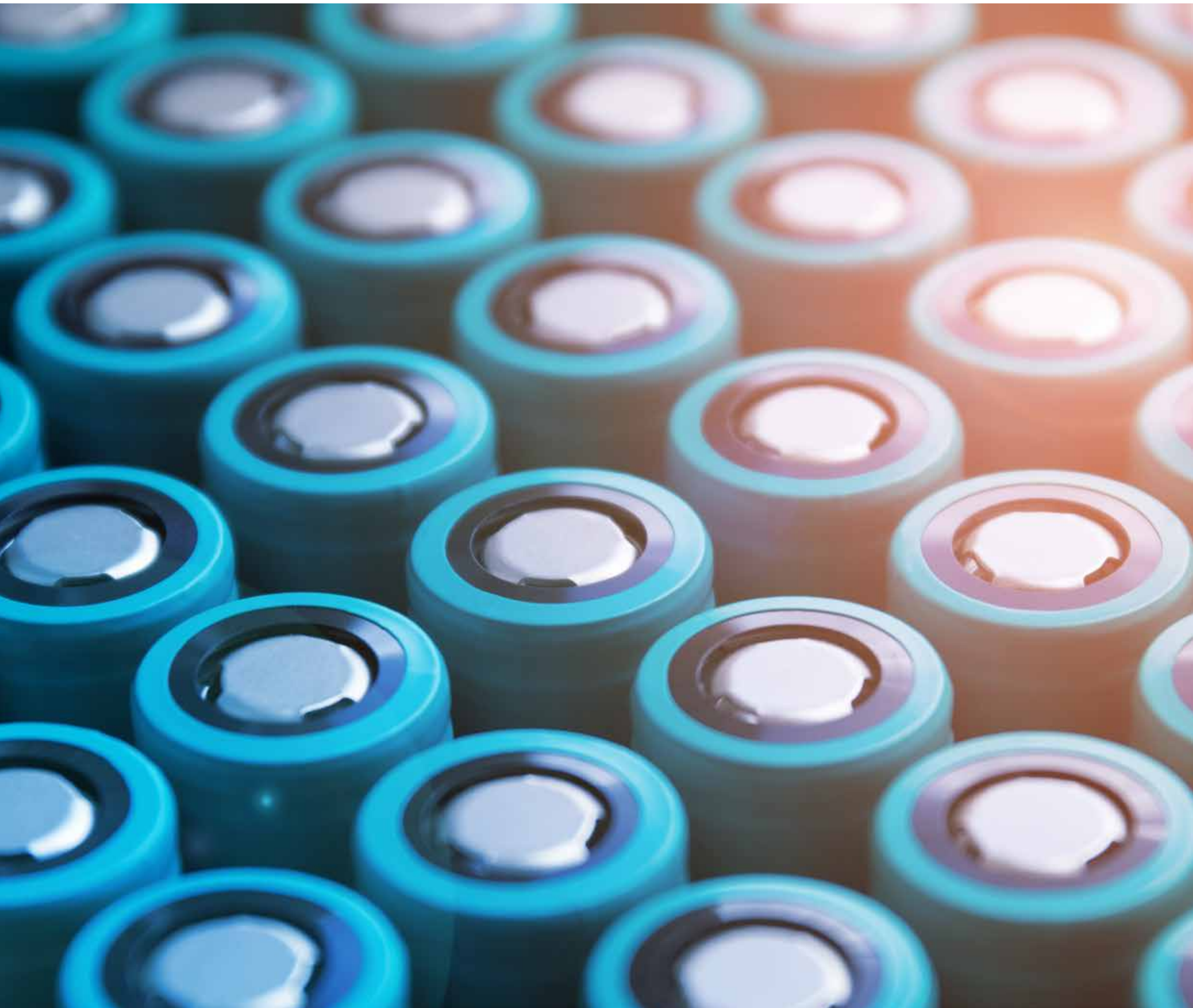
Innovate UK
KTN

US-UK Battery Technology Research and Innovation Summit 2022



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Welcome

In June 2021, the US President and UK Prime Minister issued a revised Atlantic Charter and a Joint Statement in which they committed to strengthening science and technology collaboration between the UK and the US, with a particular emphasis on energy storage. Research into and development of next-generation batteries is a high priority, enabling the UK's commitment to a cleaner, greener and ultimately net-zero economy.

According to the International Energy Agency, in response to the Paris Agreement and the global fight against climate change, electrification of the economy's energy demand will increase ten times by 2040. In the transport sector, which is responsible for 28% of the UK's emissions, the Department for Business, Energy & Industrial Strategy predicts the number of electric vehicles (EVs) in the UK will grow from 200,000 today to 42 million by 2050. Batteries are a key enabling technology that underpins this rapid transformation towards net zero. International collaboration is critical to enable innovation across the value chain to meet the urgent need for decarbonisation and the electrification of transport.

The Faraday Battery Challenge, Innovate UK and the Faraday Institution, with support from the UK's Department for Business Energy & Industrial Strategy (BEIS), delivered an online event as part of the mission that aims to bring together government, academia, and industry from across the two nations. In this publication, we provide an overview of the findings from the Online Summit.

This US-UK Battery Technology Research and Innovation Online Summit was the first activity in a larger programme to strengthen US-UK battery technology collaboration.

The objectives of the mission:

- Highlight UK expertise in battery research and innovation to promote academic and industrial partnerships
- Identify specific areas of US-UK collaboration with a focus on sustainability, safety and regulation
- Map out opportunities for further cooperation

The key themes for the summit:

- Battery Technology Research and Innovation Landscape in the UK and US
- Battery Chemistries for the Future
- Battery Development, Systems and Integration
- Towards Sustainable Battery Technologies
- Sustainable Battery Supply Chains

Speakers for this online summit represented organisations from the following categories, with some extending across multiple areas:

	Government Bodies	Research Programmes and Organisations	Industry Organisations and Facilities
US	DOE DOE EERE/VTO FCAB	21CTP ARIES Battery500 Behind the Meter Storage LIBRA model (NREL) LiBridge Li-ion Battery Recycling Prize ML Cell Design ReCell VTO Cathode Projects	6K Nth Cycle OnTo Technology Solid Power USABC
UK	BEIS Faraday Battery Challenge UKRI Innovate UK Innovate UK KTN	Advanced Propulsion Centre The Faraday Institution - CATMAT - FutureCat - LCA Modelling - LiStAR - Multi-scale Modelling - Nextrode - ReLiB	Britishvolt Faradion Ilika Johnson Matthey Tevva UKBIC Williams Advanced Engineering

1.0 Overview

1.1. Battery Market Overview

The global demand for lithium-ion batteries is forecast to be 3 TWh by 2030, predominantly due to the growth of the transportation sector and the proliferation of EV technology.

Lithium ion battery demand: 2020–2030

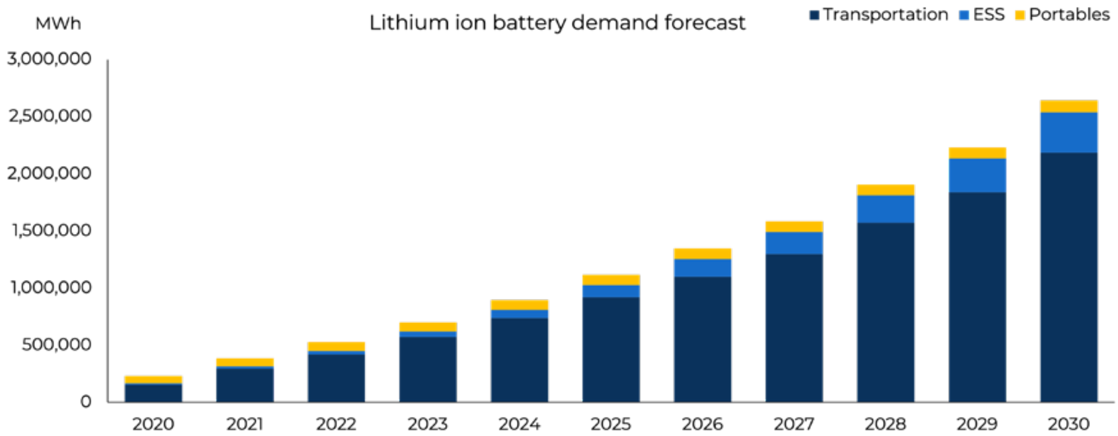


Figure 1: Lithium ion battery demand: 2020-2030 **Source:** Benchmark Mineral Intelligence

Battery manufacturing capacity continues to grow in Europe and the US. Worldwide, there are more than 200 "Megafactories" which are >1 GWh scale battery production facilities, with 149 (75%) located in China.

Battery demand foundations continue to expand in number, scale and geography

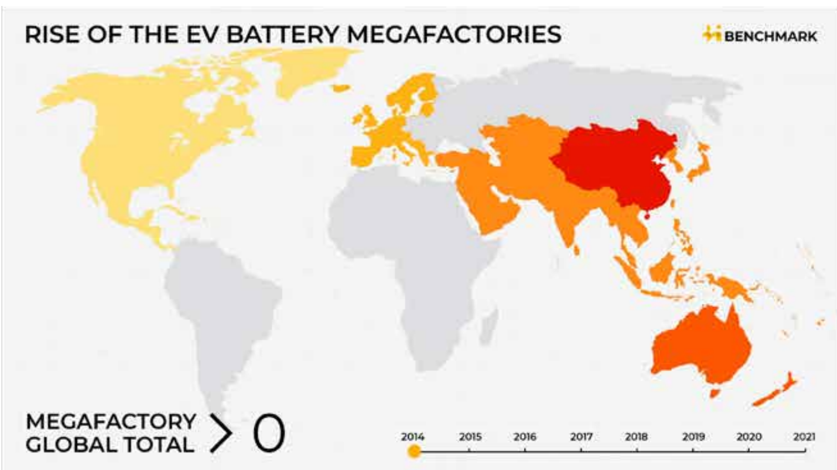


Figure 2: Rise of the EV battery megafactories **Source:** Benchmark Mineral Intelligence

This rapid growth in global demand will place significant strain on raw materials markets such as lithium, cobalt, nickel and graphite. Due to the sheer scale of raw material consumption, each gigafactory would need a new facility in each supply chain input area such as refining, extraction and mining. Therefore, there is a shifting priority to securing these supply chains to account for the volume of material required per gigafactory.

Figure 3: How much raw material does a 30GWh NCM Li-on gigafactory consume? **Source:** Benchmark Mineral Intelligence

These components are not established commodity markets (except for nickel) but rather specialist mineral markets. Many of these are forecast to grow exponentially by 2030, which means their market structure and scale of production will change significantly in a short space of time. The development and growth of battery technology is highly dependent on the responsiveness of these raw material markets and is a key challenge that needs to be addressed. Increased raw material supply generated from battery recycling will be vital to alleviate supply chain issues in the future as well as reducing reliance on primary extraction of critical raw materials.

If all of the world's planned gigafactory projects are successfully developed, a 14% CAGR is expected, and structural imbalances are already starting to occur. For example, since late 2021, lithium prices have already increased 300%–400%.

By the mid-2020s, the lithium deficit will be as large as the whole 2015 market. By 2030, Benchmark Mineral Intelligence forecasts a deficit of 600,000 t (best case) or 1.7 mt (worst case).

