The Faraday Institution – Written evidence (BAT0012)

Introduction to organisation: The Faraday Institution (FI)[1] is the UK's flagship programme for electrochemical energy storage research, skills development, market analysis and early-stage commercialisation. It brings together research scientists and industry partners on major 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 FI regularly publishes evidence-based assessments of the market, economics, commercial potential, and capabilities for energy storage technologies and the transition to an electrified economy.

We limit our evidence presented here to the role of batteries as our remit does not currently extend into fuel cells. We recognise that multiple technologies, including fuel cells, have an important and complementary role in meeting Net Zero targets.

Summary: To meet Net Zero commitments and transition to an electrified future – from transport and aviation to power generation and distribution – will require many types of batteries, some as yet to be imagined. These batteries need to be researched, developed, commercialised and manufactured in the UK to deliver maximum economic value for the UK. For the country to compete globally in this field of national and global importance, a long-term commitment to research and development into next generation energy storage technologies is warranted.

1. To what extent are battery and fuel cell technologies currently contributing to decarbonisation efforts in the UK? What are the primary applications of battery and fuel cell technologies for decarbonisation, and at what scale have they been deployed?

The highest carbon emissions in the UK are from transportation (27%[2]), energy supply (burning coal, oil and natural gas), commercial use and residential – all areas where batteries will play a critical decarbonisation role.

Automotive: The UK is at the front of the push towards the electrification of road transport, with the government recently announcing the end of the sale of new diesel and petrol vehicles by 2030. Sales of battery EVs (BEVs) have increased to 6.6% of all new car sales in 2020[3] and are expected to reach a market share of 9.3% in 2021 and 11.9% in 2022.[4] BEVs, plug-in hybrids and hybrids in total are expected to account for around 24.9% of registrations in 2021 and 28.5% of registrations in 2022.

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[1] The FI launched its research programme in 2018 and is a key element of the Faraday Battery Challenge.

[2] Final UK greenhouse gas emissions national statistics 1990-2019, BEIS.

[3] SMMT (2021 February). https://www.smmt.co.uk/vehicle-data/car-registrations/

[4] January/February 2021 - SMMT UK New Car and LCV Registrations Outlook to 2022.

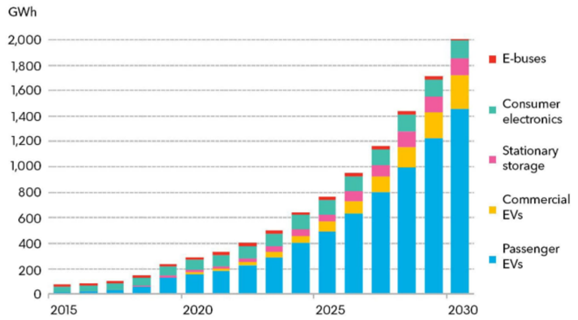

Figure 1: Global annual lithium-ion battery demand by application

The global transition to EVs will drive lithium-ion battery (LIB) demand, as projected in Figure 1[5]. About 70% of global LIB demand in 2030 is from passenger EVs, with the remainder from electric buses, consumer electronics, grid stationary storage and commercial EVs. We estimate demand for seven 20GWh gigafactories in the UK by 2040.[6]

Looking beyond automotive, an FI report[7] published in 2020 provides an overview of current battery technologies and markets for high energy applications by sector and energy requirements (spanning portable consumer electronics, electric vehicles, civil aviation, unmanned systems and large-scale energy storage) and an indication of what battery technologies are currently state of the art, and those that are emergent and may be coming to market over the next 5-10 years, such as lithium-metal cells and solid-state batteries.

<u>Grid-scale Storage</u>: There is an opportunity for the use of stationary battery systems to store renewable energy from the grid. Storage provides the increased flexibility needed to fully utilise renewable generation during periods of low demand so that it can be used at peak times. Energy storage is useful for both delivering balancing services and frequency response to ensure the stability of the grid. Potential applications within this wider market include energy storage for national grids, renewables, local microgrids and ship energy storage, where there is a large market for modular, often containerised energy storage in unit sizes of tens to hundreds of kW hours.

Potential technologies for grid-scale energy storage include lithium-ion, sodium-ion, lithium-sulfur, redox-flow and zinc-air. Additional research efforts are required to improve performance and lower cost by exploring new materials, new chemistries, minimising degradation, increasing safety and reducing the overall cost of ancillary equipment needed in a full system.

<u>Aviation and Aerospace</u>: Batteries have been used to power onboard systems in aircraft for decades, but fully electric-powered flight is still in its infancy. Electric aircraft offering short-range flights or vertical take-off and landing are distinct possibilities in the coming decades. New markets for drones and urban air mobility vehicles are starting to be developed, with the first large-capacity

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[5] www.seekingalpha.com/article/4330100-battery-cells-tesla-lose-competition-for-independence

[6] UK EV and battery demand to 2040, Faraday Institution report, January 2020

[7] High-Energy Battery Technologies, Faraday Institution report, January 2020

electric passenger aircraft perhaps 20 years away. The FI published a report on lithium-sulfur battery technology in July 2020[8] which is the most likely chemistry for aviation as it has the potential to be a cheaper, lighter and safer technology than lithium-ion.

