UK Research and Innovation – Written evidence (BAT0045)

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Operating across the whole of the UK with a combined budget of more than £7 billion, UKRI brings together the seven research councils, Innovate UK and Research England.

Accompanying tables and graphs referenced throughout our response are included at Annex A of this document, while Annex B outlines some of our key investments across battery and fuel cell technologies.

1. To what extent are battery and fuel cell technologies currently contributing to decarbonisation efforts in the UK?

Batteries and fuel cells are chemical technologies help us to manage or convert energy from a time, location or condition in which there is abundant supply to one where it can be used. There are many types, sizes and markets of each. Electrochemical batteries (of which lead-acid, nickel-cadmium and lithium are the best known) help us manage electricity, while thermal batteries (such as phase-change materials) help us manage heat.

Batteries and fuel cells are complemented by other energy storage and conversion technologies such as redox flow batteries and capacitors. Each technology has its own weight, timescale, power, energy, space and cost characteristics which define the markets in which the technology is most valuable. Smart integration of *multiple* energy storage and conversion technologies allow for high system performance and resilience across a wide range of timescales and conditions.

Batteries

Battery technology has a broad number of applications, from electric vehicles to consumer products through to grid scale storage. It is even used in vehicular fuel cell systems to overcome inertia and provide acceleration.

Battery electric vehicles in the UK have substantially lower greenhouse gas emissions than conventional petrol or diesel cars, even considering the energy mix of the electricity to charge the vehicle and the electricity used for battery production. By 2050, as the UK electricity grid decarbonises, we expect emissions from UK electric vehicle and battery manufacturing, and from driving EVs in the UK, to reach near zero greenhouse gas emissions.

In 2019, the UK was the fifth biggest car manufacturer in the European Union, making ~1.4m vehicles[1]. However, our specialisation in internal combustion engine propulsion means that we produce more engines than vehicles – ~2.3m in

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[1] https://www.statista.com/statistics/430324/leading-european-automotive-manufacturing-countries-in-2014/

2019 – making the automotive sector a key industry for the UK economy. We expect the battery manufacturing sector in the UK will need 100GWh (approx. 5 Giga-factories) of annual capacity by 2035, with further growth expected beyond that. Today's capacity is approximately 2GWh.

While the electrification agenda will have the greatest impact in helping the UK reach Net Zero by 2050, cells, batteries and electric vehicles have an equally important role to play in achieving that objective. In the long run, vehicle manufacturing will anchor itself in areas where the critical supply and value chain components including batteries and fuel cells can be mostly readily accessed. At present, ~81% of the cars made in the UK are exported to other markets[2]. Therefore, we need to maintain the momentum created by government investments in these sectors to secure long term UK prosperity and avoid the potential economic damage from this transformation if vehicle manufacturing should migrate elsewhere.

With global demand for batteries rapidly increasing, the £318m Faraday Battery Challenge has been central to the wider funding landscape enabling the transition to a Net Zero economy. If battery cells are imported, and only the modules and packs assembled in the UK, only 20% of the value of the battery would be captured. If the cells are made here, that value increases to 45%. If upstream chemicals are also processed here, then the value to the UK is 80%+, whose value is estimated to be up to £9bn by 2035[3].

The mission of the Faraday Battery Challenge has been to create the research, innovation and commercialisation pathways and an ecosystem that will enable the UK to flourish as a battery science superpower, by nurturing innovation, growing domestic battery companies and attracting large scale battery manufacturing to the UK. Since its launch in 2017, it has been instrumental in positioning the UK as a go-to location globally for battery science, innovation and manufacturing. This has been achieved in the face of global competitors also developing their capability at pace.

The Faraday Battery Challenge has been critical to the training and development of over 450 scientists in 22 institutions, who have been collaborating with over 50 businesses working on 9 large-scale research projects, 124 organisations working on 64 business-led collaborative projects and a world-class industrialisation centre completed 3 years ahead of its nearest European competition. The effect it has had in catalysing significant private investment into the sector – including the chemical supply chain where a substantial element of the economic value lies – means there is now a realistic prospect of UK-supplied mass production batteries for automotive by 2025, when 3 years ago the stated goal had been to achieve this by 2035.

Fuel Cells

The graph in **Figure 1** in Annex A illustrates the rapid speed at which fuel cell markets are growing, with around 10% annual growth rate in many markets. It shows that the primary applications for fuel cell technologies are in transport, stationary uses such as combined heat and power (CHP) or providing portable power. Fuel cells have been researched, developed and demonstrated in the UK.

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[2] https://www.smmt.co.uk/vehicle-data/manufacturing/

[3] https://faraday.ac.uk/wp-content/uploads/2020/03/2040_Gigafactory_Report_FINAL.pdf

However, with the exception of growing use in bus fleets, fuel cells have yet to be deployed extensively in the UK.

The mobility sector has seen steady growth in the uptake of fuel cell technologies, although market growth tends to be overshadowed by progress with battery electric equivalents. Hydrogen fuel cells are seen as a viable energy source to power heavy vehicles such as lorries, buses, coaches or large vans in the short to medium term. One company – Optare – has this year started to roll out a fuel cell powered double-decker bus which has been developed with Arcola Energy[4]. Another company – Wrightbus – is getting further support from OLEV to scale up its hydrogen bus operations across Northern Ireland and beyond[5]. In rail, hydrogen powered locomotives such as the HydroFLEX train have been trialled in the UK[6].

In the maritime sector, despite the technology still being in its infancy, hydrogen fuel cell powered vessels are seen by the industry as one of the most promising technologies to help it eliminate its greenhouse gas emissions, with projects such as HySeas III serving to demonstrate its potential[7]. The aerospace sector is similarly optimistic about the potential for hydrogen fuel cell powered aircraft. At present, material handling vehicles – namely, forklift trucks – continue to be the most commercially mature fuel cell transport application, although awareness and adoption outside North America remains low.

The Hydrogen Council's 'Path to hydrogen competitiveness' study has made clear that hydrogen propulsion has the potential to be a major part of the future propulsion technology mix[8]. However, as the table in **Figure 2** indicates, current deployment of fuel vehicles in the UK and globally remains low, although the number of vehicles deployed is projected to increase rapidly. Companies such as Toyota and Hyundai are leaders in hydrogen-fuelled road vehicles, although a number of others – including Jaguar Land Rover – have also been active in this arena. Lesser known or newer providers are producing diverse vehicles, including the Wales-based UKRI-funded Riversimple[9]. Hydrogen vehicles for motor sports are also an emerging category. Future hydrogen vehicle development and deployment is unsurprisingly closely tied to the availability of hydrogen refuelling infrastructure.