A decade of perpetual change lies ahead for critical battery inputs

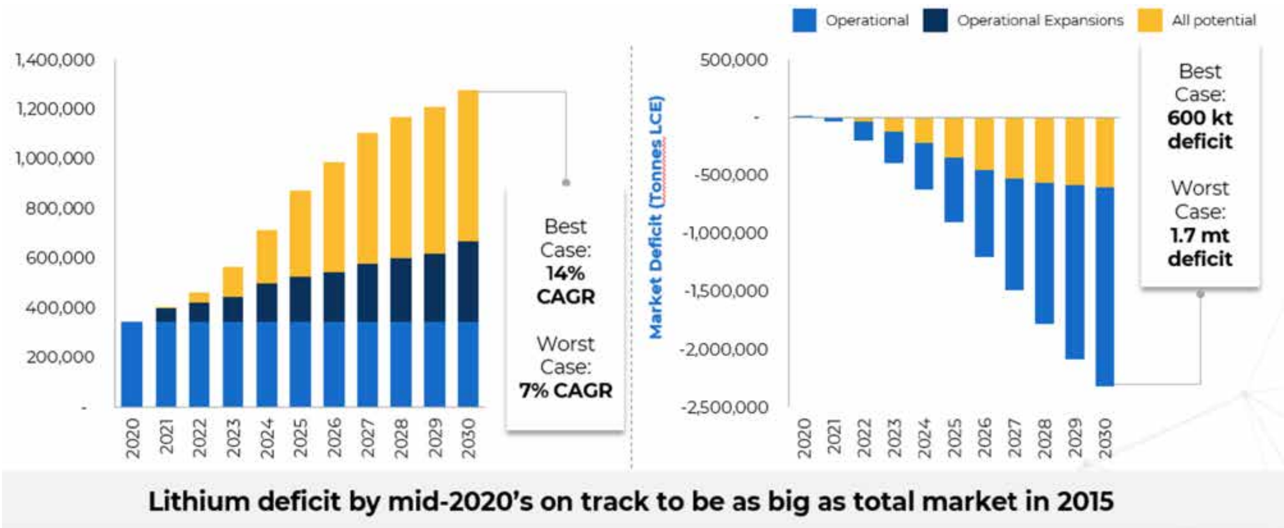


Figure 4: A decade of perpetual change lies ahead for critical battery inputs **Source:** Benchmark Mineral Intelligence

Supply disruption is not exclusive to lithium and will affect each of the raw materials markets in different ways with regards to the location, extraction, and chemical processing of the material. Thus the resulting CAPEX requirements for these upstream markets will be huge in order to sustain the downstream battery and EV markets. The skills deficit relating to the deployment of new technologies around the globe also presents a challenge for the market.

Sustainability credentials and localisation are both important factors. There is considerable lead time for battery development and application, with the longest timelines for deployment being at either end of the life cycle (mining and application).

Availability issues compounded by sustainability, localization and qualification timelines

Figure 5: Availability issues compounded by sustainability, localisation and qualification timelines **Source:** Benchmark Mineral Intelligence

1.2 Battery Electric Vehicles in the UK

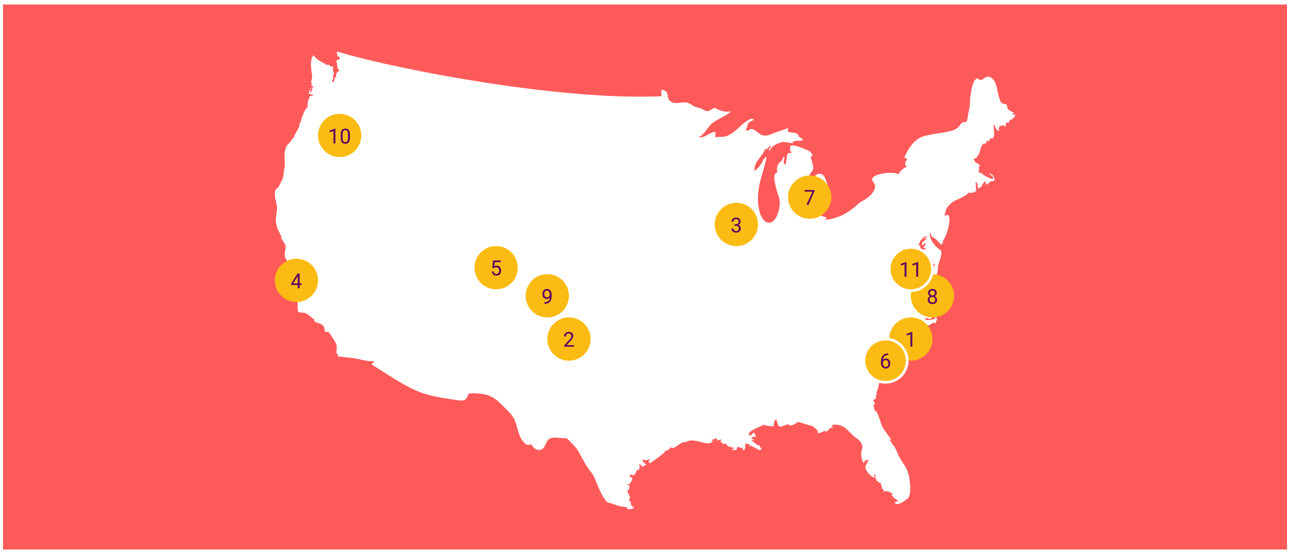
The UK battery electric vehicles (BEVs) market is dynamic and rapidly evolving to comply with direct and in-direct legislation. One such example is the Brexit trade deal on electric vehicles (EVs) and batteries, with major implications for the automotive industry. Effective from 1 January 2021, the Trade and Cooperation Agreement (TCA) stipulates Rules of Origin for traded goods between the EU and UK, which can be carried out with zero tariffs if the goods originate in the UK. The TCA drives for localisation of the battery supply chain as by 2027, the battery pack, cells and cathode active materials must be produced or manufactured locally in order to circumvent an applied 10% tariff to the BEV[1].

With 80% of cars made in the UK exported, mostly to the EU, European battery demand is set to grow significantly by 2030 to 800-900 GWh (approximately 30% of global demand), meaning the UK needs to increase its production capacity to 90 GWh (11% of European demand)[2].

The UK's current capacity is 2 GWh per year at Sunderland, and the projected Britishvolt gigafactory in Blyth will have 30+ GWh capacity. Whilst there has been a real focus on cathode active materials due to increasing domestic production capacity and incoming regulation, capacity for other key battery materials such as anode active materials, battery electrolytes and separators must also be addressed. These shifting priorities are also observed in the electrified transport sector in the US.

1.3 Landscape Maps of Technology and Stakeholders in Partner Country

Selected US battery technology stakeholders



	Organisation	Type	Location
1	Department of Energy (DOE)	Government Body	Washington, D.C.
1	Department of Energy, Office of Energy Efficiency & Renewables Energy (EERA)	Government Body	Washington, D.C.
1	Department of Energy, Vehicle Technologies Office (EERE/VTO)	Government Body	Washington, D.C.
1	Department of Energy, Advanced Manufacturing Office (EERE/AMO)	Government Body	Washington, D.C.
2	National Renewable Energy Laboratory (NREL)	Research Programmes & Organisations	Golden, CO
3	Argonne National Laboratory	Research Programmes & Organisations	Lemont, IL
4	Lawrence Berkeley National Laboratory	Research Programmes & Organisations	Berkeley, CA
5	Idaho National Laboratory	Research Programmes & Organisations	Idaho Falls, ID
6	Pacific Northwest National Laboratory	Research Programmes & Organisations	Richland, VA
7	United States Advanced Battery Consortium (USABC)	Industry Organisations & Facilities	Southfield, MI
8	6K	Industry Organisations & Facilities	North Andover, MA
9	Solid Power	Industry Organisations & Facilities	Louisville, CO
10	OnTo Energy	Industry Organisations & Facilities	Bend, OR
11	Nth Cycle	Industry Organisations & Facilities	Beverly, MA

Selected UK battery technology stakeholders

	Organisation	Type	Location
1	Department for Business, Energy & Industrial Strategy (BEIS)	Government	London
1	National Physical Laboratory (NPL)	Research Programmes & Organisations	Teddington
1	Imperial College London	Research Programmes & Organisations	London
1	University College London (UCL)	Research Programmes & Organisations	London
1	Tevva	Industry Organisations & Facilities	Tilbury
2	Innovate UK	Government	Swindon
2	Faraday Battery Challenge	Government	Swindon
2	Williams Advanced Engineering	Industry Organisations & Facilities	Wantage
3	The Faraday Institution	Research Programmes & Organisations	Harwell
3	University of Oxford	Research Programmes & Organisations	Oxford
4	University of Birmingham	Research Programmes & Organisations	Birmingham
4	Warwick Manufacturing Group (WMG)	Research Programmes & Organisations	Warwick

5	University of Sheffield	Research Programmes & Organisations	Sheffield
5	Faradion	Industry Organisations & Facilities	Sheffield
6	Ilika	Industry Organisations & Facilities	Southampton
7	Johnson Matthey (Research Centre)	Industry Organisations & Facilities	Reading
8	Britishvolt	Industry Organisations & Facilities	Blyth
9	Advanced Propulsion Centre (APC)	Industry Organisations & Facilities	Coventry
9	UK Battery Industrialisation Centre (UKBIC)	Industry Organisations & Facilities	Coventry
10	Centre for Process Innovation (CPI)	Industry Organisations & Facilities	Redcar

2.0 National and Industry Priorities

2.1 Relevant Policies and Stimulus Programmes in the US

The US Government has committed to a 100% clean energy electricity grid by 2035 and a net zero transport sector by 2050. As a key enabling technology, global battery demand and manufacturing capacity is forecast to skyrocket, with investment into manufacturing capacity running into the tens of billions of dollars in the US alone.

The Biden Administration has issued two documents that acknowledge this trend.

The first, Executive Order 14017: America's Supply Chains: Supply Chains for High-Capacity Batteries, acknowledges the priority issues for the US.

Upstream	• US vulnerability for mineral refining and processing • Global shortage of Class I nickel, lithium and cobalt supply
Midstream	• US has less than 10% of global manufacturing capacity for anode, electrolyte and separators • Cathode and anode manufacturing capacity lacking
Downstream	• Demand is below the levels to justify investment in local manufacturing • Pushback on waste generation and increase recycling capability

This set out key goals to acknowledge these challenges:

- Create an estimated 450 GWh of battery demand by electrifying federal, state and local purchases of vehicles and buses
- Invest in mineral-specific strategies
- Establish a National Recovery and Recycling Policy

The second related document is the Bipartisan Infrastructure Law (BIL), a piece of legislation passed by Congress celebrated as a "once-in-a-generation investment in American infrastructure and competitiveness" containing approximately $1.2 trillion in spending. Combined with the President's Build Back Framework, it will add on average 1.5 million jobs per year for the next ten years.

It contains several stimulus programmes to address the identified challenges in the market:

- Battery Material Processing Grants[3]: $3 billion total over 5 years
- Battery Manufacturing and Recycling Grants[4]: $3 billion total over 5 years
- Lithium-ion Battery Recycling Prize Competition[5]: $10 million total
- Battery and Critical Mineral Recycling: Battery Recycling Research, Development and Demonstration Grants[6]: $125 million total over 5 years
- Electric Drive Vehicle Battery Recycling and Second Life Applications Program[7]: $200 million total over 5 years

The emphasis on battery technology research and development (R&D) is as follows:

1. Accelerate lithium metal battery R&D
   Reduce the cost of EV battery cells by 50% to less than $60 per kWh to achieve EV cost parity with ICE vehicles by 2030
2. Accelerate next-generation lithium-ion
   Develop and scale-up no cobalt, no nickel cathodes.
   Develop and scale-up silicon-based anodes
3. Expand lithium battery recycling R&D
   Establish a lithium battery recycling ecosystem to recover metals and reintroduce 90% of key materials into the supply chain by 2030

The US Department of Energy (DOE) is primarily responsible for funding many of the incentivisation schemes to achieve these goals through the following offices:

- Office of Energy Efficiency & Renewable Energy (EERE)
  - Vehicle Technologies Office (EERE/VTO)
  - Advanced Manufacturing Office (EERE/AMO)
- Advanced Projects Research Agency - Energy (ARPA-E)
- Office of Electricity (OE)

Department of Energy (DOE) National Laboratories

The Department of Energy (DOE) funds 17 National Laboratories around the United States with the mandate to “tackle the critical scientific challenges of our time”. Many of them have capabilities that are found nowhere else in the world.