Defence Sector Applications (e.g., Drones/Unmanned Vehicles): Battery technology is beginning to be used in niche markets such as satellites, drones and military vehicles. The global market for unmanned aerial vehicles is expected to increase from US$ 25.59 billion in 2018 to US$ 70 billion in 2029, according to analysis from BIS Research, with potential applications spanning multiple sectors such as infrastructure, agriculture, transport and security.

In the maritime environment, the unmanned underwater vehicle and unmanned surface vehicle markets are forecast to reach over US$ 5 billion and US$ 1 billion respectively by the early 2020s, driven the maritime security and offshore oil and gas industries. The defence sector is likely to remain at the forefront of unmanned ground vehicle technology, with the market predicted to reach US$ 7 billion by 2025.

Replacement of diesel generators: There is a market for replacing diesel generators in weak-grid and off-grid stationary energy storage settings, particularly in countries such as India, Nigeria and China. Replacement demand is estimated to be 560 GW with an additional demand of 130 GW from new on-grid or utility-scale applications. As well as lithium-ion and sodium-ion, emerging battery technologies such as zinc-air and lithium-sulfur, which are based on lower-cost materials, might be able to break into the market.[9]

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)?

Improvements to lithium-ion battery technology occur incrementally rather than by substantive breakthroughs. Over the past 30 years, performance improvements have compounded to the point that EVs have become desirable to consumers. In the immediate term, reducing battery costs is undoubtedly the most significant challenge limiting the mass adoption of EVs. For mass market EVs to reach cost parity with internal combustion engine equivalents, battery pack costs will need to reach ~$100/kWh. In recent years, the biggest cost improvements have been driven by massively increased scale of production and improved manufacturing, as demonstrated by the successes of Tesla/Panasonic. Several new manufacturing technologies have been demonstrated at pilot level in recent years, which may begin to enter the market before 2025. For example, Maxwell technologies has developed a dry electrode processing method that does not require expensive solvents. Likewise, Tesla has demonstrated a ‘tab-less’ cell architecture, which eliminates the need for a bottleneck manufacturing process, increasing manufacturing output and decreasing costs. To meet performance requirements of customers, whilst meeting net zero targets, EVs

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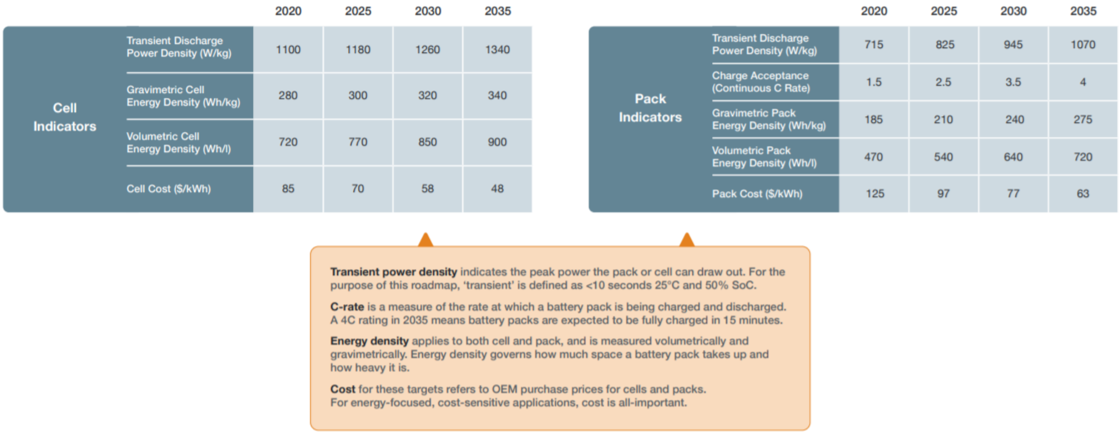
[8] Lithium-sulfur batteries: lightweight technology for multiple sectors, Faraday Insight, July 2020

[9] Bringing Cheap, Clean and Reliable Energy to Developing Countries, Faraday Insight, Oct 2019

will require improved energy density and faster charging times, with greatly decreased raw material costs.



		2020	2025	2030	2035
Cell Indicators	Transient Discharge Power Density (W/kg)	1100	1180	1260	1340
	Gravimetric Cell Energy Density (Wh/kg)	280	300	320	340
	Volumetric Cell Energy Density (Wh/l)	720	770	850	900
	Cell Cost ($/kWh)	85	70	58	48

		2020	2025	2030	2035
Pack Indicators	Transient Discharge Power Density (W/kg)	715	825	945	1070
	Charge Acceptance (Continuous C Rate)	1.5	2.5	3.5	4
	Gravimetric Pack Energy Density (Wh/kg)	185	210	240	275
	Volumetric Pack Energy Density (Wh/l)	470	540	640	720
	Pack Cost ($/kWh)	125	97	77	63

Transient power density indicates the peak power the pack or cell can draw out. For the purpose of this roadmap, ‘transient’ is defined as <10 seconds 25°C and 50% SoC.

C-rate is a measure of the rate at which a battery pack is being charged and discharged. A 4C rating in 2035 means battery packs are expected to be fully charged in 15 minutes.

Energy density applies to both cell and pack, and is measured volumetrically and gravimetrically. Energy density governs how much space a battery pack takes up and how heavy it is.