In its 'Hydrogen Roadmap Europe: A sustainable pathway for the European Energy Transition', the Fuel Cells and Hydrogen 2 Joint Undertaking proposed that by 2030 Fuel Cell Electric Vehicles (FCEVs) could account for 1 in 22 passenger vehicles and 1 in 12 of light commercial vehicles (LCVs) sold, leading to a fleet of 3.7 million fuel cell passenger vehicles and 500,000 fuel cell LCVs. Furthermore, fuel cell trains could also replace roughly 570 diesel trains by 2030[10].

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[4] https://www.arcolaenergy.com/press/optare-and-arcola-energy-announce-launch-of-metrodecker-h2-1
[5] IDP13_OLEV_Ultra_Low_Emissions_Stream_2_CRD2_-_Competition_Results.pdf
[6] https://www.porterbrook.co.uk/news/uks-first-hydrogen-train-takes-to-the-mainline
[7] https://www.hyseas3.eu/the-project/
[8] https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf
[9] https://www.riversimple.com/
[10] https://www.fch.europa.eu/sites/default/files/Hydrogen%20Roadmap%20Europe_Report.pdf

In order to support global decarbonisation efforts, continued R&D into retrofitting existing technologies and appliances to make them compatible with innovative fuel cell technologies is vital. This would also present opportunities for the UK to capture a sizeable share of the growing global market in retrofitted appliances.

2. What advances have been made in battery and fuel cell technologies in recent years and what changes can we expect in the next ten years (for example, in terms of energy density, capacity, charging times, lifetimes and cost reduction)?

Electrochemical batteries

Pack-level battery costs have decreased by 80% since 2013 for automotive applications[11]. In its Roadmap Report, the Advanced Propulsion Centre for volume automotive targets show the expected progression in the technology until 2035[12].

Battery technology opportunities in the UK include lithium-sulphur, sodium-ion and solid-state technologies. The Faraday Battery Challenge's work to promote understanding and awareness of the UK ecosystem has identified performance targets for other sectors – such as aerospace – resulting in the identification of three further 'clusters' of potential applications:

- energy-focused, weight and power sensitive batteries (for example, those capable of powering next generation eVTOL and lightweight aircraft);
- power-focused weight sensitive batteries (for very high-performance hybridisation and fuel cell applications across all sectors); and
- power-focused, cost-sensitive batteries (for volume automotive hybridisation).

Furthermore, additional application areas identified for the volume automotive 'cluster' include, *inter alia*, stationary energy storage; low-cost and efficient mobility; e-motorbikes; large, medium and heavy goods vehicles; e-rail; and maritime applications. These clusters' requirements will be well served by the emerging UK strengths of lithium-sulfur, sodium-ion and large format solid-state batteries, all of these being global markets.

While this next generation of battery chemistries should satisfy the energy needs of such sectors in the longer term, advanced lithium-ion batteries are needed in the short to medium term. This requires high-performance integration at the module and pack level, as well as detail advances in cell performance which are also UK strengths.

Batteries will not be suitable for all applications. Energy and power density limitations mean that for extreme applications, other energy sources will be better suited. Nevertheless, batteries have a vital role to play alongside other zero emission technologies – such as fuel cells – in reaching Net Zero.

Next generation battery technologies also have the potential to accelerate the development of newer, fast charging technologies, although they are unlikely to render slower chargers obsolete. Charging needs depend on zero-emission vehicles (ZEV) use-cases (be that logistics, emergency services and/or passenger

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[11] https://about.bnef.com/blog/battery-pack-prices-cited-below-100-kwh-for-the-first-time-in-2020-while-market-average-sits-at-137-kwh/

[12] https://www.apcuk.co.uk/app/uploads/2018/06/roadmap-report-26-6-18.pdf

transport) and owners' circumstances as much as on ZEV battery specifications. In some locations, such as transit stops, faster charging will be required to enable convenient, long-distance EV journeys, which bigger batteries and next generation technology will enable.

Fuel Cells

There are several types of fuel cells currently under development, each with its own advantages, limitations, and potential applications. These are: Polymer Electrolyte Membrane (PEM) Fuel Cells; Direct Methanol Fuel Cells; Alkaline Fuel Cells; Phosphoric Acid Fuel Cells; Molten Carbonate Fuel Cells; Solid Oxide Fuel Cells (SOFCs); and Regenerative Fuel Cells. While research has focussed on hydrogen fuel cells to date, there is growing interest in bio-based fuel cells, which provide low power but long-lasting and low maintenance energy, particularly for Internet of Things applications.

Figure 3 illustrates the shipments from 2016-20 of different fuel cell type. In automotive sector, the predominant technology is PEM, but use of SOFCs is becoming more widespread. Data from the Automotive Council's 2020 Fuel Cell Roadmap – **Figure** 4 in Annex B – paints a significantly improving picture in terms of cost reduction and technology advances between now and 2035.

In aviation, the cost of liquid H_2 is projected to drop by factor 4 from today to roughly the same cost per unit energy as for kerosene by 2050. While challenges exist with larger aircraft due to higher volume requirements when compared to kerosene, for commuter and regional aircraft, fuel cell-powered propulsion is widely seen as the most energy-efficient, climate-friendly and cost-effective option[13].

Fuel cell stack technology, and the complete fuel cell system – including the stacks, ancillaries and balance-of-system – are both expected to develop further, leading to increased capability and demand. This includes new electrode technologies, SOFCs running at lower operating temperatures of <450°C, novel bipolar plate materials and higher power efficiency platinum group metals and fuel efficiency.

New fuel cell advances are meanwhile being developed and demonstrated globally within an extremely competitive landscape. This includes a team of researchers from Washington University, which has developed a Direct Borohydride Fuel Cell (DBFCs) using a pH-gradient-enabled microscale bipolar interface. DBFCs are a newer type of fuel cell, which are currently being investigated due to their high-power density and voltages over existing technologies. With funding from BEIS, the UK's Advanced Propulsion Centre is currently supporting Intelligent Energy – part of the Meditor group of companies – to deploy their evaporatively cooled fuel cell system with Alexander Dennis and Changan vehicles[14]. There are also opportunities beyond fuel cell manufacture along all parts of the value and supply chain for fuel cells. This includes catalyst and membrane development, materials science and engineering and design.

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[13] https://www.euractiv.com/wp-content/uploads/sites/2/2020/06/20200507_Hydrogen-Powered-Aviation-report_FINAL-web-ID-8706035.pdf

[14] https://www.intelligent-energy.com/news-and-events/company-news/2019/10/16/government-funding-secured-for-continued-development-of-intelligent-energy-high-power-fuel-cells-for-vehicles/

Within aerospace, the choice of energy source will have a significant impact on whole aircraft architecture. For example, the Airbus Zero-e concept aircraft will require a significantly different wing and fuselage configuration to implement the storage of liquid hydrogen. UK businesses have historically been strong within the supply chain for conventional kerosene powered aircraft. However, there are potential opportunities for other countries gain a competitive edge and move design and manufacturing of these new systems away from the UK. The UK government should remain vigilant to this and create a long-term strategy and policy environment for sustained growth in green aviation.