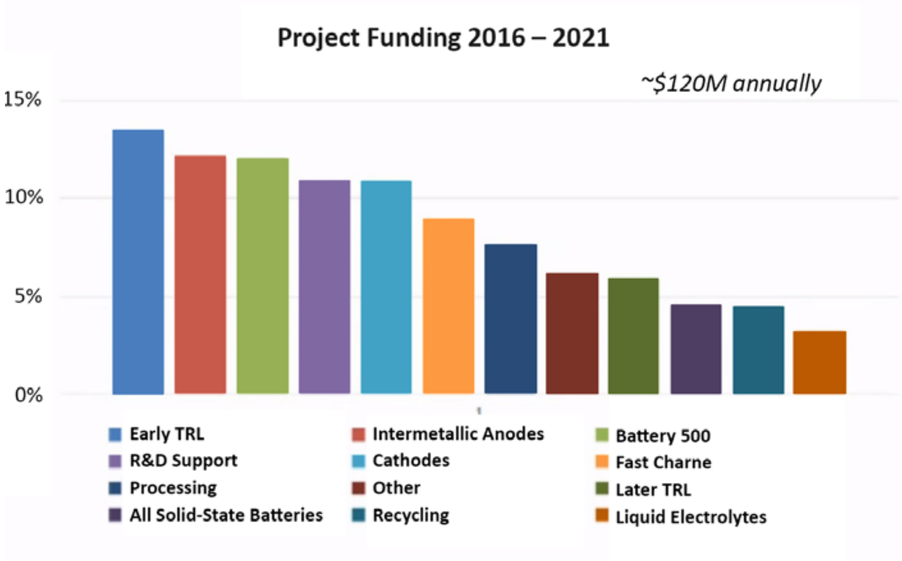
Whilst many of the labs conduct energy storage research, the following labs have notable programmes:

- National Renewable Energy Laboratory (NREL)
- Argonne National Laboratory
- Lawrence Berkeley National Laboratory
- Idaho National Laboratory
- Pacific Northwest National Laboratory
- Oak Ridge National Laboratory

Project Portfolio

The DOE/EERE/VTO battery R&D project portfolio totals approximately $120 million annually in the form of Funding Opportunity Announcements (FOA) that any US organisation can lead and Lab Calls that only DOE National Labs can lead (although they can involve other organisations).

Project Portfolio of DOE/EERE/VTO Batteries R&D



Early TRL	13.4%
Intermetallic Anodes	12.1%
Battery 500	12.0%
USABC & Testing	10.9%
R&D Support	10.9%
Cathodes	10.8%
Fast Charge	8.9%
Processing	7.6%
Other	6.2%
Later TRL	5.9%
All Solid-State Batteries	4.5%
Recycling	4.4%
Liquid Electrolytes	3.2%

Figure 6: Project portfolio of DOE/EERE/VTO batteries R&D **Source:** US Department of Energy (Peter Faguy)

Ninety four per cent of the portfolio is early-mid stage where there is opportunity for collaboration, with only 6% of the portfolio at later stage where IP issues are a concern.

Battery Materials Research (BMR)

Some of the EERE's Battery Materials Research areas of focus align well with the UK's interests. These include:

- Lithium metal
- Sulphur electrodes
- Modelling
- Sodium-ion
- Solid-state

Charter

Research new, high-capacity materials that are affordable and promote a safe, high-energy cell design. Present emphasis on sulfur, solid electrolytes and lithium.

Issues

- Li Metal: High reactivity and dendrite growth
- Sulfur: Polysulfide shuttle and poor utilization
- Solid-State Electrolytes: Low ionic conductivity and high interfacial resistance

Approaches

✓ Engineer a host and/or an artificial SEI layer to protect lithium surface
✓ Design novel structures to encapsulate polysulfides
✓ Investigate new, low-cost and conformal solid-state electrolytes
✓ Develop advanced modeling and characterization techniques to investigate the reactivity in the interphases and at interfaces

Participants:
National Labs (7), Academia (13), Industry (3)

Topic Area	Projects
Modeling	12
Diagnostics	8
Polymer and Solid-State Electrolytes	13
Metallic Lithium	6
Sulfur electrodes	5
Air Electrode/Electrolyte	3
Sodium-ion Batteries	4
Total	51

Figure 7: Battery Materials Research **Source:** US Department of Energy (Peter Faguy)

Lithium-ion Battery Recycling Prize

Recycling is recognised as important for sustainable stewardship but also as a good source of materials input for the US battery supply chain. The US Lithium-ion Battery Recycling Prize focuses on identifying innovative solutions for collecting, sorting, storing, and transporting spent and discarded lithium-ion batteries. These can be sourced from electric vehicles, consumer electronics or stationary applications for recycling and materials recovery.

The prize is a $5.5 million phased competition designed to incentivise American entrepreneurs to contribute to DOE's goal of capturing 90% of all spent Li-ion batteries, for eventual recycling of critical materials and reintroduction into the supply chain.

The first round of this DOE-funded programme was split into three phases:

Phase 1: Concept development and incubation ($1 million). COMPLETE
Phase 2: Prototype and partnering ($2.5 million). COMPLETE
Phase 3: Pilot validation ($2 million). ONGOING
- Six projects selected are a mixture of second use, sorting, and even a digital marketplace between recycling companies

The second round of the Battery Recycling Prize has had $10 million authorised and the design process is underway. It will be a US-only prize, so any entrants must have a US incorporated business entity.

Federal Consortium for Advanced Batteries (FCAB)

The Federal Consortium for Advanced Batteries (FCAB) consists of 17 federal agency members, representing 40-50 offices with a stake in the high capacity battery supply chain.

The National Blueprint for Lithium Batteries 2021-2030[8] (published June 2021) outlines key levers for federal levers for “domestic or resilient” supply chain (with international collaboration recognised as a crucial component).
The FCAB has five goals:

1. Access to materials: Secure access to raw and refined materials and discover alternatives for critical minerals for commercial and defence applications.
2. Materials processing: Support the growth of a US materials-processing base able to meet domestic battery manufacturing demand.
3. Cells/packs: Stimulate the US electrode, cell, and pack manufacturing sectors.
4. Recycling: Enable US end-of-life reuse and critical materials recycling at scale and a full competitive value chain in the US.
5. Innovation: Maintain and advance US battery technology leadership by strongly supporting scientific R&D, STEM education, and workforce development.

Li-Bridge

Led by Argonne National Laboratory, Li-Bridge is a public-private alliance committed to accelerating the development of a robust and secure domestic supply chain for lithium-based batteries.

Demand for batteries will be driven by EV growth but also the net-zero grid. The US will need 10+ TWh of dispatchable energy storage to achieve net zero, reducing to 2-4 TWh with more interconnectors between states and US regions.

However, the US is behind in cell manufacturing capacity, with China dominating (see Figure 8).

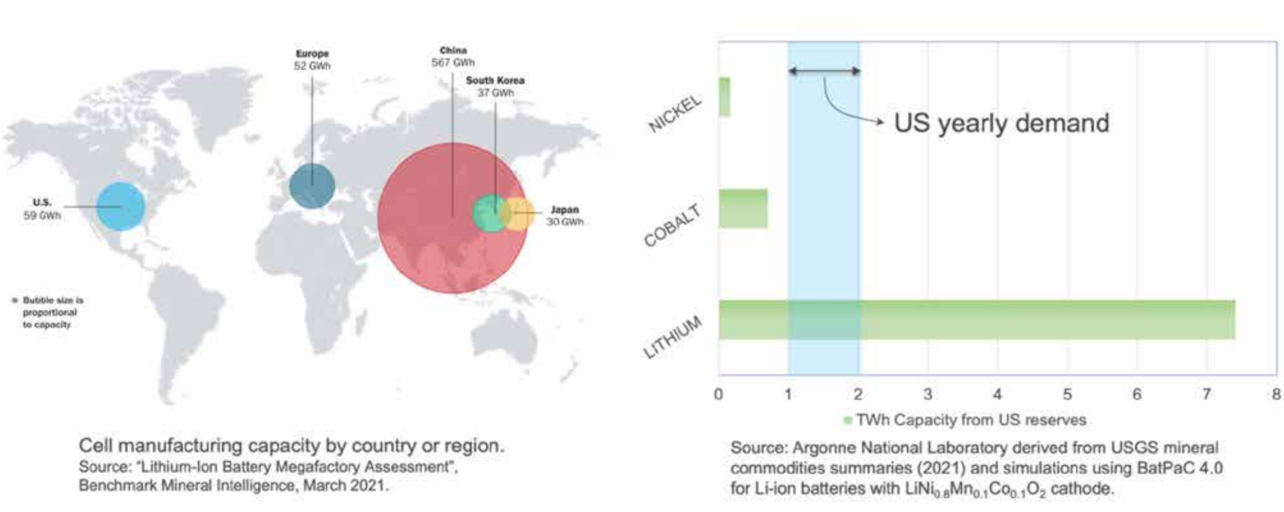


Figure 8: Cell manufacturing capacity by country or region **Source:** Li-Bridge

The innovation required includes 1) increasing material supply, 2) expanding recycling, and 3) discovering substitute materials. Grid storage will diverge from vehicle storage, but Li-ion will "continue to play an outsized role".

The US has more than 600 companies working in this area, so Li-Bridge was set up as a National Energy Storage public-private partnership (PPP) to create an innovation ecosystem that can bridge the lithium-ion battery supply chain gap.

Li-Bridge identifies challenges and creates plans to address them but does not provide funding. The Boston Consulting Group (BCG) has been engaged to help develop the roadmap.

Li-Bridge will organise a series of forums in 2022:
- Recycling
- Battery materials
- Cells/packs
- Minerals/refiners
- Other key topics (the large military demand is a significant factor)

Advanced Research on Integrated Energy Systems (ARIES): Energy storage

ARIES is a research platform, hosted at NREL, developed with DOE and DOE EERE to support the American transition to a decarbonised energy system.

ARIES is able to match the complexity of the modern energy system, with physical hardware capability allowing research at the 20 MW level (renewable energy generation, energy storage, and typical demand devices). This represents a substantial scale-up in experimentation capability from existing research platforms, which is amplified by a virtual emulation environment powered by NREL's 8-petaflop supercomputer.

ARIES has five key research areas:
- Energy storage
- Power electronics
- Cybersecurity
- Hybrid energy systems
- Future energy infrastructure

ARIES benefits from strong collaboration across the DOE National Laboratory network, which helps run experiments in high fidelity.

Battery500 Consortium

The Battery500 consortium is one of the most important battery research programmes in the US and works to address the fundamental challenges of rechargeable lithium metal batteries. Battery500 is working to develop next-generation lithium metal anode cells with energy density progressing to the 500 Wh/kg level (hence the name).

Led by Pacific Northwest National Laboratory (PNNL), this programme consists of four National Laboratories, eight universities and the vehicle OEM General Motors (GM), as well as an Industrial Advisory Board. Two notable members of the consortium are Professor Stanley Whittingham (Binghamton University) and Professor John Goodenough (the University of Texas at Austin), who received the 2019 Nobel Prize in Chemistry for their work in Li-ion batteries.

In the Battery500 consortium there are three keystone projects:
- Materials and interfaces
- Electrode design
- Cell design, fabrication and integration

Achievements include:

- The establishment of a patent portfolio that has been licensed to nine industrial organisations
- A number of papers and articles in scientific journals that advance fundamental lithium metal research
- A leading safety protocol for pouch cell research in the lab that was published for wider industry.

Vehicles Technology Office (VTO) Cathode Projects

Cathodes are an important focus of innovation as 51% of manufactured EV cell costs are down to the cathode materials alone. A typical 100 kWh pack has approximately 8-10 kg of cobalt, which has a complex supply chain, including unregulated and informal aspects relating to artisanal mining, where human rights issues and abuses of power may go unchecked.

