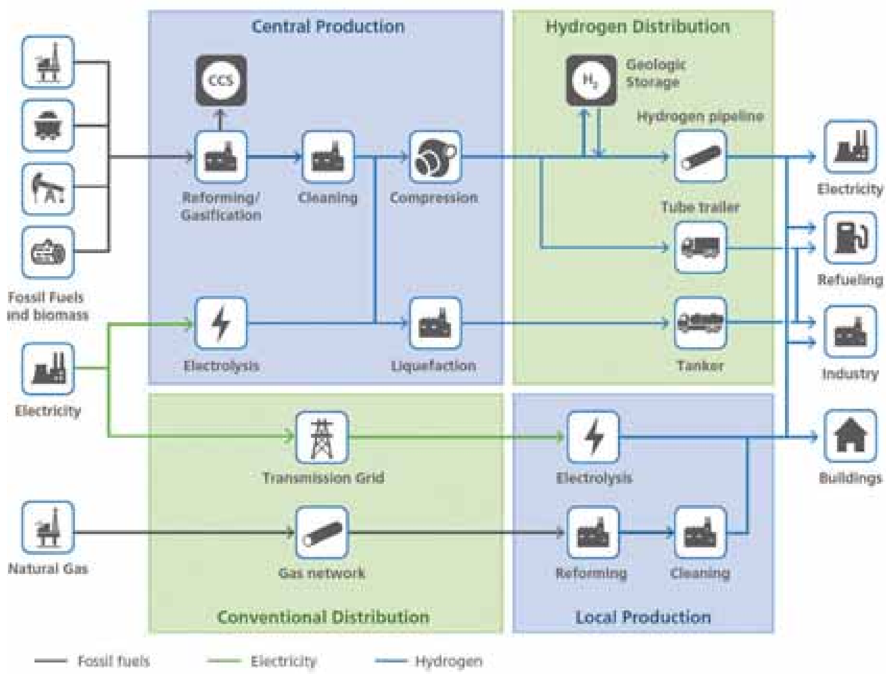
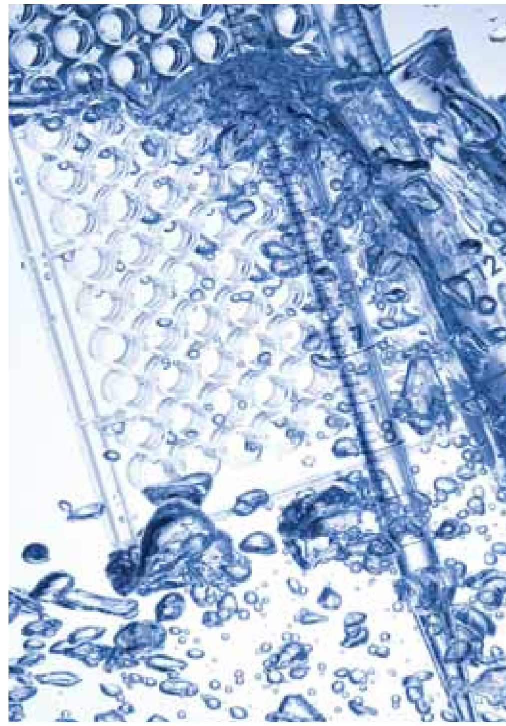


Figure 2: Hydrogen delivery pathways presented in the white paper: *The Role of Hydrogen and Fuel Cells in Future Energy Systems*



A network for new ideas

Kevin Fothergill, chair of the Hydrogen Hub, explains the need for collaboration between industry, government and academia in promoting a clean energy future

Cyrus Harding, a character in Jules Verne's *The Mysterious Island,* said: "I believe that water will one day be employed as fuel… water decomposed into its primitive elements… by electricity." For the last century and more, we have benefited hugely from the energy stored in coal, oil and gas but this has come at great cost in the form of pollution and climate change.