3. **What are the opportunities and challenges associated with scaling up the manufacture of batteries and fuel cells, and for manufacturing batteries and fuel cells for a greater number and variety of applications? Is the UK well placed to become a leader in battery and fuel cell manufacture?**

The UK is in a strong position to become a significant force in battery and fuel cell markets. However, the landscape globally is highly competitive, with other nations competing aggressively. The size of the UK battery sector will be determined by the needs of industry. Once manufacturers decide to make a fundamental switch towards development of EVs, they need the local supply chains to facilitate this shift. There is, however, a significant gap between projected battery demand and supply. For scale, the most optimistic predicted manufacturing capacity by 2030 is 2068.3 Gwh, which could provide the battery capacity for 40 million cars or 150 million home batteries. Global demand in 2030 is estimated to be 2,623 Gwh in a base case scenario significantly outstripping supply.

Giga-factories are critical to overcoming residual investor confidence issues, by providing the vital link between electric vehicle manufacture demand and the processed chemical supply chain. Investment confidence is also stimulated by clear, consistent policy and sustained public investment in research and innovation, and in wider interventions to ensure the UK can attract investment against strong international competition.

There are a limited number of fuel cell manufacturers in the UK, but those that exist have the depth of expertise, the capability and ambition to position themselves as leaders in this field. These include Intelligent Energy, Ceres Power and Johnson Matthey. There are also a growing number of UK-based scalable fuel cell SMEs with growth potential, such as AFC Energy, Brambe Energy and Adelan. The UK has strengths in fuel cell system integration for example Logan Energy and Arcola Energy. UKRI has been supporting the work of the H2FC SUPERGEN Hub (see Annex B), as well as The Centre for Doctoral Training in Fuel Cells and their Fuels and Centre for Doctoral Training in Sustainable Hydrogen, whose aim is to provide a pipeline of skilled doctorates relevant to the area.

Companies developing new battery technologies in the UK are typically doing so in labs that can create prototype battery cells alike in chemistry and form, but not at an industrial scale. Problems then arise by having two seemingly identical batteries chemically, but with vastly different performance characteristics depending on whether it was manufactured in a lab or a factory. This is resulting in customers choosing not to place orders for batteries based on lab made cells, and companies not investing the sums required to build factories at scale without orders. The UK Battery Industrialisation Centre (UKBIC), which hosts £60 million of specialist battery manufacturing equipment of the type found in the most state-of-the-art giga-factories, but configured for manufacturing and validation rather than optimised for end-to-end production, is helping to address these challenges.

The Faraday Battery Challenge has helped build and grow a thriving community of high technology businesses right across the country, developing substantial new lithium-ion battery performance and innovative solutions that have the potential for globally significant breakthrough in performance, weight, and cost. In addition to enabling the establishment of the UKBIC, the Faraday Battery Challenge has helped catalyse "giga-scale" investment in battery pack/module production, cell production, processed chemical production and industrial R&D.

The Faraday Battery Challenge has also helped cultivate a sustainable, ethical and skilled innovation ecosystem in the UK, resulting in new forms of value creation throughout the discovery, development and deployment stages of the supply chain.

The UK Government has not been investing in Faraday Battery Challenge alone, but as part of an industry-partnered, outcome-based approach to maximising opportunities resulting from the electrification of vehicles, as part of a joined-up approach to funding across these key UK strengths, with strong partnerships providing a joined-up approach to both ecosystem developments and response to investment enquiries.

4. **Is the right strategy, funding and support in place to enable the research, innovation and commercialisation of battery and fuel cell technologies in the UK? Is the UK doing enough to accelerate new developments from low technology readiness levels right through to commercial application in the UK?**

The skills landscape is complex, spanning many training levels across several different but inter-related sectors, and there are many skills initiatives and providers already operating in this space. Many sectors will need to switch to greener, electrical technologies which places a massive reskilling (and upskilling) requirement on the current workforce. In addition, the quality and scale of the trained workforce needs to increase. This is further compounded by a steady decline in the number of engineers due to an aging workforce and a lack of new entrants into the field[15] [16] [17]. The Faraday Battery and Driving the Electric Revolution Challenges are playing a part in ensuring that the skills to enable the manufacture and use of these batteries can be found within the UK workforce.

There is a promising future for giga-scale manufacturing in the UK, made possible by public support through the Faraday Battery Challenge and the Office for Zero Emission Vehicles' £multi-million R&D grant calls helping to underpin advances in both battery and fuel cell technology, alongside commitments from leading

[15] https://www.raeng.org.uk/publications/reports/engineering-skills-for-the-future

[16] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/31795/11-1073-power-electronics-strategy-for-success.pdf

[17] https://aerospacegrowthpartnership.files.wordpress.com/2020/02/aerospace-sector-deal-one-year-on-vf-1.pdf

industry players such as Nissan and JLR to continue investing in the UK[18]. Due to the scale of these investments, and their long-term economic return to the UK, these companies expect the UK Government to provide sustained, long-term support to the electric vehicle and battery innovation industry. De-risking and establishing an environment conducive to research and innovation are critical components, alongside these investments, to securing successful outcomes.

In terms of capital opportunities, the newly established Automotive Transformation Fund is helping to grow the UK's future electrified vehicle supply chain. This includes supporting prospectuses around battery and fuel cell manufacturing facilities and the supporting supply chain.

Beyond the automotive sector, DfT's rail R&D programmes have supported the demonstration of these technologies over the past few years, including the aforementioned HydroFLEX project.

UKRI has also partnered with DfT to launch a new £20m funding opportunity in March this year around maritime decarbonisation, for which both battery and fuel cell projects are sought. The DfT has also recently announced its ambitions for a Transport Hydrogen Hub in the Tees Valley along with a 'masterplan' for its delivery and impact[19] [20]. Fuel cell technology and its adoption within vehicles will play a fundamental role in the Hub's success.

In aerospace, through the Aerospace Technology Institute Programme and the ISCF Future of Flight Challenge, advances in the use of batteries and fuel cells are being made. Meanwhile, the new Jet Zero Council – a partnership between industry and government whose aim is to deliver zero-emission transatlantic flights within a generation – is driving the ambitious delivery of new technologies and innovative ways to cut aviation emissions.

Nevertheless, demand for UK R&D and capital funding continues to outstrip supply. This presents a significant and immediate risk that businesses currently vested into the UK will simply relocate to where both a market and "support" is more accessible. By contrast, the EU and specific EU member states have allocated significantly more funding into these technologies.