Cost for these targets refers to OEM purchase prices for cells and packs. For energy-focused, cost-sensitive applications, cost is all-important.

Figure 2: Battery technology indicators that industry is expected to achieve in a mass-market competitive environment. Source: APC Electrochemical Storage Roadmap (2021)

Over the next 10 years (2020-2030) there is likely to be a transition to low cobalt / high nickel content cathode materials due to the demand for increased energy density and ethical considerations associated with the mining of cobalt. The FI’s FUTURECAT and CATMAT projects, led by the universities of Sheffield and Bath, are developing next generation cobalt free electrodes. However, low cobalt cathodes degrade more rapidly than current cathode materials; therefore, research is currently underway to improve stability and battery life. Validation of long-term performance of new battery materials is critical to providing ~10-year battery warranties and abating the liability concerns associated with deploying new materials into a mass market. The FI’s Degradation project led by the University of Cambridge is undertaking research to address these challenges. Over the coming decade, the silicon content of anodes is expected to be gradually increased in commercial EV batteries. Silicon anodes have the potential to store significantly more lithium than graphite equivalents, at the expense of extreme volume expansion (400%) during charging. Currently cells are available with up to approximately 10% silicon mixed into the graphite anode material for modest gains, whilst retaining reasonable life spans.

Towards the end of the decade (2025-2030) a number of next generation battery technologies are expected to enter production:

- **Solid-state batteries** are expected to be the technological successor to lithium-ion batteries and will offer a step-change in energy density, faster charging rates and significant safety advantages. However, many technical issues need to be solved before solid-state batteries become viable on the scale required for automotive production. None of these problems are trivial but the technology is developing rapidly, and several companies (Toyota, QuantumScape /Volkswagen) have ambitions to deploy these technologies in EV applications before 2030. The FI’s solid-state battery programme, led by the University of Oxford, is a notable example of where the UK can seize the

opportunity to lead the world in this battery technology (critical to the future of automotive, aviation, consumer electronics and beyond).
- **Sodium-ion batteries** are sodium analogues of lithium-ion batteries, but they require simpler manufacturing and lower cost / naturally abundant materials. At scale sodium-ion batteries will be more economic to produce than lithium-ion batteries. Therefore, over the next 10 years the technology is likely to be employed in stationary applications, such as grid storage for renewables, residential storage, and low performance vehicles. Sodium-ion technology is unlikely to be used in EV power trains due to its relatively low energy density. Sodium ion battery technology is relatively new and under-developed. The FI's NEXGENNA project led by the University of St Andrews is working with industry to develop a critical mass of IP for commercialising sodium-ion batteries in the UK.
- **Lithium-sulfur batteries** offer greater gravimetric energy density than lithium-ion, whist also being cheaper to produce. The lightweight nature of lithium-sulfur batteries is expected to open up a number of new markets and have a transformative effect on aerospace applications, such as small drones (civilian and military); high altitude pseudo satellites (HAPS); unmanned aerial vehicles (UAVs), including unmanned combat aerial vehicles (UCAVs). Current lithium-sulfur cells suffer from short cycle lives and research to solve these challenges is underway. The FI's LISTAR project led by University College London is exploring strategies for solving the technical challenges currently holding back this technology.

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?

To achieve the low battery costs necessary for mass market electric vehicles, lithium-ion cells need to be manufactured at enormous scale (GWh-TWh production). The capital required to build such a 'gigafactory' is considerable (multiple £billions). However, the profit margins from the direct sale of batteries are typically small, with all profits essentially derived from sale of the end user product. As a result, batteries have been traditionally manufactured by consumer electronics companies (Sony, LG Chem, Samsung SDI, Panasonic) who realise large profits during the sale of an electronic device. This model is likely to carry over to EV manufacturing so vertical integration of the supply chain is essential. Until recently, battery manufacturing at this scale had only been performed in Asia, therefore, there was insufficient track record to assess risk needed for private investments of this nature in the west at the scale necessary to hit the price points needed for EV applications. However, the success of the Tesla gigafactory in Nevada (USA) has demonstrated the viability of the economics of battery manufacturing in the west and several gigafactories are now planned for North America and Europe, including Tesla Berlin, Italvolt and Northvolt.

In addition to financial considerations there are numerous technical difficulties for new market entrants to build and operate lithium-ion battery gigafactories. The existing lithium-ion battery manufacturers have spent 30 years optimising the manufacturing processes and the underlying cell chemistries. Establishing complete inhouse technology for lithium-ion battery manufacturing is impossible for new market entrants and the intellectual property for the newer generation technology is fiercely protected. Therefore, new entrants are unlikely to gain access to the most competitive technology without partnering with leading established Asian companies. For example, Tesla partnered with Panasonic to develop Gigafactory 1 and CATL for Giga Shanghai. Given the anticipated demand for batteries by large automotive companies, competition for access to both expertise and IP is considerable. Furthermore, manufacturing at this scale requires a highly developed supply chain. The UK is already home to several leading materials companies. Although, some lithium-ion battery manufacturing will take place in the UK, it is unlikely that the UK could become a leader in lithium-ion technology.

China has undoubtedly secured a first-mover advantage and has cornered a substantial proportion of the EV market. In 2018, around 68% of lithium-ion batteries were manufactured in China, compared to 10% in the US and just 4% in Europe. However, with the market set to increase substantially, there is a massive opportunity for Europe to take a bigger portion of the global market.