There are many projects focused on low/no cobalt approaches in the VTO portfolio, such as:

- Realizing Next-Generation Cathodes (RNGC) led by Argonne National Lab
- Goal: To understand the role of cobalt in these materials and find replacement strategies
  - Engineered surface (particle surfaces that are more stable)
  - Develop electrolytes
- Cation Disordered Rock Salts as Cation Active Materials (DRX) led by Lawrence Berkeley National Laboratory (LBNL)

Additional low/no cobalt cathode material projects funded by VTO included:

Additional VTO Projects on low or No Co Cathode Materials

Seven FAO awarded projects with 25 team members from academia, national labs and industry.

PROJECT	LEAD	TEAM	CATHODE CHEMISTRY	INNOVATIVE APPROACH
Aerosol Manufacturing Technology for Production of Low Cobalt Li-ion Battery Cathodes	Cabot	CABOT, Argonne, SAFT	*Disordered rocksalt TMOs & NCMs*	Implement structural and morphological modifications through flame spray particle production process.
Co-Free Cathode Materials and Their Novel Architectures	UCSD	UC San Diego, TEXAS, ARL, TESLA	*LNMO spinels*	Realize novel thick electrode architecture and develop new electrolyte formulations.
Enhancing Oxygen Stability in Low Cobalt Layered Oxide Cathode Materials	UCIrvine	UCIrvine, Berkeley, Virginia Tech, Pacific Northwest, American Lithium Energy	*High Ni, low Co NCMs*	Develop a novel hierarchical surface and bulk (3D) doping targeting oxygen loss and interfacial stability.
Novel Lithium Iron and Aluminum Nickelate (NFA) as Advanced Cobalt-Free Cathode Materials	ORNL	Oak Ridge, XALT Energy, NISSAN	*NiFeAl TMOs*	Optimize structure and scale-up production of these novel CO-free cathode materials.
High Nickel Cathode Materials for High-energy, Long-life, Low-cost Lithium-ion Batteries	UTAustin	TEXAS, NREL, TESLA	*High Ni, low Co NCMs*	Overcome the challenges of high-Ni layered cathodes through elemental doping and new electrolyte formulations.
Cobalt-Free Cathodes for Next Generation Li-Ion Batteries	Nexceris	NEXCERIS, NAVITAS, The Ohio State University	*LNMO spinels*	Develop surface passivation layers on the oxide surfaces to stabilize the electrochemical interface and enhance cycle and calendar life.
High-Performance Low Cobalt Cathode Materials for Li-ion Batteries	PSU	PennState, Pacific Northwest, Oak Ridge	*High Ni, low Co NCMs*	Achieve interfacial stability through inorganic and organic modification of the oxide surface.

Figure 9: Additional VTO projects on low or no cobalt cathode materials **Source:** Lawrence Berkeley National Labs

21st Century Truck Partnership (21CTP)

21CTP is a programme to decarbonise transport, focusing on the electrification of medium-heavy-duty vehicles funded by the VTO. To achieve net zero by 2050, the US requires significant emissions reductions throughout its transport system. These can be achieved with efficiency improvements and a 100% clean energy grid.

On-road vehicles (light, medium, heavy) account for 83% of energy use and can be electrified, whereas long haul freight and air, marine and rail will probably require the use of hydrogen and biofuels. Focusing on HGVs is important not only because of the beneficial impact on emissions but also their role in the economic health of the US.

21CTP is a PPP formed in 2001 that provides a framework for strategic and deep technical engagement between industry and government experts, acting as a forum for pre-competitive technical information exchange among partners to:

- Discuss R&D needs
- Develop joint goals and technology roadmaps
- Evaluate R&D progress for a broad range of technical areas

21CTP helps the DOE to focus funded R&D programmes on high-risk barriers to commercialisation, avoids duplication of OEM effort and accelerate progress towards decarbonisation. 21CTP boasts impressive industry engagement and is organised into Technical Teams (i.e. working groups) that include:

- Internal combustion powertrains
- Electrified powertrains
- Freight operational efficiency
- Safety

Another related programme run by the VTO is US DRIVE (Driving Research and Innovation for Vehicle efficiency and Energy sustainability), a non-binding and voluntary PPP focused on the interface between automotive and related energy infrastructure R&D. This provides a similar forum for the vehicle OEMs to coordinate efforts with vehicle fuel and electricity companies.

Behind-the-Meter Storage

NREL is leading efforts to approach the need for Behind-the-Meter Storage from a whole systems perspective.

By taking into account demands on the grid from aggressive targets for EV requirements (such as the VTO fast-charging target of 200 miles in 10 minutes or less), NREL is assessing the requirements for distributed energy storage and investigating appropriate battery chemistries to deliver them.

Machine Learning for Life Prediction and Cell Design

Idaho National Laboratory is delivering a world-leading project to address the related challenges of battery testing, life prediction and cell design.

Battery testing is time-intensive, and so is the process of co-optimising design for life and cost. A human expert usually makes life predictions, but Idaho has found a way to use machine learning (ML) algorithms to move through 15-20 regression models focusing on calendar life.

The algorithm can predict performance with twice the accuracy of a typical human, saving a month of labour on average. Uses of ML such as this will provide insights on cell design and usage guidelines to mitigate ageing.

Using 26,000 synthetic data sets able to rapidly aid classification of failure modes has been combined with other ML and modelling work to yield an ageing mode-informed lifetime prediction framework. They have implemented a deep learning (DL) framework that leverages an incremental capacity model and high-fidelity model for different chemistries.

Capacity and Loss of lithium inventory (LLI) can now be successfully predicted based on limited cycling data with less than 4.6% error.

ReCell Centre

Led by Argonne National Laboratory in collaboration with NREL, Oak Ridge National Laboratory and several American universities, ReCell is a VTO-funded project to decrease the cost of recycling lithium-ion batteries to ensure a future supply of critical materials and decrease energy usage compared to raw material production.

ReCell's focus areas include:
- Direct cathode recycling
- Design for sustainability
- Other material recovery
- Modelling and analysis

They have developed a free online model called Everbatt that allows people to see the value of their design decisions at various stages of a battery's life cycle.

ReCell hosted an Industry Collaboration Meeting in November 2019 with 134 people from 76 organisations; stakeholders from the entire vehicle battery value chain. They had visitors from the UK but would like more at the next one.

Lithium-ion Battery Resource Assessment Model (LIBRA)

Developed by NREL, the Lithium-ion Battery Resource Assessment Model (LIBRA) is a system-dynamics model that evaluates the economic viability of the battery manufacturing, reuse, and recycling industries across the global supply chain under differing dynamic conditions.

By characterising the full circular economy pathway for batteries, LIBRA aims to reduce waste in a way that strengthens the Li-ion battery manufacturing and recycling supply chain. As such, anyone can access the model and examine activity.

Arguably the most important function of the model is the sensitivity analysis, which shows that up to 80% of materials for American EV battery manufacturing could be met by the cobalt and nickel recycling industry. However, this will reduce over time as chemistries change and cobalt content is reduced (e.g. increased uptake of LFP battery chemistry).

2.2 Relevant Policies and Stimulus Programmes in the UK

The Department for Business, Energy & Industrial Strategy (BEIS)

The UK government is legally committed to carbon reduction, targeting net zero emissions by 2050. The way this is planned is via a carbon budgeting process. The current Sixth Carbon Budget requires an economy-wide transformation, which has resulted in the creation of the Net Zero Research and Innovation Framework[9].

Faraday Battery Challenge

Transport accounted for 22% of emissions in 2019 (CCC), with cars and vans making a major contribution. Given that cars have an approximate lifetime of 15 years and that the UK needs to eliminate exhaust emissions by 2035, battery electric vehicles (BEVs) are key to achieving this with the technology matured for commercial development. The projected growth in BEVs means that the UK will need 7 or 8 gigafactories by 2040 to cope with domestic battery demand.

UK Research and Innovation (UKRI) is a non-departmental government body sponsored by BEIS which spans Innovate UK and the Engineering and Physical Sciences Research Council (EPSRC). These are two of nine organisations responsible for deploying UK government support into industrial innovation and academic research respectively.

The Faraday Battery Challenge (FBC) was launched as part of the Industrial Strategy Challenge Fund and is run through Innovate UK, to ensure the UK can prosper from a just and fair transition to an electrified economy.

With an investment of £330 million between 2017 and 2022, the FBC aims to support world-class scientific, technology development and manufacturing scale-up capability for batteries in the UK.

Specifically, the funding is allocated across three main pillars:

- £98 million: Collaborative R&D
- £113 million: UK Battery Industrialisation Centre
- £108 million: The Faraday Institution

As well as supporting research, industry, and skills development, the FBC is also seeking to join up ecosystems (through the Innovate UK KTN's Battery Systems Innovation Network[10]) and address standardisation gaps (through the BSI Faraday Battery Challenge Standards Programme).

Collaborative R&D

Through Innovate UK, over £90 million has been awarded competitively to UK businesses for feasibility studies and collaborative research and innovation projects to develop new and improved cost-effective battery technologies and catalyse the building of future UK battery supply chains.

To date over 81[11] projects and 149 organisations have been supported, as well as the creation of over 500 high skilled jobs.

UK Battery Industrialisation Centre (UKBIC)

The UK Battery Industrialisation Centre (UKBIC) is an open-access scale-up facility opened in September 2021 for UK businesses to bridge the gap from battery R&D to mass production. Focusing on TRL7+ (sometimes TRL5), UKBIC allows businesses in the UK (and those looking to expand into the UK) to eliminate the need to invest in a £100+ million CAPEX facility during product development.

UKBIC allows technology developers to fill the gap between laboratory-scale R&D and real-world mass manufacture. Their scale-up programme allows companies of all sizes to rapidly move new battery technologies to market.

Key facts:

- 20,000 square metre manufacturing research facility outside Coventry
- Manufacturing capability for battery electrodes, cells, modules and new pack structures at industrial rates
- Takes no intellectual property - all foreground IP generated will remain with the developer

The Faraday Institution

The Faraday Institution (FI) is the UK's independent institute for electrochemical energy storage research, skills development, market analysis and early-stage commercialisation. It is a key delivery partner for the Faraday Battery Challenge to bring forward bold and transformational change in application-inspired battery research. Since the launch of its research programme in 2018, the FI has assembled a unique community in a nationally distributed model: 500+ university researchers from various fields from 27 UK universities, committed industry partners, and technology business development specialists.

The three main research streams are:

1. Lithium-ion
   - Nearer term market challenges (SoTA and just beyond)
   - Projects presented at the summit include FutureCat, CATMAT, Multi-scale Modelling, ReLiB and Nextrode
2. Beyond Lithium-ion
   - Promising chemistries that could open up new technologies (such as the LiSTAR project)
3. Batteries for Emerging Economies
   - Funded through the Foreign Commonwealth and Development Office's Transforming Energy Access programme

Key to the Institution's mission is the need to maximise the UK economic impact of research. To support the evaluation of risk and reward in a research portfolio, the TSCAN tool was developed to assess appropriate commercialisation routes for relevant projects.

LiSTAR (Lithium Sulphur Technology Accelerator)

LiSTAR is a £7.5 million project, funded by the Faraday Institution and led by UCL, to develop an attractive candidate for a post-Li-ion chemistry: lithium sulphur (Li-S). It is a broad consortium of eight UK universities alongside industrial partners.

Li-S is a promising next generation chemistry, which is comparatively mature to rivals and will theoretically achieve better performance than incumbent Li-ion batteries. It is important to research alternatives to Li-ion batteries to achieve higher performance batteries which can enable electrification of difficult to electrify sectors with high performance requirements, such as aerospace.

FutureCat

FutureCat is a £9.9 million project, funded by the Faraday Institution and led by the University of Sheffield, to discover, design and develop next-generation cathodes for Li-ion batteries. FutureCat is a consortium of UK universities and institutions plus eight industrial partners (including Rolls Royce, Johnson Matthey and QinetiQ) that acts as a strategic advisory board.

Cathode materials are highly important topics as cathodes are responsible for the largest share of cost in modern cells (47% on average). Raw materials represent 86% of the average cost of overall battery manufacture.