We now recognise that we need to get our energy from clean, renewable sources but this is much less convenient because we need to either use it immediately or create some means of storing it for later use. We need an alternative energy carrier to replace the conventional fuels that we are so used to. This has to be easily produced from renewable electricity, stored for long periods in large quantities and transported to where it is needed.

This "new" fuel is hydrogen, produced, as Verne predicted, by a process called electrolysis using the effectively unlimited supplies of renewable electricity and water that we have at our disposal. The great news is that hydrogen produced by electrolysis can be used to produce heat and power without producing any CO_2 or pollutants whatsoever – a truly sustainable answer to our energy needs.

The UK faces an unprecedented challenge to meet its obligations on carbon emissions and air quality. We will become more and more dependent on renewable electricity, probably more so than we expect, as we will need to fill the gap left by delays in the installation of nuclear capacity. Renewable generation tends to be intermittent and the more we have, the harder it is to balance supply and demand. Effective balancing of supply and demand will require storage of large amounts of energy which can readily be turned back into electricity when needed. Currently, when we think of storing energy, we assume that we can use batteries but, in this case, the speed of charging and discharging and the amount of energy that needs to be stored is beyond their capabilities. Many countries, such as Japan, Korea and Germany, have identified the production and storage of hydrogen as the best means of capturing and holding excess energy for large-scale grid balancing. It

We must avoid being reliant on other countries

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has the highest chemical energy content of any fuel by weight. For comparison, it has about three times the energy density of both petrol and natural gas and this is the reason why it is used as a rocket fuel. The other big benefit of hydrogen is that it can be readily used to produce heat, electricity or as a fuel for more mundane forms of transport, as convenient and versatile as the fossil fuels that we have all become used to.

Hydrogen can be burned in air like conventional fuels and although this produces no CO_2, the high temperatures cause the nitrogen in air to form poisonous oxides (NOx). A better way to use hydrogen is in a fuel cell. This involves no burning and produces only water, electricity and heat. It is the reverse of the electrolysis process that produced the hydrogen in the first place, making this a truly sustainable, circular, clean energy process. Fuel cells were first demonstrated as long ago as 1842 by Sir William Grove but didn't find serious use until the space programmes of the 1960s. In the last few years, the technology has matured and fuel cells are now being used to power cars and buses, provide heat and electricity for homes and businesses .

The environmental benefits for the UK are large but the economic benefits are potentially enormous if we play our cards right. The Hydrogen Council, a collective of 18 major car, energy and gas companies including Toyota and Shell has predicted that global sales of hydrogen and fuel cell-related equipment will be a massive $2.5 trillion in 2050. We need to be sure that the UK can capture its fair share of this opportunity.