Furthermore, **if the UK is to retain its automotive manufacturing and meet net zero targets, battery manufacturing must necessarily occur in the UK**, as the economics for manufacturing the car at or close to the site of battery manufacturing are favourable due to the battery weight and risks associated with battery transport. By 2040, the FI estimates that seven gigafactories will be needed in the UK.[4] At present, the AESC Envision plant is the only large-scale EV battery factory operating in the UK. Britishvolt intend to build a gigafactory in Blythe and plans for a West Midlands gigafactory at Coventry Airport has been announced.

The UK can become a leader in the manufacturing of next generation technology (namely: solid-state, sodium-ion and lithium-sulfur batteries). Currently, no country manufactures these batteries at significant commercial scale. These technologies represent a massive opportunity for the UK to capture economic value and jobs. The UK has world-leading expertise in these technologies and could gain a first-mover advantage provided the lessons have been learned from the failure to commecialise lithium-ion batteries in the UK in the 1980s. Since new manufacturing methods will be needed for next-generation batteries, the success of Japan and South Korea with lithium-ion batteries could be emulated in the UK for next-generation technology. This will require government to adopt a strategic approach, convening the supply chain and committing long-term capital to high-risk manufacturing scale-up research activities. A willingness to try and fail and then iterate quickly is critical to developing the manufacturing capability and securing the IP necessary to guarantee UK manufacturing. However, these activities are often too risky for the private sector and rely on government financing as a catalyst.

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?

As the UK's flagship national programme for electrochemical energy storage research and early-stage commercialisation, the FI was intended from the outset to be a 10-year programme, a sensible estimate of the time needed to make research breakthroughs and to commercialise them for the benefit of the UK economy. It is currently funded through to March 2022. For the UK to play a significant role in battery manufacture and to decarbonise a range of industrial sectors it will require long term commitment in R&D of next generation energy storage technologies.

Professors Thomas and Brandon will supply an additional paper on this topic to the committee per Lord Patel's request.

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?

The UK is world leading on high power batteries, spurred on by niche high tech applications such as Formula1 KERS systems. Scientifically, the research on anodes Professor Clare Grey has carried out with Toshiba and others, including with the spin-out Nyobolt, investigating next generation long-lasting, high-power batteries is world leading. The UK is amongst the leaders on battery pack and system design with companies such as Williams Advanced Engineering, and McLaren manufacturing battery packs for high end road cars and motorsport including Formula E. Further, the UK is amongst the leaders and probably world leading in developing battery systems with high energy lithium-sulfur battery packs. In the development of next generation sodium-ion batteries as a lower-cost alternative to lithium ion, the UK is amongst the leaders and is probably world-leading.

The UK has a strong track record of producing world leading academic research in the battery space. Historically, the foundations of the lithium-ion battery were developed at the University of Oxford in the late 1970s, for which Professor John Goodenough and Professor Stanley Whittingham were awarded the 2019 Nobel Prize in chemistry.

The UK has been historically weak at capturing the value generated by battery research and development domestically. For example, the lithium-ion battery invented in the UK was commercialised overseas, with 97% of lithium-ion battery manufacturing currently concentrated in the Asia-Pacific region. Factors for this included: historic lack of strategic planning for national economic impact, lack of risk bearing capital for scale up activities, lack of understanding that battery research needs long-term projects (5-10 years) and close engagement between academia and industry, and the lack of demand from end user applications due to the absence of consumer electronics manufacturing.

However, in recent years the UK has greatly strengthened its ability for capturing the value of battery research. The Faraday Battery Challenge and the FI have been established to strategically convene the UK battery community and ensure commercialisation is accelerated for the benefit of the UK economy. The FI has been successful in strengthening this academic battery research community in the UK and its links into industry. There are currently 9 major research programmes across 21 UK universities with more than 50 industrial partners across the UK. [10] UK universities rank among the best in the world, with notable energy storage research groups at Cambridge, Oxford, UCL, Imperial College London, Warwick and Edinburgh.[11] Further, the UK now has growing demand for batteries from EVs, stationary storage and aerospace end-user applications.

Domestic battery manufacturing capability is strongly correlated with world class R&D and the generation of valuable intellectual property. China, Japan and Korea currently dominate battery research. Companies and research institutions based in these countries own the majority of battery patents and critical intellectual property for current generation lithium-ion battery technology.

The UK ranks 10th in the world for battery patents. The chance of the UK becoming a leader in current generation lithium-ion battery technology is negligible. However, the UK has strengths in the next generation technologies (sodium-ion, solid-state and lithium-sulfur batteries) and there are opportunities to commercialise these technologies and capture significant economic benefits for the UK (worth £ billions). This will require a highly coordinated strategy with industry, continuation / acceleration of research and a willingness to engage in higher risk scale-up and industrialisation efforts, and a willingness to fail whilst trying. If strategic bets are placed, with sufficient backing and continued research, the UK could become a leader in these technologies. Capturing and developing next generation battery and fuel cell technology in the UK will be critical to the competitiveness and health of the automotive industry and the associated supply chains.