The procurement of innovative technologies – whether through public procurement, enhanced capital allowances, green finance products or VAT reductions – can be an extremely powerful lever in driving the development and deployment of innovative battery and fuel cell technologies. Furthermore, building agile, responsive regulatory frameworks in areas such noise and air quality across sectors, or improving energy markets for distributed electricity generation, can help catalyse innovation that positions UK industry at the cutting-edge of these sectors.

Skills

[18] https://www.bbc.co.uk/news/uk-england-tyne-55766314; https://www.bbc.co.uk/news/business-48875406

[19] https://www.gov.uk/government/news/uks-first-ever-hydrogen-transport-hub-kick-started-by-3-million-government-investment

[20] https://www.gov.uk/government/publications/tees-valley-multi-modal-hydrogen-transport-hub

The UK's workforce is skilled, stable, flexible, and one of Europe's most productive. The country is ranked highly for automotive labour productivity, and we have a long history of EV production at Nissan's Sunderland plant. Around 864,000 people are employed directly and indirectly across the wider automotive industry[21]. However, in surveys conducted by the H2FC SUPERGEN Hub, industry had cited a lack of skills in fuel cells one of its leading concerns in the UK[22].

There is a significant upside from attracting giga-factories to the UK. We forecast that the overall industry workforce of the EV and EV battery ecosystem would grow by 29% from 170,000 to 220,000 employees by 2040.

To ensure our workforce is prepared for this transition to energy storage research and manufacture, the Faraday Institution is working across the elements of the Faraday Battery Challenge – UKBIC, APC and UKRI (Innovate UK and EPSRC) – to ensure that we are tackling key skills challenges within the future battery workforce across skills levels, job types and sectors.

At the research end, the Faraday Institution is supporting and training over 130 PhD researchers through our research projects to pursue industrial or academic battery careers. In the manufacturing sectors, the Faraday Institution has been leading an effort for the Auto Council working in partnership with High Value Manufacturing Catapult and WMG to develop a National Skills Framework for Electrification. This Framework will facilitate the development of a common framework of knowledge, skills and behaviours for current and future training requirements by job type and skills level to meet demand driven by electrification of the automotive sector. It will also propel the development of modular training activity for which the content and delivery mechanism can be tailored to the needs of the individual depending on requirements such as skills level.

Having a trained workforce with the right skillset is critical to ensuring that the work of the broader Faraday Battery Challenge delivers the flourishing battery manufacturing sector within the UK it has set out to realise. The Faraday Battery Challenge leadership has been working in partnership with delivery partners to develop a future battery R&D talent pipeline, whose success will be measured by an increase the size of the battery-ready workforce within the UK. The Faraday Battery Challenge has also been working with other ISCF challenges to agree and implement a coordinated approach to delivering the skills needed for UK-wide electrification.

As a centre for battery technology scale-up, the UKBIC is also playing a key role in enabling the future battery manufacturing workforce in the UK, which it is doing in partnership with industry.
For instance, the UKBIC is developing battery manufacturing apprenticeship standards to help address the upskilling, reskilling and new skills needs of the battery manufacturing workforce. The initial focus of this work is on Level 2 manufacturing production operatives and Level 3 technicians, but there is scope to expand this to other areas such as Level 4 battery management/quality.

[21] https://www.smmt.co.uk/wp-content/uploads/sites/2/SMMT-Motor-Industry-Facts-Nov-2020.pdf
[22] http://www.h2fcsupergen.com/wp-content/uploads/2019/01/UK-H2FC-Capability-Document.pdf

5. Which countries are currently the leaders in battery and/or fuel cell science and technology and where, if anywhere, does the UK have a lead or other advantages?

Figure 5 is a recent Bloomberg study evaluated 14 countries across five sectors and a range of assessment categories (Policy & Regulation, Infrastructure & Market Sophistication, Research, Development & Demonstration) to arrive at a H_2 Economy score. The UK placed sixth behind Germany and France[23]. These results underscore the importance of supporting investment into fuel cell development and deployment in narrowing this gap.

Japan's approach to fuel cells and hydrogen technologies is one that merits particularly close analysis. Currently a significant energy importer with a high fossil fuel consumption, the country has instituted an ambitious plan to recast itself as a hydrogen-based economy. This could potentially position Japan as a leading exporter of fuel cell technologies.

6. In what sectors could battery and fuel cell technologies play a significant role?

The suitability of batteries and fuel cells varies between transport modes. Fuel cells can be used in a wide range of applications, including transportation, material handling, stationary, portable, and emergency backup power applications. Fuel cells are well suited to heavy-duty trucks and buses, and could power cars and trains, with opportunities arising in the maritime sector – with Japan already developing hydrogen fuel cells for shipping[24].

Batteries

Batteries are integral for fuel cell and ammonia/biofuel/hybrid fuel vectors for heavier duty applications on land, sea and air, as they provide the mechanism for these systems to overcome inertia. Battery developments are complimentary to these systems as they come onstream too[25]. Recent analysis has also illustrated the diversity of requirements for cross-sector batteries, and the importance of consistent target-setting across sectors to ensure R&D agendas are aligned[26].

Fuel Cells

Across transport modes, widespread commercial adoption of fuel cells has been hindered by the lack of hydrogen refuelling infrastructure, as well as higher costs when compared to incumbent propulsion systems such as internal combustion engines. Lowering the cost of manufacturing fuel cells, and the hydrogen which fuels them would bring it into line with conventional options and other novel solutions such as battery electric vehicles, which are expected to become a leading technology option in the very near term. The source of the hydrogen is also a determining factor in the perception of fuel cell powered vehicles and its emission reductions against a fossil fuel equivalent.

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[23] https://sponsored.bloomberg.com/news/sponsors/features/hyundai/h2-economy-today/?adv=16713&prx_t=aXwFAX-0-AXSkPA

[24] https://www.argusmedia.com/en/news/2163082-japanese-firms-develop-hydrogen-fuel-cells-for-shipping

[25] https://ktn-uk.org/energy/batteries/

[26] https://i.emlfiles4.com/cmpdoc/8/5/0/4/3/1/files/93002_20201015-wmg-battery-manufacturing-targets-report.pdf

While advances in fuel cell technology are expected to continue at pace, in line with projections, there is a growing issue with aligning supply, demand and the requisite infrastructure for hydrogen. The major opportunities for fuel cells to contribute is in the transport sector in heavy-duty vehicles such as trucks, buses, trains, and shipping, where electrification is not practicable. It is likely that the demand for hydrogen will also rely on this demand for fuel cells in the case of transport. A recent survey found that 79% of automotive directors believe that fuel cell vehicles will be the real breakthrough for electric mobility. Sustainable demand and use must be created to support long term hydrogen production.