FutureCat has six highly-integrated workstreams:

1. Electrode longevity (coatings, additives, interfaces)
2. Electrode resilience (mechanical testing)
3. Standard testing protocols (collaborate with NPL)
4. Extending existing chemistries (new architectures)
5. Novel material by informed design (computationally-driven discovery)
6. Materials discovery (no/low cobalt alternatives)

Much like US initiatives such as the United States Advanced Battery Consortium (USABC), FutureCat has a strong focus on connecting to industry targets. One of the main success criteria is the delivery of at least one new cathode material from lab to industry partner. Collaboration with USABC and others will open up new opportunities for sharing industrial challenges and learnings around IP generation.

CATMAT

CATMAT is an £11 million project funded by the Faraday Institution led by the University of Oxford and the University of Bath, backed by universities and research institutions alongside twelve industry partners, to develop next-generation Li-ion cathode materials.

Currently, NMC (nickel-manganese-cobalt) is the dominant cathode chemistry, but there is an industry push to reduce cobalt content, improve energy density and lower costs.
The CATMAT programme focuses on three main work packages:

1. Understand high energy density cathodes
2. Materials scale-up and cell design
3. Materials discovery and synthesis

Research highlights include:
- Materials scale-up of Ni-rich NMC (to higher TRL).
- The study of new disordered rock salts towards high energy density (>250 mAh/g)
- New insights into lithium rich cathodes

Nextrode

Nextrode is a £12 million research project, funded by the Faraday Institution and led by the University of Oxford, to improve battery performance by investigating and advancing the science of electrode manufacture.

Today, all electrodes for mass-market Li-ion batteries are made by slurry casting. However, recent research at the laboratory scale has demonstrated that new manufacturing methods can produce "smart" electrodes with 30% more capacity and 50% lower degradation rates.

By improving our understanding of what happens during manufacture, we can move from trial and error to successfully exploiting electrochemical deformation, microstructure and intrinsic electrochemical properties. The work packages are as follows:

- WP1: Smarter particles
- WP2: Deposition and drying
- WP3: New electrode structures and manufacturing methods
- WP4: Structural characterisation and modelling
- WP5: Optimised AI/ML training datasets and digital manufacturing

Nextrode is creating new structures and the manufacturing processes to achieve them. For example, research and modelling show that varying the carbon intensity across the cross-sectional thickness of an electrode can create "smart electrodes" that have superior qualities to traditional electrodes. However, the typical slurry casting manufacturing process makes it challenging to manufacture these.

The picture below shows an innovative process explored by Nextrode to fabricate electrodes using spray deposition. This technique allows for materials to be mixed at different concentrations across the cross-section of the electrode. This is more flexible than a slurry and cheaper than vacuum deposition.

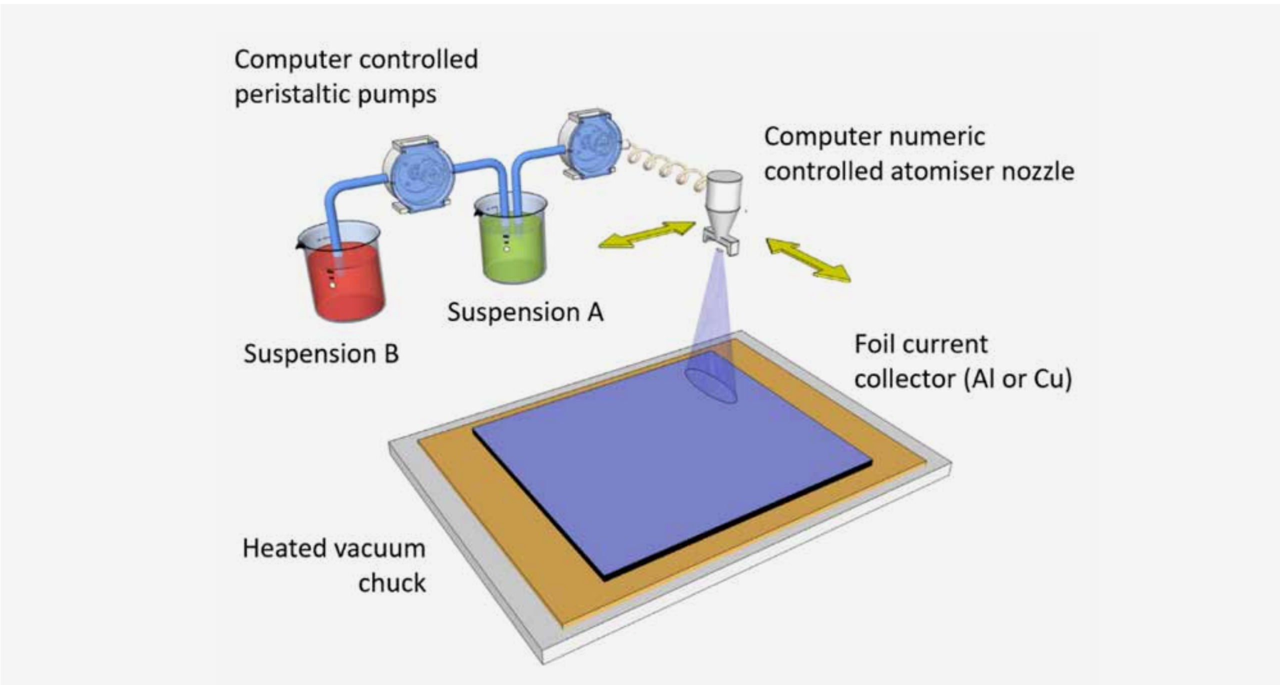


Figure 10: Micro-scale graded electrodes for improved Li-ion battery performance **Source:** C. Cheng et al.

ReLiB

ReLiB is a project, led by the University of Birmingham and funded by the Faraday Institution, which aims to develop alternative recycling routes that could provide UK businesses with a competitive advantage. Key activities include how to minimise time/cost when dismantling packs, efficiently recover high-value materials, minimise remanufacture cost, and design more recyclable EV batteries in the first place. ReLiB is pioneering processes at TRL 3 such as autonomously dismantling packs using robotics; using bacteria to bio-separate manganese, nickel and cobalt from battery leachates; recovery and reuse of graphite-SiOx; and ultrasonic fast delamination.

Lithium-ion Battery Multi-scale Modelling

Professor Gregory Offer of Imperial College is the Principal Investigator for the Multi-scale Modelling project, a £17.9 million programme of work funded by The Faraday Institution. The project has an extensive team spanning nine UK universities as well as working collaboratively alongside fourteen industrial partners.

The overarching objectives of the Multi-scale Modelling project are:

- Invent and validate more complete battery physics
- Exploit novel methods to design better devices
- Bridge the disparate modelling gaps
- Develop a common modelling framework
- Make the models trusted and usable by industry

The Multi-scale Modelling project is helping to create global collaborative communities, and some of the key achievements of the project so far are detailed below.

PyBaMM (Python Battery Mathematical Modelling) is an open-source battery modelling tool that promotes multi-institutional and interdisciplinary collaboration, by providing an open framework accessible to the battery modelling community. Contributors can share ideas and test user models to provide fast simulations and ensure the robustness of new battery models. The most recent training workshop had more than 400 attendees from all over the world, with the industry well represented.

LCA Modelling

Imperial College is leading a workstream of the Faraday Institution funded Multi-scale Modelling project that focuses on the life cycle analysis (LCA) of Li-ion batteries.

Sustainability is complex, especially for the many different electrode materials that exist and the life cycle itself. A consistent framework of definitions for sustainability is needed, especially to compare chemistries. Currently there is a focus on materials, but there are other factors which determine battery sustainability:

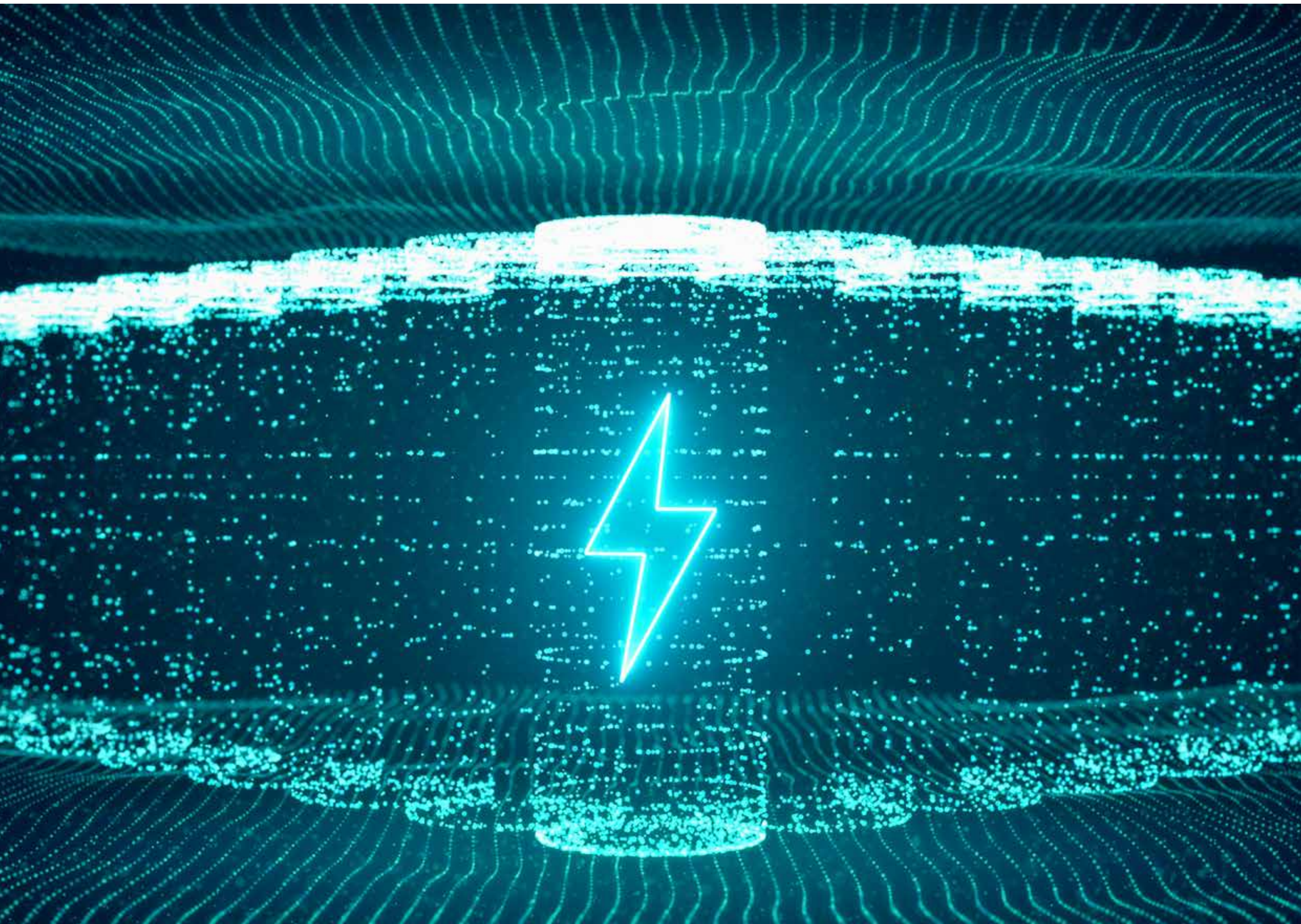
- Manufacturing
- Performance
- End-of-life (recycled or landfilled)
- Ease of dismantling
- "Airmiles" between supply chain nodes (mine, refinery, manufacture etc)

Understandably, there are trade-offs across the life cycle. However, we need to act fast as there will be over 30 gigafactories operational worldwide by 2030, leading to a looming “battery mountain”. Building a circular battery ecosystem will take time and is a critical activity, given that degraded batteries cannot be safely landfilled or stockpiled.

Environmental impacts during manufacture include chemical release, water use, habitat destruction, sulphur pollution and more. Refineries and recycling plants are found mainly in China, with gigafactories elsewhere. Increased localisation of refineries, production facilities and recycling plants will be needed to reduce these impacts.