The UK can learn from the success of Japan and Korea with lithium-ion batteries and apply this to next generation technologies for automotive, aerospace and stationary storage applications. The governments of these countries have been forward thinking in understanding the strategic importance of energy storage technology, which has rewarded them with enormous economic benefits and value added across the whole supply chain. They have understood that developing new energy storage technologies occurs over ~10-year time scales and have realised the value of long-term research projects (5–10-year time horizons) over short-term funding for commercialisation. In doing so, they brought together industry with leading researchers to solve the big challenges and maximise national economic benefit and have realised that manufacturing is critical to generating valuable intellectual property. This has in turn has led to significant private R&D funding; for example, Korean companies, LG Chem Ltd, Samsung SDI Co. and SK Innovation Co. spent a combined US$1 billion on R&D projects in the first half of 2020 alone.

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

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[10] The Faraday Institution Annual Report 2019/2020

[11] Published FI research emerging from UK universities has a field weighted citation impact of 2.15, indicating FI papers receive more than twice as many citations as would be expected for the field. 69% of its papers are published in the top 10% of journals (CiteScore), and 49% have international co-authors.

What are the engineering and commercial challenges associated with using these technologies, or deploying them to a greater extent, in these sectors?

The sectors in which battery technologies could play a role are wide-ranging, including in the automotive (cars, vans and HGVs), aviation, defence, rail, marine, grid, mining and home battery systems. The FI published a report on this topic in January 2020[12].

Automotive

Most EV batteries are based on lithium-ion chemistry. The most important engineering challenge associated with deploying lithium-ion batteries in the automotive industry is battery performance. Lithium-ion already offers the best combination of energy density, longevity, versatility and affordability. The ability to pack so much energy into such a small space makes lithium-ion the battery of choice for virtually every mobile electronic device. Scaled up, these same qualities make lithium-ion attractive for EVs. The ability to travel long distances on a single quick charge will be essential for increasing the market penetration of EVs.

The battery chemistry and the raw materials used for the cathode present a research and engineering challenge. The main cathode chemistries are nickel manganese cobalt (NMC), nickel cobalt aluminium oxide (NCA) and lithium iron phosphate (LFP). NMC is currently the cathode chemistry of choice for EVs and is estimated to account for around 80% of the current global market and will likely reach 90% by 2030, as LFP and lithium nickel cobalt aluminium oxide (NCA) cathode chemistries decline in importance. Recent gains in the battery performance have been achieved by exploring new materials for anodes and cathodes. Increasing amounts of silicon are being introduced to increase the capacity of graphite anodes.

Another innovation in lithium battery technology is the move to high nickel content batteries such as NMC 811 (in which metals in the cathode are comprised of 80% nickel, 10% manganese and 10% cobalt) instead of NMC 622 (60% nickel, 20% manganese and 20% cobalt). The low cost and high capacity of nickel relative to cobalt makes it an attractive prospect for mass-market applications. The major trade-off is between capacity and stability. Higher nickel content offers more energy, but reduced cycle life, and also higher manufacturing costs as dry rooms are required.

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[12] High-Energy Battery Technologies, Faraday Institution report, January 2020

Table 1: Strengths and weaknesses of key EV lithium-ion battery cathode chemistries

Cathode material	Strengths	Challenges
Lithium nickel cobalt aluminium oxide (NCA)	• High specific energy • Good specific power • Long life cycle	• Safety issues • Cost
Lithium nickel manganese cobalt oxide (NMC)	• Ni has high specific energy; Mn adds low internal resistance • Can be tailored to offer high specific energy or power	• Nickel has low stability • Manganese offers low specific energy
Lithium iron phosphate (LFP)	• Inherently safe; tolerant to abuse • Acceptable thermal stability • High current rating • Long cycle life	• Lower energy density due to low operating voltage and capacity

Source: Automotive Batteries 101, WMG University of Warwick (2018).

This move to less cobalt intensive lithium batteries is important. Cobalt has properties that make it ideal for EV battery applications such as safety (thermal stability) and high energy density. However, it is expensive and more resource-constrained, with social issues around mining. All these factors are resulting in a concerted effort by the FI and other organisations to develop battery chemistries containing less cobalt.

Safety is a challenge for the lithium-ion battery. Its use of flammable electrolytes, stored under pressure, means there is a small risk that it could catch fire. Although this is a very low risk, it makes lithium-ion chemistry challenging for use in aviation.

An engineering challenge that is closely linked to the take-up of EVs is cost. Costs are, however, reducing quickly and the total cost of ownership of EVs, which includes running costs, is now lower than conventional internal combustion engines (ICEs). The cost of the battery represents up to 40% of the upfront cost of a BEV. Average battery costs have fallen by 85% since 2010 and are expected to continue to drop over the next few years. Falling costs on this scale will change the economics of EV ownership and lead to the acceleration of EV purchases from the mid-2020s.

Another issue with lithium-ion is that annual improvements in performance are slowing down and the technology could reach a theoretical limit within a decade. This means that investment in other emerging technologies – in particular, solid-state batteries – may yield bigger returns and there is a possibility that progress could mean performance overtaking that of lithium-ion.