Hydrogen-powered fuel cells have been proposed for flights over shorter distances. The UK HyFlyer project is converting a six-seater aircraft to use fuel cells as a demonstration project[27]. It is also suggested that fuel cells could be used to power drones. Hydrogen-fuel cells for flight are also being explored, with Zero Avia working across the UK and USA to develop new flight technology.

There is also an opportunity for fuel cells to work alongside electrification, in battery-fuel cell hybrid systems, to provide range extender technology, which is currently filled by fossil fuel combustion.

Stationary fuel cells for CHP could also play a role. Ceres Power's solid oxide fuel cells have potential applications in CHP, having produced a world-class micro-CHP fuel cell. There is evidence that deploying fuel cell micro-CHP in the UK would also facilitate electrification of heating in other houses. Although the CCC considered micro-CHP to be too expensive relative to hydrogen boilers and hybrid heat pumps, modelling by UCL identified a role in up to 10% of UK homes[28] [29].

7. **How should battery and fuel cell technologies be integrated into the wider UK energy system, and what are the challenges associated with integration (e.g. infrastructure, deployment, system operation, regulatory frameworks)?**

The UK is a world leader in trialling innovative energy storage. UKRI has funded research, development and demonstration projects cover the full scale of energy needs from milliwatts (for example, in nanorobots or pacemakers) to grid scale (Megawatt-Gigawatt). Batteries and fuel cells can provide short-timescale frequency response to long-duration. On their own or in combination they can unlock entirely new products and services that improve wellbeing.

Smart charging applications could boost the share of renewable energy used to charge the EVs; in particular, wind and solar energy is becoming an important research topic. Ultimately, the vehicle-to-grid strategies have shown a promising solution to the energy market[30].

In 2018, Pivot Power installed of a 3.7MWh battery array at The Emirates Stadium capable of supplying electricity to power the 60,000-seat ground for a full match. On a larger scale, Pivot Power has also orchestrated the development of two battery storage 'superhubs' to be built in Oxford and Kent by 2021. These SES

[27] https://www.zeroavia.com/press-release-hyflyer-2-grant
[28] https://www.theccc.org.uk/publication/hydrogen-in-a-low-carbon-economy/
[29] https://www.ucl.ac.uk/energy-models/models/uk-times
[30] https://www.mdpi.com/2071-1050/12/7/2935/pdf

hubs will not only ensure faster EV charging, but will also provide the electricity capacity for EV charging on a large scale, resulting in reduced pressure on the grid.

The batteries being used in these superhubs are first-life and are being supplied by the Finnish smart technology company Wärtsilä. However, as the utilisation of spent EV batteries stationary applications grows, it is possible that the supply chain for these kinds of superhub will change[31]. There is thus growing interest in the use of battery hubs to provide short term (minutes to hours) energy storage, to provide flexibility to a renewables-heavy electricity grid that fossil fuels currently provide.

Further research is needed on understanding durability of fuel cells and degradation mechanisms, developing materials and strategies that will mitigate them. Affordability is another key concern, as is the performance and energy density capabilities of the battery and fuel cell storage systems. There are also large ammonia and other industries that use hydrogen produced using fossil fuels on or near site. These industrial clusters create high potential demand for hydrogen production.

Managing additional power demand from EVs is both a challenge and an opportunity for distribution utilities, with the opportunity for Vehicle-to-grid technology, allowing EVs to serve as mobile electricity storage units developing. High concentration of EV home charging during peak periods could overload local transformers, but renewable energy sources and intelligent control strategies will offer solutions to mitigate fluctuating energy demand. An intelligent control of the charge could better accommodate the photovoltaic energy and reduce the ramps. The vehicle-to-grid could additionally help harnessing the photovoltaic energy to shave the peaks of the conventional load profile[32].

8. What are the life cycle environmental impacts associated with batteries and fuel cells (e.g. in resource extraction, product manufacture, operation, reuse and recycling), and how can these be managed as production and usage increase?

Fuel cells do not produce any greenhouse emissions by their use. They are also typically easier to recycle than batteries. There is a need to take a full Life-Cycle Assessment approach to the use of both batteries and fuel cells, including recycling and choice of materials.

The Government is aware of the social, ethical, environmental and supply concerns surrounding the mining of raw materials for electric vehicles, and is working to address these. The Faraday Battery Challenge is funding research to reduce our dependency on raw mineral supply and make better use of global resources, including the reduction and replacement of critical raw materials such as cobalt, in lithium-ion batteries.

R&D activities are being sponsored to reduce dependency on elements such as cobalt by minimising their content within batteries. Ethical and sustainable

[31] https://airqualitynews.com/2020/12/01/the-importance-of-second-life-batteries-for-energy-storage/
[32] https://www.sciencedirect.com/science/article/abs/pii/S0038092X14004745

sourcing of batteries is important for UK industry, actively working with the Global Battery Alliance on sustainable sourcing.

Mining for the elements in batteries is energy intensive, while battery manufacture produces a carbon footprint. However, life cycle analysis demonstrates that batteries and their component materials can be mined more sustainably, and when the emissions from use are considered then vehicles are not only lower in emissions than an equivalent internal combustion engine (ICE), but there is also the potential for them to become significantly lower than the entire ICE and fossil fuel supply chain. The Faraday Battery Challenge has also sponsored projects looking at the extension of first life of vehicle batteries as this drives significant life cycle impact reductions.

The Faraday Battery Challenge has sponsored over £20m of research and development into recycling to reduce dependency on virgin materials and changing way batteries are manufactured to reduce energy requirement for manufacture. This includes researching recycling inhouse scrap from manufacturing processes through to second life applications. The Faraday Battery Challenge also chairs a Steering Group looking at regulation, life cycle impact and recycling whose membership comprises 40 policymakers and public sector officials, including WMG. The group has recently published its report on battery recycling[33].

In addition, three years ago there were no permitted waste sites with electric vehicle battery recycling permits. In the last 6 months, 2 UK waste sites have received permits to recycle electric vehicle batteries and it is understood further permits are under consideration by UK environmental regulators.

Fuel cells

As **Figure 6** illustrates, for fuel cell electric vehicles (FCEVs), the energy conversion of hydrogen production phases ranges from 23%~69%. The variety in efficiency is due to the different hydrogen production pathways.

FCEVs have higher percentages of their overall lifetime emissions coming from its manufacturing and end-of-life processes. Materials used in the energy systems FCEVs, as well as their associated assembling processes are two major incremental GHG emissions compared with GHG emissions of ICE Vehicles during manufacturing.