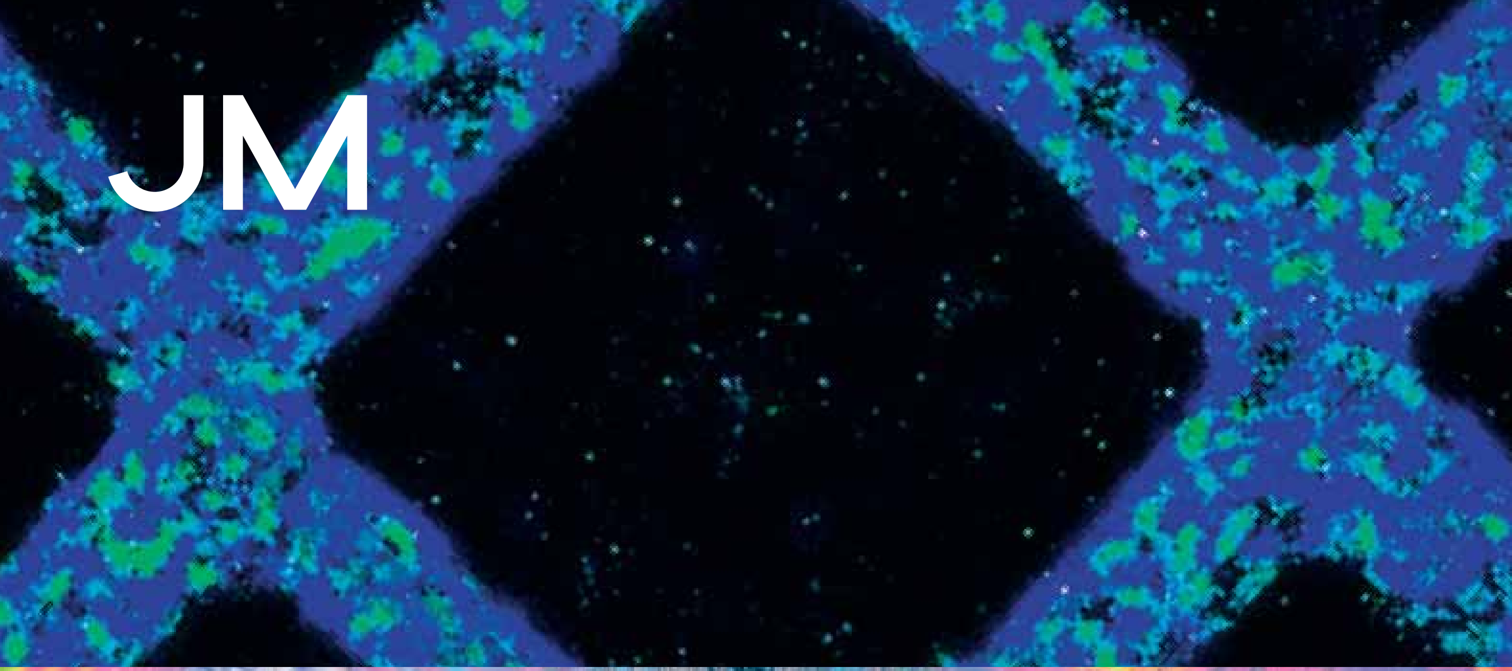
The sooner we embrace this technology and start using it, the sooner we will reap the environmental benefits and at the same time develop skills and know-how in the design, manufacture and installation of the equipment. If we delay, we will become dependent on technology developed and supplied by other nations. The Hydrogen Hub is an organisation which operates at a local and national level to foster the development and use of hydrogen and fuel cells in the UK. A local focus brings together end users, equipment suppliers and local authorities to share assets and learning, creating economies of scale around specific projects.

The first Hydrogen Hub, established in 2016, has focused on Swindon, with success in developing a local hydrogen fuelling infrastructure and a fleet of fuel cell cars operated by Nationwide Building Society, National Trust, The Science Museum and other businesses based in the town. 2018 has seen the launch of the second Hydrogen Hub, in Oxfordshire, where there is a strong appetite for clean and sustainable transport and energy generation. This is demonstrated by the plan to introduce the world's first zero-emission zone in the city of Oxford. Projects under consideration include a fuel cell bus fleet, delivery vehicles, refuse trucks and combined heat and power installations at a number of sites.

Nationally, The Hydrogen Hub seeks to drive investment in hydrogen and fuel cell innovation by shaping energy and transportation policy in the UK. It does so by developing costed, evidence-based recommendations for policy change drawing on its interactions with customers and supply chain stakeholders at local level. This process is supported by extensive knowledge in the technical and commercial aspects of hydrogen and fuel cells developed over many years in the industry.

Ultimately the goal is to replicate the Hydrogen Hub model in numerous locations across the UK, creating the infrastructure needed for a larger hydrogen economy. Verne's vision of a society powered by water is coming in the form of a sustainable, renewable energy system that features hydrogen as a key component. Our challenge is to see this opportunity and develop a national strategy to make it a reality within the shortest time and at the lowest cost. The Hydrogen Hub is focusing on local opportunities to stimulate close collaboration between government, industry and the public to kick-start the transformation.

The Hydrogen Hub, which is managed by Ecuity Consulting LLP, is supported by contributions from members, grants and funded programme income.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