Aviation and Aerospace

Lithium-sulfur battery technology is the most likely chemistry for aviation. Lithium-sulfur technology has the potential to offer considerably greater gravimetric energy density than lithium-ion, whilst also being cheaper to produce. The lightweight nature of lithium-sulfur batteries is expected to open up a number of new markets and have a transformative effect on aerospace applications, such as small drones (civilian and military); high altitude pseudo satellites; unmanned aerial vehicles, including unmanned combat aerial vehicles.

Current lithium-sulfur cells have short-cycle lives due to a large volume change in the cathode upon lithiation causing mechanical breakup, and side reactions with the electrolyte causing a loss of active sulfur over the cell lifetime. The FI's LISTAR project led by University College London is exploring strategies for solving the technical challenges currently holding back this technology.

One engineering challenge for aviation is to improve battery safety. The FI has assembled a project team that is investigating the science of battery safety in collaboration with UK industry partners working in the automotive and aerospace sectors.

What will be the likely balance between battery and hydrogen fuel cell technologies (and other options) in a fully decarbonised land transport sector (e.g. heavy and light vehicle transport)?

Battery technology is likely to become dominant for private cars. The cost of battery technology has fallen significantly in the past decade, with the average cost of a battery pack declining from US$ 668 per kWh in 2013 to US$ 137 per kWh in 2020.[13] Battery performance is also improving with longer range and faster charging delivered by new EV models.

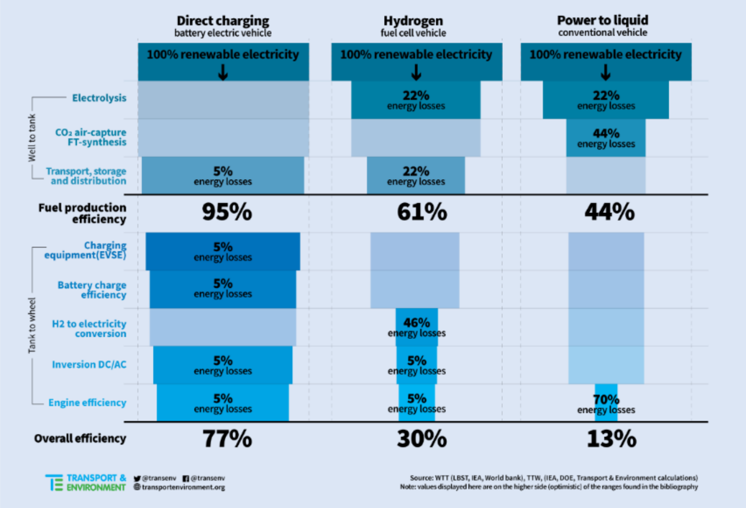

Figure 3: Energy efficiency of different technologies in a passenger car. Source: Roadmap to decarbonising European cars. Transport & Environment (2018)

One factor influencing the balance between the take up of battery versus hydrogen fuel cell technology across different applications is energy efficiency. Figure 3 illustrates that battery-charged EVs lose 5% of energy from the well-to-tank and 22% from tank-to-wheel, compared to much high levels of energy lost for hydrogen fuel cell vehicles (FCVs). FCVs are forecast by BNEF to make up just 1% of the global passenger fleet by 2040. Hydrogen could be suitable for long-distance travel and very heavy loads. BNEF estimate that FCVs will account

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[13] BNEF (2020 prices).

for 1.5% of medium-duty truck sales, 3.9% of heavy-duty truck sales and 6.5% of municipal bus sales globally in 2040.[14]

7.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? Please give examples of successful battery reuse or recycling, including the intentional design of second life applications. Given a potential global vehicle fleet approaching 2 billion vehicles by 2050, will all of the materials needed for battery and fuel cell production be available for manufacturing based in the UK?

<u>(i) What are the life cycle environmental impacts associated with batteries and fuel cells?</u>
Calculating lifecycle carbon emissions can be set within the context of a specific application such as an EV. The lifecycle impact will depend on carbon emissions from (1) vehicle production (2) battery manufacturing, (3) electricity production for EV charging and use and (4) end-of-life recycling.

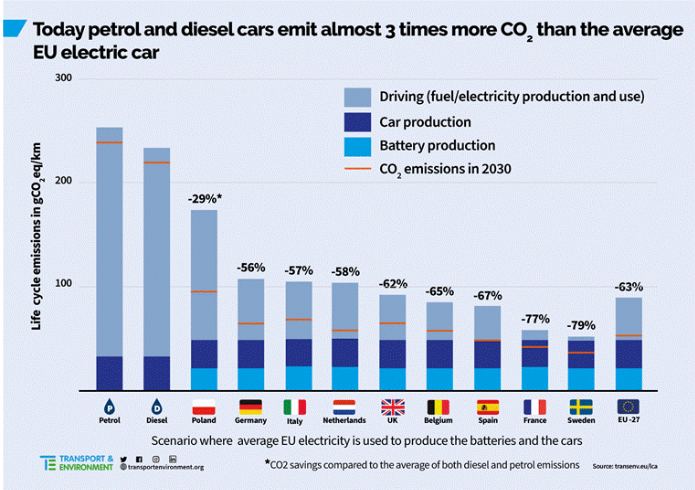

Figure 4: Comparison of life cycle CO2 emissions of EVs for EU countries. Source: Transport & Environment (2020)

Two detailed studies have recently been undertaken that quantify the difference between the lifecycle impacts of EVs and petrol/diesel ICE. 'Transport & Environment' estimate that in Europe, petrol and diesel cars produce three times (Figure 4) more carbon emissions than the average EV in 2020. In the UK, it is estimated that EVs emitted 92 gCO2/km, compared to 253 gCO2/km for petrol engines and 233 gCO2/km for diesel engines in 2020.[15] Ricardo[16] also recently undertook a detailed study of lifecycle impacts for the European Commission

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[14] BNEF Electric Vehicle Outlook 2020.