Understanding degradation, thermal management and disassembly is ongoing, and outputs are being fed into work such as PyBaMM, a unique and versatile battery modelling package. There is a need for long-term strategic road mapping for recycling while battery volumes are low, to ensure battery recycling can keep pace with market growth.

DandeLiion is an ultra-fast solver for electrochemical models of Li-ion cells developed by the University of Southampton and the University of Portsmouth. It is a SaaS platform that solves models first described in the mid-90s, now commonly known as Newman models (and can be extended to new chemistries as they emerge).



About:Energy is a company jointly spun-out by the University of Birmingham and Imperial College London. About:Energy was set up to help commercialise the battery modelling capability developed by the Faraday Institution's Multi-scale Modelling Project. About:Energy facilitates the use of battery modelling by UK industry, increasing the speed of battery prototype development and giving technology developers a competitive advantage.

About:Energy partners with PyBaMM and DandeLiion to provide physics-based modelling tools to battery innovators to improve manufacturing, design and application. The company's core IP is battery testing and parameter extraction (based on a patent at Imperial College London and significant know-how at the University of Birmingham).

Breathe Battery Technologies is another research-led Imperial spin-out, developing advanced battery management software that provides deep insights into battery health. Customers and partners include Rimac, the Croatian manufacturer of electric hypercars, drivetrains and battery systems.

Advanced Propulsion Centre (APC)

The Advanced Propulsion Centre (APC) is a non-profit organisation jointly founded by the automotive industry and the UK government to fund low carbon vehicle R&D projects and bridge the gap between the UK's historical strength of creating new concepts but weakness in full commercialisation, manufacturing readiness and scale-up.

It manages the Automotive Transformation Fund (ATF), a £1 billion fund to help companies build industrial capital assets that will strengthen the EV supply chain (system design, batteries, power electronics), with finance provided by the Automotive Council and BEIS. Each project must have a route to market and a Tier 1 OEM partner.

The APC also runs a support programme for SMEs called the Technology Developer Accelerator Programme (TDAP), which provides funding and guidance to commercialise low TRL concepts and writes the automotive roadmaps for the UK (e.g. Battery Value Chain).

The APC also supports the drive to ease bottlenecks and gaps in the UK supply chain directly and by securing investment into the UK. For example, the APC is very focused on midstream battery materials supply (such as helping Phillips 66 adapt existing processes at a major plant that could help fill a gap in the UK's anode production).

2.3. Key Initiatives by Business Communities and Industry (US)

6K

6K is a Massachusetts-based advanced materials manufacturer that has developed a novel technology called UniMelt.

Both the UK and US are heavily reliant on China for elements of battery production (see table overleaf). This over-reliance on China not only means the supply chain is very fragile, but is a major concern given the fact that the US and China are competitors in the EV space.

China	85%	**Japan**	2%
Korea	8%	**UK**	0%
EU	4%	**US**	0%

Figure 11: Global Cathode Production **Source**: BNEF

Over 400 GWh of new cell production capacity by 2025 has been announced in the US in order to address booming EV demand, representing $125 billion of investment.

The challenge is that, with conventional production techniques, production of the relevant materials is 15%-20% more expensive than in China, even when factors such as economies of scale and transport efficiencies are included. To meet growing domestic demand, the US, therefore, needs disruptive innovations to compete with China.

6K's mission is to transform domestic battery material production to compete with China directly. They have an MIT-derived technology that uses the world's first and only high-volume microwave-derived plasma to deliver a range of metal powders that are essential in the manufacture of batteries.

These range across the energy supply chain, including:

- LTO anode
- Silicon anode
- Oxide cathode
- Solid-state electrolyte
- LFP cathode
- Recycled cathode

Using UniMelt's advanced plasma-based process yields many intriguing benefits:

- Significantly simplified process
- 95% reduction in process time, translating to 50%-60% cost reduction
- 90% water usage reduction
- Estimated savings of $500 per finished vehicle (assuming 100 kWh battery pack)
- Smaller plant CAPEX and footprint, meaning flexibility of location
- Chemistry flexibility (as new battery chemistries emerge, the process can be tweaked)

6K has launched 24/7 production with current capacity running at 800 t/year. Twenty-one customers across the supply chain are evaluating their technology.

Their first-generation plants are limited to 120 t/year of production, but their second-generation plants will have 500 t/year capacity.

Solid Power

Solid Power is a sulfide solid-state battery technology developer listed on the NASDAQ, with two vehicle OEMs as keystone investors.

They view sulfides as the most well-rounded materials to displace liquid electrolytes, although the main drawback is moisture sensitivity and the need for an inert atmosphere.

The manufacturing process is nearly identical to Li-ion, which will allow them to mitigate the high barriers to entry for new materials and benefit from faster commercialisation with reduced requirement of new battery manufacturing infrastructure.

United States Advanced Battery Consortium (USABC)

The United States Advanced Battery Consortium (USABC) is a subsidiary of USCAR (the United States Council for Automotive Research). It is a public-private partnership between DOE and vehicle OEMs (GM, Ford and Stellantis). USABC also collaborate with battery OEMs (e.g. LGChem had a series of programmes) and National Laboratories in the US.

USABC's activities include:

- Technology gap assessment
- Grant funding support for R&D projects
- Technology Assessment Program (TAP)
  - Evaluate a developer's existing or slightly modified cells or modules
- Technology Development Program (TDP)
  - R&D approach to develop an advanced energy storage system that surpasses USABC tech goals
- Testing support (guidelines and testing)

Current programmes

Technology Category	Developer	Technology Novelty	Timing (mo./ total mos.)	Cost ($M)
Low-Cost, Fast-Charge EV	Farasis	System -Ni-rich NCM cathode, coated anode, Fluorinated solvents	8/36	4.0
	Zenlabs	Pre-lithiation solutions for high SiOx anodes, and optimized cell designs	32/ 36	4.8
	WPI	Solvent-free electrode manufacturing	21/36	2.4
	Microvast	Development of cathode material, electrode, electrolyte additives	21/36	4.5
	EnPower TAP	Multilayered cathodes and anodes	8/9	0.4
	Nanoramic TAP	Neocarbonix™ polymer binder-free electrode technology	9/9	0.7
Beyond Lithium-Ion	ISS TAP	High energy density NMC cathode foil, Li metal anode	3/18	0.5
Materials	NanoGraf	Rapid commercialization of high energy Anode Materials	29/36	7.5
Pre-Lithiation	Applied Matls.	Prelithiation R2R physical vapor deposition high volume manufacturing	6/24	7.5
Separator	Microvast TAP	Meta-aramid separator	15/15	1.0
Electrolyte	Gotion	Additives to form surface protection on electrode	31/43	2.6
Recycling	WPI Phase III	Recovered NMC from spent batteries, >80% recycled content	7/36	2.0
	ABMC	Integrated, zero discharge process train, no tipping model	2/ 30	2.0

Figure 12: Current programmes **Source:** USABC

OnTo Technology

The summit provided a great case study of an existing UK-US partnership between Johnson Matthey (a UK corporation) and OnTo Technology (a US SME).

OnTo Technology has the only patented technology to produce manufacturing-quality electrode materials from recycled batteries. OnTo Technology has been working with Johnson Matthey to scale up their technology as part of a UK pilot project, in conjunction with the UKBIC, and funded by the Office for Zero-Emission Vehicles (OZEV) and Innovate UK.

Their proprietary process, called Cathode-Healing, is a direct recycling innovation that allows cathode material to be harvested and converted into cathode-ready material with a relatively low amount of energy input. They have demonstrated effectiveness on addressing early-stage manufacturing scrap (the short term "easy" step).

Nth Cycle

Asian dominance in the mineral supply chain means battery recycling will increasingly become more important for both the US and UK. The US relies on Asia for raw material processing and end-of-life processing. Today this material makes three trips, with China representing a severe bottleneck.

Asia dominates global metal processing creating severe bottleneck

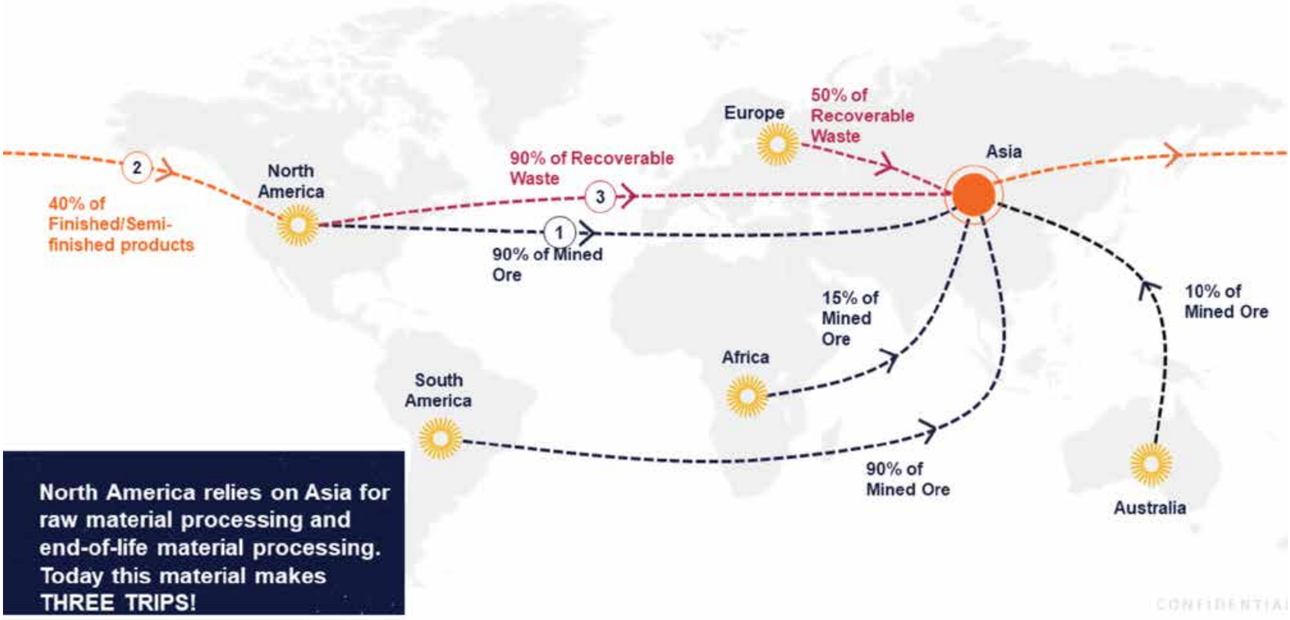


Figure 13: Asia dominates global metal processing creating severe bottleneck **Source:** Nth Cycle

Existing techniques (hydrometallurgy, pyrometallurgy) are expensive, centralised and carbon-intensive. Nth Cycle has developed a new technology for recyclers and miners called electroextraction, which hybridises filtration and electro-winning. This results in a process which has 75% lower cost and GHG emissions and increases the output purity of black mass from 20% to 90%.

Nth Cycle are working on their first commercial deployment at a battery shredding and recycling facility in the US. They are looking for more deployments, preferably with small scrappers and mining companies.

2.4. Key Initiatives by Business Communities and Industry (UK)

Faradion

Faradion is a Sheffield-based firm developing Sodium-ion batteries. Sodium-ion (Na-ion) is an interesting technology for several reasons:

- Can be fully discharged, thus making it safer and easier to transport
- Same equipment and processes as Li-ion, so low CAPEX to begin manufacturing
- Does not contain copper, lithium, cobalt or graphite, so supply chain issues are mitigated
- Primarily uses sodium, which is the sixth most abundant element on Earth
- Collectors can be made from aluminium and the anode from hard carbon (much easier to source and use in manufacture)
- Significantly lower global-warming potential than Li-ion battery chemistries

Ilika

Ilika is a British pioneer of solid-state battery technologies, with immediate application in medical technology and industrial IoT.