Though hydrogen production plays the key role in terms of energy consumption and GHG emission of FCEVs, the manufacturing process of the fuel cell system cannot be neglected. The GHG emissions of fuel cell system manufacturing make up around half of the GHG emissions of the FCEV manufacturing and disposal process

The PEM fuel cell system is comprised of a fuel cell stack and other supporting components. The fuel cell stack consists of components such as the catalyst layer, membrane, gas diffusion layer, and bipolar plates all of which require base materials. There is an environmental impact associated with this which should not be overlooked and R&D advances can limit this impact over time.

[33] https://warwick.ac.uk/fac/sci/wmg/business/transportelec/22350m_wmg_battery_recycling_report_v7.pdf

The Faraday Battery Challenge has helped fund the £10m 'ReLib' Faraday Institution research project. ReLib is developing the technological, economic and legal infrastructure to allow high percentages of the materials in lithium-ion batteries at the end of their first life to be reused or recycled. The Faraday Battery Challenge will continue to support projects looking to reduce, replace and recycle the use of critical raw materials in battery manufacture. Meanwhile, the innovation strand of the Faraday Battery Challenge is supporting several business-led collaborative R&D projects on the re-use and recycling of electric vehicle batteries (~£10m of funding). Organisations involved in these range from chemical companies to automotive manufacturers, who are working together to develop efficient and economically viable technologies.

The availability of critical materials is key to UK manufacturing and productivity across a range of strategically important sectors such as aerospace, automotive, energy and chemical. With growing international competition for key resources both in terms of securing supply of materials already in high demand, as well as needing a diversity of critical raw materials to develop new materials, both of which are needed for the creation of vital components for low carbon technologies, including electric vehicles, and renewable energy infrastructure (e.g. wind turbines), and digital technologies (e.g. computers, smartphones).

To meet the anticipated global demand for batteries for EVs, production needs to increase significantly worldwide. Along with the increase in production of current Li-ion technology required to supply markets in the near term, there is also an opportunity to develop and scale the technologies of tomorrow. Affordable supplies of critical materials for battery manufacturing, notably cobalt, may be placed under pressure, while assembly plants will require large capital investments to scale up EV production sufficiently[34].

Many countries have strategies on raw materials, including the United States – which developed its critical mineral list to ensure secure and reliable supplies in 2018[35] – and the EU[36]. The UK currently has no such strategy, with the UK dependent on imported critical minerals[37] which may have a limited or depleting availability of supply, affecting the security of supply of these crucial materials of national importance.[38] Demand for lithium in particular is expected to greatly outstrip supply, which is forecast to grow by over 20% a year in the next decade[39]. Access to these rare earth minerals will be crucial to enable the future growth.

The Faraday Battery Challenge is involved in looking at the feasibility of extracting lithium in the UK. Cornish Lithium is a partner in the Li4UK project[40], assessing the viability of extracting lithium from domestic primary sources and trialling different mineral processing routes to produce battery quality lithium chemicals from UK

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[34] https://projects.iq.harvard.edu/files/energyconsortium/files/rwp18-026_lee_1.pdf
[35] https://www.federalregister.gov/documents/2017/12/26/2017-27899/a-federal-strategy-to-ensure-secure-and-reliable-supplies-of-critical-minerals
[36] https://ec.europa.eu/commission/presscorner/detail/en/ip_20_1542
[37] https://post.parliament.uk/research-briefings/post-pn-0609/
[38] https://www.mining-technology.com/features/featuremined-into-extinction-is-the-world-running-out-of-critical-minerals-5776166/
[39] https://roskill.com/market-report/lithium/
[40] http://www.li4uk.co.uk/

mined material. The study has indicated that domestic sources of lithium have the potential to provide a substantial portion of the UK’s future lithium demand. Research during the Li4UK project has also shown how vital it is that the UK builds the rest of the downstream supply chain domestically, to ensure that battery quality chemicals and batteries can also be produced here – and that the value this new industry generates is captured in the UK.

Sodium batteries could be manufactured with a reduced reliance on metals such as nickel, lithium, and cobalt. The prevalence of sodium in the Earth’s crust would mean supply could more easily meet demand and alleviate resource procurement challenges. The success of sodium ion batteries would mitigate problems of access to finite mineral resources, and offers the opportunity to reduce our reliance on a complex and competitive global supply chain. They are safer than Li-ion batteries and do not have the toxic waste associated with lead acid batteries. The British company, Faradion Ltd are a leading in the research of sodium batteries. Sodium batteries are ideal for grid-storage or in a home battery environment, due to their lower energy density than lithium ion ones.

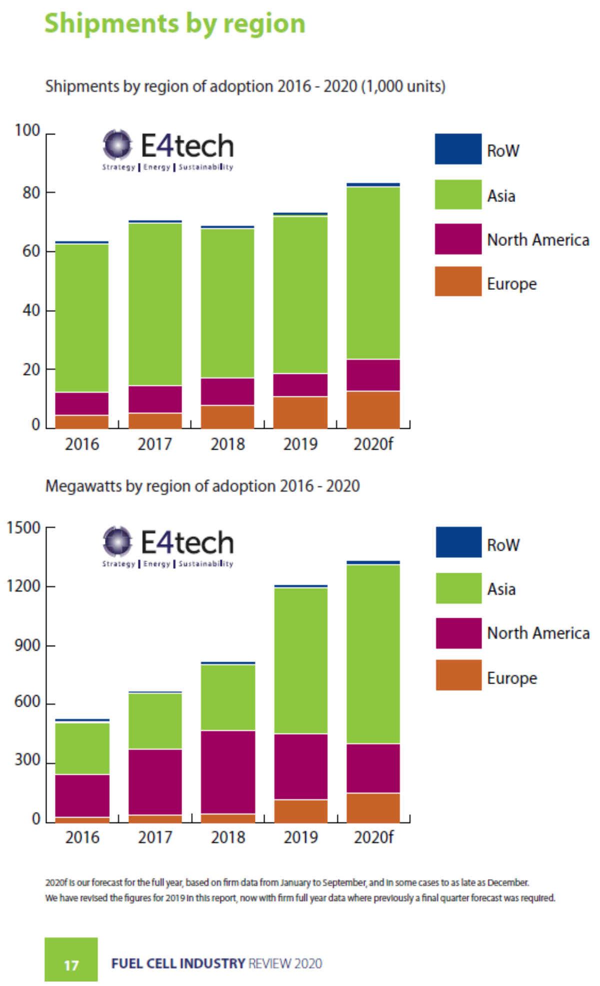
Battery disposal and recycling is a key challenge that needs to be addressed, with questions surrounding the safe disposal of toxic chemical waste and potential for reclamation of lithium.
Alkaline fuel cells should be a key area of focus for Britain and the industry at large, they are the cheapest fuel cell type to manufacture, do not require noble metals and have a reduced pollution footprint compared to acidic fuel cells.