[15] How clean are electric cars? www.transportenvironment.org/what-we-do/electric-cars/how-clean-are-electric-cars

[16] Ricardo (July 2020). Determining the environmental impacts of conventional and alternatively fuelled vehicles through LCA, for the European Commission, DG Climate Action. (See Figure ES5 for country comparisons).

with country differences in emissions largely explained by the carbon intensity of electricity generation.

Carbon emissions from recycling are not included in the above estimates. Recycling could have both a positive and negative impact on emissions, as it takes energy to recycle but the recycled material could also go towards second life, reuse or repurposing. The PEFCR battery study estimates that 12% of the greenhouse gas emissions over a lithium-ion battery's lifetime occurs at the end-of-life stage.[17] Transport & Environment calculate the recycling would be net positive, achieving a reduction of about 1 to 2 kgCO_2e per kg in CO_2 emissions.[18]

(ii) How can life environmental impacts be managed as production and usage increase?

One way to minimise environmental impacts is to design battery systems that would enhance the reuse of components and the eventual recycling of materials at end-of-useful life. So far, the focus has been on developing performance for EVs. Large improvements will be necessary if the end-of-life processing of EV batteries is to be economic for most battery chemistries. It is important that new batteries are designed with the ability to recycle and also with second life applications in mind. The UK needs to establish appropriate policy, regulation policies and facilities for recycling batteries. Regulation could be used to influence business models in favour of those that promote re-use and safe and effective end-of-life management. This will require a mix of carrot and stick within an extended producer responsibility (EPR) model. Targets could be set for recycling and other second life use. For example, there could be allowances for OEMs exceeding the target to trade with those lagging behind (the carrot) alongside strict waste controls on disposal (the stick).

There are no substantial EV battery recycling facilities in operation or planned in the UK. Many UK manufacturers currently export used lithium-ion batteries to European facilities for recycling, such as the Umicore facility in Belgium. This is expensive, logistically challenging and only viable in the short term while the numbers of EV batteries reaching their end-of-life is relatively small. Without the early development of UK waste recycling facilities, a serious waste problem will be created as waste volumes build up.

Government support to help develop a UK recycling industry should be considered, as the industry may not otherwise develop at the required pace to tackle the substantial levels of battery waste. Investments required include a battery dismantling and pre-processing facility and a processing facility for recovered material. The FI's ReLiB research programme led by the University of Birmingham has recently published a study examining the most promising locations in the UK for a recycling facility.[19]

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[17] https://ec.europa.eu/environment/eussd/smgp/pdf/PEFCR_Batteries.pdf

[18] How clean are electric cars? T&E's analysis of electric car lifecycle CO_2 emissions (April 2020)

[19] "An Economic, Environmental and Geospatial Analysis of Recycling Electric-vehicle Lithium-ion Batteries" (forthcoming 2021)

(iii) Examples of successful battery reuse or recycling

There is a growing interest in second life in which EV batteries at the end of their first life are used for other energy storage uses. Many companies are interested in securing supplies of used EV batteries to recondition (for use again in EVs) or repurpose (for grid balancing or other energy storage applications).

Nissan has been successful in remanufacturing EV battery systems for reuse in vehicles and energy storage systems, whilst UK companies like Connected Energy are designing systems for reusing EV batteries in a number of applications. The duration of life in a second use application will depend on the purpose in which they are used and the acceptable minimum state of charge in that use.

Another example is to change the model of ownership. Currently, the most common form of ownership is that an individual owns the EV and all the components. This means that the battery state of health is not something that the manufacturer can understand or influence before the used battery is returned. There is therefore a risk that the owner uses the battery well below 70%-80% capacity (the optimal time for batteries to be reused or repurposed). This issue could be addressed by automakers retaining ownership of the EV battery throughout its life.

Second life batteries from EVs can be used for grid-based energy storage, including for load-shifting, peak-shaving and energy backup. Batteries previously used in EVs can also be reused as part of a strategy to integrate wind power to minimise grid outage impacts and coupled with photovoltaic generation.[20]

(iv) Will all of the materials needed for battery and fuel cell production be available for manufacturing based in the UK?

Ending UK sales of new vehicles running on diesel and petrol by 2030 will massively increase the UK demand for lithium, cobalt and nickel used to manufacture electric vehicle batteries. Raw materials are needed for all parts of the battery including the cathode powder, graphite for the anode, separators and other key chemicals that are used in the manufacturing process. The FI has forecast that the UK and global EV battery demand in 2040 would reach 137 GWh per annum and 5.9 TWh per annum respectively.[21] Taking into account EV sales, battery demand, chemistry mix and material intensity, we estimate UK 2030 demand of 9,400 metric tonnes cobalt, 44,500t lithium carbonate equivalent (LCE) and 48,500t nickel (Figure 5).[21] Demand continues to increase sharply after 2030 as other countries around the world transition to EVs and given that approximately 80% of cars produced in the UK are exported.