Ilika's approach is based on the Stereax technology, pioneered in the 1990s at the US's Oak Ridge National Laboratory, with modifications to the design. They are developing IP with the aim of being a global leader in solid-state battery design and manufacture.

Ilika's batteries are useful for industrial IoT and medical technology as they:

- Can be miniaturised, allowing medical implants to be actively-powered for ten years); and
- Are tolerant of high temperatures, whereas lithium-ion cells should not be operated above 60ºC (Stereax tolerant up to 150ºC).

Manufacturing processes for Stereax cells are not suitable for EV cells, as they are made using vacuum deposition, and photolithography to define cell architecture. Their second technology, Goliath (TRL 3) pouch cells, uses totally different processes similar to lithium cell manufacture.

Solid-state battery technologies present interesting advantages over conventional liquid electrolyte-based batteries:

- **Enhanced safety** – due to the absence of volatile and flammable liquid components
- **Better energy density at the pack level** – because there is no danger of a fire or explosion, there is no need for safety components or cooling systems, which saves space and allows for more active material in the battery
- **Fast charging capability** – solid-state batteries can be recharged quickly as the electrolyte cannot overheat

They have several R&D projects underway with vehicle OEMs in the UK (Honda, McLaren, Jaguar Land Rover), research institutes (UCL, CPI, WMG) and UK government battery stakeholders (UKBIC and the Faraday Institution).

Williams Advanced Engineering

Williams Advanced Engineering (WAE) is a world-leading technology and engineering business, born out of the Williams Formula One team in 2010.

WAE is emerging as the go-to provider of high voltage battery systems in motorsport based on their battery expertise gained thanks to the introduction of KERS (Kinetic Energy Recovery Systems) to F1 in 2009.

WAE approach to the challenges in electric motorsport:

Energy Density	Advanced chemistry (silicon anodes, Lithium metal anodes etc)
	Regenerative braking
	Maximised usable energy
	Light-weighting
Power Density	Model-based power limits
	Optimal control
	Novel architectures
Thermal Management	Advanced design concepts
	Model-based design
	Degradation sensitivity studies
Cycle Life	Cell optimisation and supplier collaboration
	Degradation mode tracking
	Intelligent fast charge
Sporting Equity	Digital Twin for performance equalisation
	Predictive maintenance

WAE has developed world-class expertise in battery performance algorithms. Logging thousands of data points per second from sensors onboard a vehicle's battery management unit (BMU) allows detailed models of the cells to be built. Feeding this telematics data into digital twins of the battery systems that use machine learning to optimise design and operation, WAE can enhance battery performance in an extremely short time period. Additionally, it is increasingly possible to perform predictive maintenance by pre-empting failure.

Tevva

Tevva is a British SME that designs and manufactures pioneering zero-emission medium-duty trucks.

Most goods vehicles travel 80 miles to 200+ miles a day, with 99% travelling up to 180 miles a day. For an EV truck, the battery needed would be 160 kWh (7.5 t vehicle). However, due to the distribution of journey lengths, this would result in a poor total cost of ownership (TCO).

To improve the TCO, Tevva is pursuing a range-extender approach using a hydrogen fuel cell, which keeps the aggregate energy cost to around £0.13 per kWh to £0.19 per kWh on an average day. Additionally, Tevva recommends second life deployment as static storage, which cuts the effective cost of the battery by 75% and customer lifetime TCO by 5%.

Johnson Matthey

Johnson Matthey is a FTSE-250 speciality chemicals corporate with core capabilities in precious metal recycling, where it has been a market leader for over forty years.

Johnson Matthey is investigating Li-ion battery circularity which they believe will be dominated by cell scrap (to 2030) and then by end-of-life recycling. Regulation from the UK and the EU around recovery rates and minimum recycled content is a major driver.

Johnson Matthey refines black mass obtained from recyclers before providing material outputs to cathode manufacturers (see diagram below). Black mass is generally regarded as a commodity by the market, but in practice how it is processed has a huge effect on the composition. Recycling organisations can add value to the process when preparing black mass.

Figure 14: Partnerships, enabler for success **Source:** Johnson Matthey

Johnson Matthey is partnering with upstream recycling partners to provide an innovative hydrometallurgy-based solution. It has been developed and patented in the UK and now has a pilot plant just outside of London.

One project that was presented was a pilot project with the American SME, OnTo Technology, to scale up their proprietary cathode recycling process. This was done in partnership with the UKBIC and funded by the Office for Zero-Emission Vehicles (OZEV) and Innovate UK.

Britishvolt

Britishvolt is a new British battery OEM working on the design and development of advanced Li-ion technology, aimed initially at light commercial and high-performance vehicles. Britishvolt has several existing collaborations with world-class academic institutions (Oxford, Imperial, UCL, Durham, Coventry, Northumbria, and Newcastle) as well as support from the Faraday Institution, CPI, BEIS, and Innovate UK.

Britishvolt is developing the UK's flagship gigafactory in Blyth, Northumberland. It is an ideal site, benefitting from ample water supply, a deepwater port and railhead, and 1.4 GW of local renewables (offshore wind, UK-Norway interconnector, on-site solar energy generation). Production at Blyth goes online in early 2024, and production capacity of 30+ GWh is projected by 2027.

Localised supply chain and greater use of renewables will reduce their embedded carbon emissions to support the production of sustainable batteries. The LCA of Britishvolt's initial glide path is that the GHG emissions associated with the production of NMC111 based Li-ion batteries is 25 $kgCO_2/kWh$, which is extremely low compared to international peers (see table below).

Location	GHG emissions of NMC111 production ($kgCO_2/kWh$)
China	91
Japan	89
South Korea	82
US	66
Europe	62
Britishvolt	25

Britishvolt has announced its joint venture with strategic partner Glencore to develop a world-leading ecosystem for battery recycling in the UK. It will be anchored at a new recycling facility at the Britannia Refined Metals site in Northfleet, Kent (a Glencore subsidiary), expected to be operational by mid-2023. The site will generate a minimum of 10 kt of End of Life (EOL) lithium scrap, which will be fed into Britishvolt's operations.

3.0 Research and Innovation Opportunities

There is a positive attitude to developing a bilateral relationship between the US and UK on lower TRL projects (academic-academic and academic-business) as these are favourable when rapid developments would be mutually beneficial for both countries. Challenges that arise at higher TRL commercial projects include IP, patents and licensing which can hinder product and technology development. However the Summit highlighted an enthusiasm for business-business collaboration in areas of strategic importance to both nations, such as cathode materials, which will help the US and UK decrease the instability of the supply chains which are currently dominated by China. Battery recycling and cathode development were highlighted to be areas of interest and a focal point for collaborative R&D across the two nations.

Battery recycling presents an area for long-term collaboration between the UK and US. There is no clear path to profitability yet, and while highly competitive, there are significant opportunities for bilateral cooperation. Recycling companies are concerned about losing market share to emerging technology and therefore, seek to engage with universities for joint R&D projects. Battery recycling is vital to the UK economy as it mitigates the need to import key materials as well as contribute to climate targets. In addition, there are opportunities to design novel efficient batteries by using computer modelling and simulation to understand battery degradation. While there is a challenge to develop a cooperative framework, there are many shared R&D challenges between the UK and US that can be worked on. Whilst rules relating to the origin of materials means that localisation of supply chain is critical, this actually promoted non-competitive supply chains for the UK and US. The UK is a route into supply for Europe (and visa versa), which could not be done from the US.

Priority opportunity 1: Recycling

The US is ramping up investment in recycling innovation, with funding for several new competitions and grant programmes included in the recent Bipartisan Infrastructure Law (BIL).

The UK funds recycling R&D, most notably the Faraday Institution's ReLiB project led by the University of Birmingham and the APC's Recovas project. However, given the magnitude of the challenge, there is an opportunity for UK funding to be stepped up in this area.

The Summit highlighted the opportunities for business-led US-UK R&D collaboration and investment in the recycling domain. OnTo Technology, an American start-up, presented their collaborative cathode material recycling project with Johnson Matthey, supported by UKBIC, the Office for Zero-Emission Vehicles (OZEV) and Innovate UK. Additionally, Britishvolt recently announced their joint venture with strategic partner Glencore to develop a world-leading ecosystem for battery recycling at a new recycling facility in Kent. These projects provide templates for potential private-led collaboration between the US and UK.

Priority opportunity 2: Cathodes

Due to the instability of the global supply chain and the dominance of China, cathode material production presents an opportunity for immediate US-UK collaboration. Both countries have several R&D activities that would benefit from transatlantic cooperation to co-develop and manufacture cathodes.

Critical mineral-free cathodes (with low/no cobalt the priority, closely followed by low nickel) is a significant challenge and opportunity for bilateral R&D. Due to geopolitical situations there is a shortage of class I nickel and ethical concerns regarding the Congolese cobalt supply chain. Therefore, it is vital to develop alternative cathode structures that are not reliant on resource-limited critical materials.

Priority opportunity 3: Lower the Cost of Manufacture

Methods to rebalance the cost of manufacture between the US, UK and China is an emerging area which presents an opportunity to launch innovative technologies to lower the cost of production. SMEs from the US, such as 6K, showed that innovation could allow the US and UK to create new, more cost-effective production methods to outperform China even despite their lower labour costs. Several projects across the US and UK are focused on modelling and computational approaches in batteries to help improve performance, degradation, and sustainability. For example, software-based methods are quicker to test and implement and have shown to rapidly yield results. International pilot projects between UK and US technology providers would be mutually beneficial. This would also complement a UK-US knowledge-sharing programme to highlight both countries' regulatory systems and health and safety policies.

Priority opportunity 4: New Battery Chemistries

Alternative chemistries remain attractive opportunities for collaboration, including sodium-ion (via the FI's Nexgenna project) and Lithium-sulphur (via the Faraday Institution's LiSTAR programme). The development of solid-state battery technology (The Faraday Institution's SOLBAT) has been referred to as the "holy grail" due to its higher energy density and improved safety characteristics. The challenge, however, is the capital investment and infrastructure required to rapidly develop and scale-up the manufacture of solid-state batteries.

3.1. Research and Innovation Challenges

The most notable challenge mentioned was around IP in cross-border collaboration. For early-TRL academic research this is not an issue, but as innovations progress through the TRLs and get closer to commercialisation, it becomes increasingly complex for groups of organisations, particularly across borders, to agree to terms for collaboration.

One factor to consider when planning UK-US collaboration is the long development and investment time for certain technologies. Developing new battery technology and chemistries often takes time and requires CAPEX investments. It typically takes about ten years to assess a new battery chemistry.

A challenge that will become increasingly important for the UK economy as the drive to electrification grows is the availability of a skilled workforce. Due to the rapid growth of the raw materials market there is a clear need to address the skills gaps to mitigate the dependency on overseas manufacturing and processing.

Several regulatory challenges were identified during the Summit. A 10% tariff is applied in the UK unless all battery packs, cells and cathode active material are manufactured locally. In the UK, there are performance standards for second-life batteries that will need to be observed, in addition to regulations on the percentage of recycled lithium, nickel and cobalt content. The US may also take this route, but does not have a regulatory framework like the UK. Therefore, collaborative R&D projects will need to consider the differences in regulation between the UK and US.

Commercialisation and route-to-market are common concerns with innovation projects, especially those with long lead times and high development costs. Both the UK and US have relevant forums for dialogue with vehicle OEMs, battery manufacturers, and other potential customers for any IP developed during R&D. Organisations and programmes such as USABC and 21CTP can be influential and leveraged to ensure the most commercially viable opportunities are pursued.