8 April 2021

ANNEX A – TABLES AND FIGURES

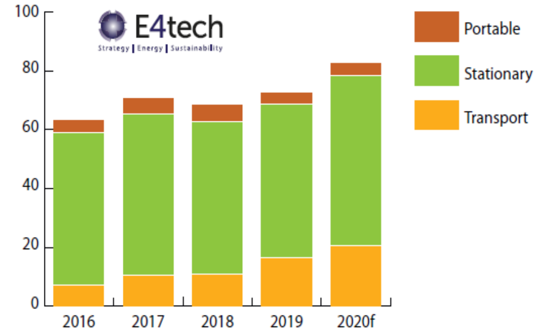
Figure 1. From The Fuel Cell Industry Review 2020. E4tech, 2020.
Figure 2. From 'Fuelling the Future of Mobility'. Deloitte & Ballard Power Systems, 2020.
Figure 3. From The Fuel Cell Industry Review 2020. E4tech, 2020.
Figure 4. From Fuel Cell Technology Roadmap. Advanced Propulsion Centre, 2020.
Figure 5. From 'H2Economy Today'. Bloomberg, 2021.
Figure 6. From 'Fuelling the Future of Mobility'. Deloitte & Ballard Power Systems, 2020.

FIGURE 1

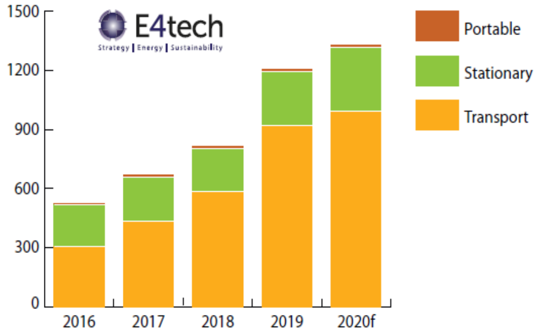


Shipments by application

Shipments by application 2016 - 2020 (1,000 units)



Megawatts by application 2016 - 2020



2020f is our forecast for the full year, based on firm data from January to September, and in some cases to as late as December.
We have revised the figures for 2019 in this report, now with firm full year data where previously a final quarter forecast was required.

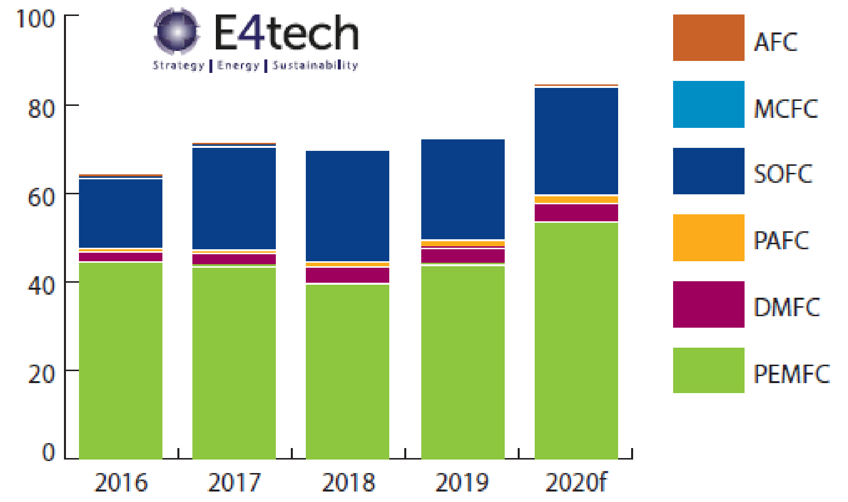
FIGURE 2

Figure 10. Current and future number of FC vehicles by type and geography*

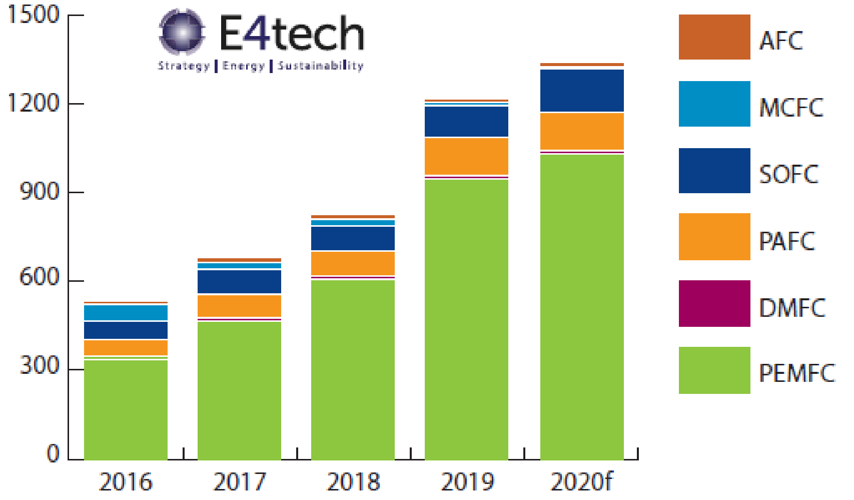
		Passenger vehicles	Buses and coaches	Trucks**	Forklifts	Refueling stations
US	Current	7,271 [44]	35 active, 39 in development	prototype test	>30,000 [335]	~42 online [37]
	Target		5,300,000 FCEVs on US roads by 2030 [337]		300,000 by 2030 [337]	7,100 by 2030 [337]
China	Current	0	2,000+ [64,83,84,85]	1,500+ [94]	2	23 [89]
	Target	3,000 by 2020 [87] 1,000,000 by 2030 [336]	11,600 commercial vehicles by 2020 [87]			100 by 2020 500 by 2030
Europe	Current	~1000+ [42]	~76 [42,73,86]	~100 [88]	~300 [42]	~152 [71]
	Target	3,700,000 by 2030 [34]	45,000 fuel cell trucks and buses by 2030 [34]			~3,700 by 2030[34]
Japan	Current	3,219 [44]	18	N/A	160	127; 10 in progress
	Target	40,000 by 2020 200,000 by 2025 800,000 by 2030 [24]	100 by 2020 1,200 by 2030 [24]		500 by 2020 10,000 by 2030 [24]	160 by 2020 900 by 2030 [24]

FIGURE 3

Shipments by fuel cell type 2016 - 2020 (1,000 units)