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[20] Examples from Energy Economics 92 (2020) Does energy storage provide a profitable second life for EV batteries? https://www.sciencedirect.com/science/article/pii/S0140988320303509

[21] Faraday Insight 6, Lithium, Cobalt and Nickel: The Gold Rush of the 21st Century

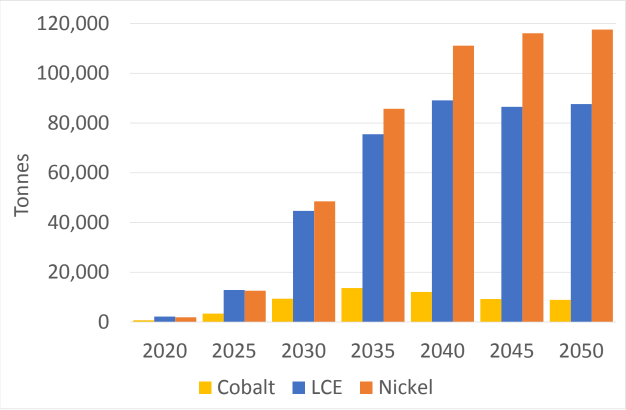

Figure 5: UK demand for raw minerals to 2030.
Source: Faraday Institution.

Global production of lithium and cobalt will also need to sharply increase, and we estimate by a factor of 5 times and 3 times respectively from now to 2035. Such growth in global production will not be easy and there could be shortages and bottlenecks, particularly as lead times for capital investment in the minerals industry are typically quite long. Inevitably, there will be a volatile market with fluctuations and spikes in prices when demand diverges from the supply in any given year. For example, the price of cobalt recently spiked across the supply chain with cobalt hydroxide prices increased by 65% year to date.[22]

The UK will face a similar scale-up challenge but more focused on the chemical industry, imports and the supply chain rather than mineral extraction. The UK is exploring some domestic supplies of key raw minerals, but it does not have abundant reserves available. The UK does, however, have some important commercial strengths such as the second biggest nickel factory in the EU, Cornish Lithium (currently investigating Cornwall's mineral potential) and Johnson Matthey (a global leader in battery material production).

Establishing a resilient battery supply chain in the UK is therefore very important and will improve the availability and affordability of key chemicals, materials and components. Key actions include:

- Attracting cell component (cathode, anode, electrolyte, etc.) suppliers,
- Expanding the existing battery reconditioning plant,
- Establishing battery recycling facilities,
- Exploring the supply chain requirements in more detail, and
- Encouraging and supporting industry groups such as Battery in Focus to simplify transport and storage rules and regulations.

The development of the UK supply chain, particularly localising more of the battery supply chain in the UK is an important policy and strategy. Importing EV batteries from Europe or further afield would not be a long-term option, as we consider that financial, legal, regulatory and safety considerations will push automotive OEMs and battery manufacturers to be located in close proximity to one another. The US is examining similar battery supply chain issues. President

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[22] Benchmark Minerals Intelligence. Cobalt Price Assessment (February 2021).

Biden recently issued an Executive Order on 'America's Supply Chains,' which required the Secretary of Energy to identify risks in the supply chain for batteries and policy recommendations to address them.

9. What are the costs and benefits of using battery and fuel cell technologies in their various applications, including when integrated into the wider energy system? To what extent are costs and benefits of the technologies affected by the levels of deployment or their regulatory treatment? Are there alternatives that should be considered for particular sectors?

The benefits of using batteries for various applications are often measured in terms of energy and power density. Gravimetric energy or specific energy is defined as the battery's energy content in relation to its mass, usually measured in Watt-hours per kilogram (Wh/kg). Volumetric energy or energy density is defined as the battery's energy content in relation to its volume, usually measured in Watt-hours per litre (Wh/l).

The Advanced Propulsion Centre & Automotive Council UK produced a roadmap for electrical energy storage and lithium batteries. The cost and performance target metrics for 2020 to 2035 are shown below. EV and battery manufacturers will need to strike a balance between the various attributes and trade-offs according to the type of market niche they are targeting.

Table 2: Technology indicators of costs and benefits for lithium battery technology

	2020	**2025**	**2030**	**2035**
Cell Indicators:				
Transient Discharge Power Density (W/kg)	1,100	1,180	1,260	1,340
Gravimetric Cell Energy Density (Wh/kg)	280	300	320	340
Volumetric Cell Energy Density (Wh/l)	720	770	850	900
Cell Cost ($/kWh)	85	70	58	48
Pack Indicators:				
Transient Discharge Power Density (W/kg)	715	825	945	1070
Charge Acceptance (Continuous C Rate)	1.5	2.5	3.5	4
Gravimetric Cell Energy Density (Wh/kg)	185	210	240	275
Volumetric Cell Energy Density (Wh/l)	470	540	640	720
Pack Cost ($/kWh)	125	97	77	63

Source: Electrical Energy Road Map (2020), Advanced Propulsion Centre & Automotive Council UK.

https://www.apcuk.co.uk/app/uploads/2021/02/Exec-summary-Technology-Roadmap-Electrical-Energy-Storage-final.pdf

29 March 2021