Megawatts by fuel cell type 2016 - 2020



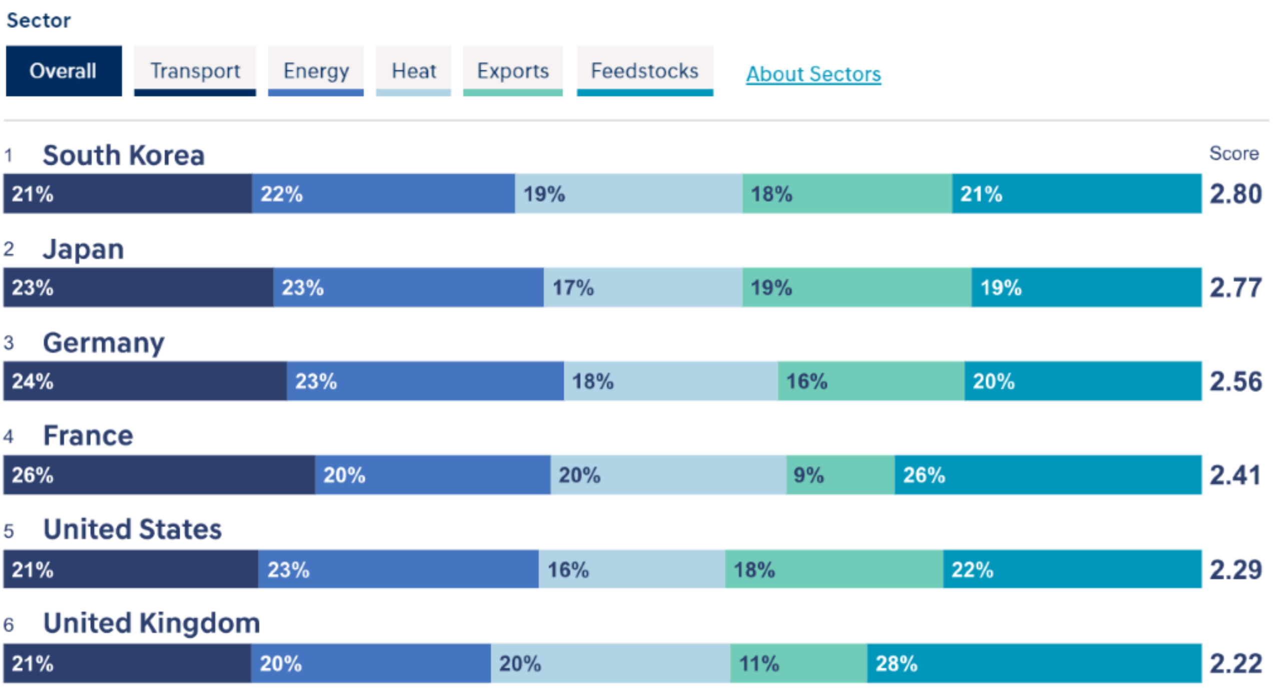
2020f is our forecast for the full year, based on firm data from January to September, and in some cases to as late as December.
We have revised the figures for 2019 in this report, now with firm full year data where previously a final quarter forecast was required.

FIGURE 4

Light Duty Vehicles	2020	2025	2035
$/kW (System)	112	68	40
$/kW (Stack)	70	40	20
System Efficiency[1] (%)	60	65	70
Stack Durability (Hrs)	5,000	6,000	8,000

Heavy Duty Vehicles	2020	2025	2035
$/kW (System)	455	195	80
$/kW (Stack)	285	115	40
System Efficiency* (%)	60	65	70
Stack Durability (Hrs)	15,000	22,000	30,000

FIGURE 5



<u>FIGURE 6</u>

Figure 70: Well-to-wheel analysis framework of vehicles by propulsion type

Energy Efficiency	Well → Tank 4.1.2 Production	4.1.3 Delivery	Tank → Wheels 4.1.4 Use	Overall WTW Energy Efficiency
FCEV	**23~69%** [228 233 234 235 236227] • Range is due to differences in hydrogen production pathways • Production efficiency = Feedstock extraction efficiency X fuel to hydrogen efficiency • See details in following pages	**54~80%** [230 231 232] • Energy loss during compressing, transportation (pipeline/truck) and storage (gaseous/liquid hydrogen)	**36~45%** [230 232] • Conversion of hydrogen to electricity, and electricity to mechanical energy • The additional energy loss compared with BEV operation, is due to added step of hydrogen to electricity	**4~25%**
BEV	**35~60%** [234 235 236] • Range varies depending on different methods of electricity production, as well as grid-mix which varies dramatically between different countries	**81~84.6%** [235 236 240] • Average conversion rate during electricity transmission is about 90%-94% • 90% energy efficiency during charging process	**65~82%** [229 230] • Energy loss during electricity conversion to move vehicle, including loss in motor, AC conversion, auxiliary parts and transmission system, excluding the charging process	**18~42%**
ICE Vehicle	**82%~87%** [234 238 239] • 13~18% energy loss during fossil fuel mining, refining processes	**~99%** [237] • Small amount of energy loss during transportation process, due to evaporation, spilling or adhesion to containers	**17~21%** [229] • Majority of energy lost as heat • Current efficiency is near the limit of ICEs after years of improvements as the incumbent vehicle type	**14~18%**

ANNEX B – OVERVIEW OF RELEVANT UKRI INVESTMENTS

Faraday Battery Challenge

This challenge is investing up to £318 million in research and innovation projects and facilities to drive the growth of a strong battery business in the UK. Its aim is to catalyse the development of battery technologies that are: cost-effective; high performing; longer range; faster charging; long-lasting; safe and recyclable.

Faraday Battery Challenge projects include:

- The **Faraday Institution**, a £108 million research institution is the UK's independent institute for electrochemical energy storage research, skills development, market analysis and early-stage commercialisation. It brings together research scientists and industry partners on projects with commercial potential to reduce battery cost, weight, and volume, improve performance and reliability, and develop whole-life strategies including recycling and reuse.
- The **UK Battery Industrialisation Centre (UKBIC)** – led by Coventry and Warwickshire Local Enterprise Partnership, WMG and Coventry City Council – is an investment of over £120 million in a first-of-a-kind specialist battery manufacturing facility. UKBIC supports companies to quickly develop their capabilities to manufacture batteries, scale up and expand to global markets.
- **Collaborative R&D projects**, through which UK businesses have been awarded grants for projects investigating such areas as improving battery lifespan, range, charging rate and the reuse, remanufacture and the recycling of batteries.

The original Faraday Battery Challenge business case was predicated on harnessing the UK's existing strengths in battery manufacturing, and the £9bn p/a opportunity this presented. In the three years since, the Faraday Battery Challenge has helped the UK build globally competitive scientific capability at scale, by facilitating collaborations between manufacturers, entrepreneurs and researchers to help unlock the economic value to the UK of battery development in transitioning to a Net Zero economy.

H2FC SUPERGEN Hub

UKRI has been supporting the H2FC SUPERGEN Hub, set up in 2012 to address the key challenges facing the hydrogen and fuel cell sector as it strives to provide cost competitive, low carbon technologies in a more secure UK energy landscape. It currently has a portfolio with £8.5m invested in fuel cell technologies research, of which £4m is invested in training.