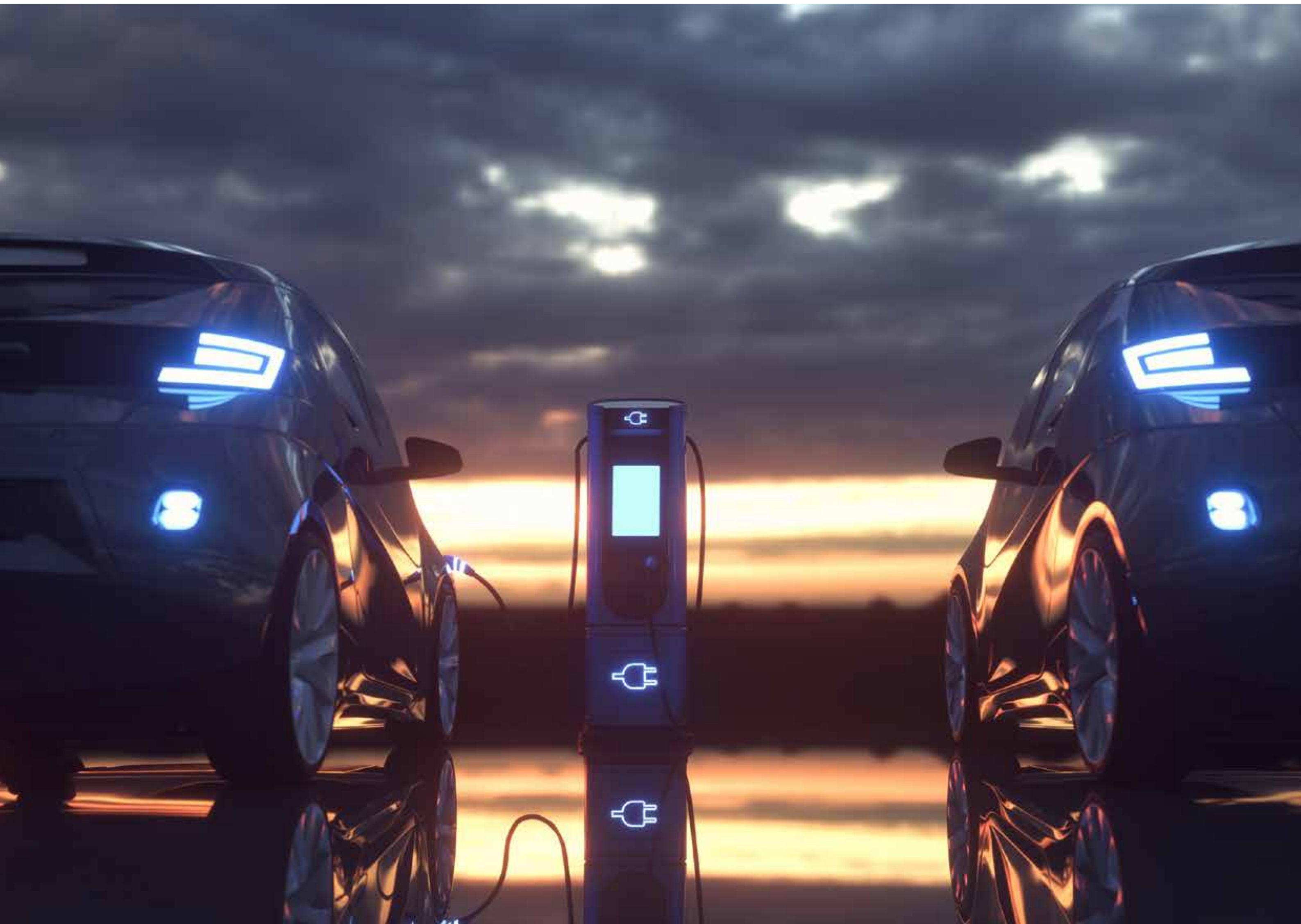
Supply chain issues, in particular for critical materials, were highlighted by several stakeholders and is vital for continued innovation and development in battery technology. In addition to the mineral supply challenges, there are a number of midstream technology gaps. For example, in the UK, the APC is working with Phillips 66 to modify their UK coke facilities to provide carbon for anode materials. Both the UK and the US have similar challenges around anode production. Therefore, developing a better understanding of the challenges and opportunities in the whole battery supply chain is a major focus in the US.

Funding is an ever-present concern for R&D organisations, especially given the capital-intensive nature of battery technology. Both the US and the UK have clear budgets and relevant institutional mechanisms to deploy funding. Some seed funding to catalyse new initiatives (i.e. joint UK-US programmes) or use of existing funds to facilitate international travel (e.g., through the Faraday Institution for a research mission to the US or Innovate UK EDGE's Global Business Innovation Programme) would be beneficial to strengthening science and technology collaboration between the UK and the US.

Finally, a simple but notable challenge is that of meeting face-to-face, as Covid-19 rule differences have made opportunities for in-person events harder to organise (for example, the National Laboratories were closed at the time the mission was set up). Time differences between the US Pacific region and the UK's time zone make some collaborations hard (as reported by OnTo Technology and Johnson Matthey), so finding a way to enable in-person meetings while complying with relevant legislation is important for relationship and partnership building.

3.2 Potential business-led innovation partnerships

Certain opportunities could be shared with businesses across the Atlantic in order for them to take the lead. For example, the Clean Energy Cybersecurity Accelerator run by NREL as part of the ARIES programme could be extremely relevant for many UK battery technology businesses that may be vulnerable to expensive cyberattacks.



There are organisations with heavy business engagement in both nations (e.g. USABC in the United States, APC in the UK) which should be leveraged to encourage businesses to create initiatives of their own.

The Summit learned from an excellent example of a transatlantic, corporate-SME partnership in the form of Johnson Matthey and Onto Technology, who presented their battery recycling technology partnership and discussed the takeaway lessons learned. A mechanism to encourage similar partnerships will be a needed element of enhanced US-UK collaboration.

4.0 Benefits and impact from future bilateral collaboration

Knowledge-sharing

Collaboration between the UK and USA will leverage existing programmes, facilitating data and knowledge sharing resulting in increased innovation output. Bilateral cooperation would result in increased access to additional R&D funding and infrastructure. The research and innovation summit identified several key partners to initiate business and academic collaboration. For example, UK universities and key stakeholders can engage with the ARIES research platform and join relevant forums and workshops through Li-Bridge. In particular, the Faraday Institution's Lithium-ion Battery Multiscale Modelling project would greatly benefit US researchers.

By increasing dialogue between relevant working groups, the USA and UK could share data and avoid duplication of effort in certain areas. This is particularly important to recycling efforts, which requires substantial financial support and coordination to improve sustainability and to help ease the challenges in the raw material supply chain (e.g. lithium, cobalt, nickel and graphite). Supply chain stability can also be achieved by aligning technology areas of strategic importance to both countries. The development of cathode materials is a topic of interest and presents an opportunity for joint innovation and to co-develop new technologies.

Access to New Markets

The new Brexit deal and Rules of Origin (see section 1.2) means that Europe and the UK are effectively one market, with a real focus on localisation of the supply chain. Similar to the US, the UK opportunities exist in building the material supply chain, recycling & the development of new battery technologies. Collaboration between the UK and US provides US companies an opportunity to gain a foothold into the European and UK markets as well access to the localised battery supply chain.

Intellectual Property

Large companies such as the vehicle OEMs have an appetite for IP to help them innovate and stay ahead of global competitors. Widened US-UK collaboration will create opportunities for these OEMs, as well as generating a return for the research institutes or SMEs that have developed the new IP.

Joint R&D funding

Financial aid to support innovators in each country to explore trials and demonstrator facilities. Joint R&D funding to develop low TRL projects and to help researchers and businesses to traverse the mid-TRL levels to develop prototype technology. UK organisations can help US businesses to launch operations in the UK (e.g. 6K or Nth Cycle) and help them access the wider European market. UKBIC can play a pivotal role to support scale-up of early-stage research. The increased R&D funding will benefit both countries help support key technology challenges in battery recycling and the development of new battery chemistries.

4.1 Collaboration models and suitable partners/ co-funders

During the Summit, several possible collaboration mechanisms were highlighted, as well as organisations that could be key enablers for the given collaboration approach.

Appoint UK technical leads to coordinate international research

Projects in the US often appoint technical leads who are responsible for coordinating larger complex projects. The leads provide guidance and ensure a structured approach to new project development and funding. In the US, the national laboratory act as technical lead, for example, Lawrence Berkeley National Laboratory on the VTO cathode project and Argonne National Laboratory on recycling. In the UK the FI's management structure provides a similar level technical coordination for its cathode (CATMAT, FutureCat) and recycling projects (ReLiB).

A key advantage of the UK's APC compared to the USA's VTO projects (e.g. 21CTP and USDRIVE) or USABC is that the APC has a role in making grants that incentivise capital expenditure and R&D directly in addition to its role shaping industry discussions. Along with the UKBIC, the APC could play a role in developing deeper collaboration with American OEMs and private sector players looking to grow new R&D and manufacturing capacity in the UK.

Joint funding initiatives and public-private partnerships (PPP)

A PPP can provide opportunities for researchers to develop commercially viable projects in partnership with industry. One mechanism to fund US-UK academic research in this field could be a joint programme between the US National Science Foundation (NSF) and the UK's Engineering and Physical Sciences Research Council (EPSRC). For engineering research, lead agency agreements provide a framework for joint peer review of proposals by two funding agencies in different countries. This could be expanded to cover energy and battery materials research.

For more formal groupings, both countries would need to build the informal relationships of the research institutions and then work towards potentially forming a joint programme (formal or informal). This was regarded as requiring a 12-18 month timeline. The first step will be to identify areas that the partner country does not cover in its research (or where the approaches are different) and which would be the best opportunities to focus on.

It was noted there are about 12-15 Principal Investigators funded by DOE and about 20 Co-investigators on CATMAT/FutureCat that would like to attend a UK-US cathode meeting. It was agreed to schedule a meeting between the Faraday Institution, DOE and other stakeholders in the future to discuss this in further detail. Boosting collaboration between recycling programmes (e.g. ReCell in the USA and ReLiB in the UK) could follow a similar path.

It was discussed that broadened UK participation at Li-Bridge Forums (e.g. Recycling) would be extremely welcome. It would allow for face-to-face meetings and connect organisations across the battery value chain facilitating business and academic collaboration.

Whether UK companies can apply to future iterations of the DOE's Lithium-ion Battery Recycling Prize was raised during the Summit. If a joint UK-US Recycling competition is not possible, then it could be useful to replicate a Recycling Prize scheme in the UK with funding from BEIS, the Faraday Institution, or Innovate UK.

UK–US pilot projects

It was clear that there was strong potential for hosting local trials or demonstrators of technology developed in the partner country, especially given that the UK can serve as stepping stone for US companies to access to the larger European market. UKBIC and APC are keen to provide these demonstrator services to US battery and vehicle OEMs respectively.

Idaho National Laboratory's Machine Learning for Life Prediction and Cell Design work has the potential to add value to several UK initiatives, including FutureCat, Imperial's LCA Modelling, the Faraday Institution's Multiscale Modelling projects, and William's Advanced Engineering's in-house R&D. The Idaho National Laboratory already collaborates with the University of Oxford and four other National Laboratories so there could be a great opportunity to broaden cooperation with additional UK partners. Idaho National Laboratory's battery data working group is open for others to join, including UK organisations, and their website goes live in late summer 2022.

Appendix 1: List of US Participants

6K

Argonne National Laboratory

Department of Energy (DOE)

Department of Energy, Office of Energy Efficiency & Renewable Energy (EERE)

Department of Energy, Vehicle Technologies Office (EERE/VTO)

Department of Energy, Advanced Manufacturing Office (EERE/AMO)

Idaho National Laboratory

Lawrence Berkeley National Laboratory

National Renewable Energy Laboratory (NREL)

Nth Cycle

OnTo Energy

Pacific Northwest National Laboratory

Solid Power

United States Advanced Battery Consortium (USABC)

Appendix 2: List of UK Participants

Advanced Propulsion Centre (APC)

Britishvolt

Centre for Process Innovation (CPI)

Department for Business, Energy and & Industrial Strategy (BEIS)

Faraday Battery Challenge

The Faraday Institution

Faradion

Ilika

Imperial College London

Innovate UK

Johnson Matthey (Research Centre)

National Physical Laboratory (NPL)

Tevva

UK Battery Industrialisation Centre (UKBIC)

University College London (UCL)

University of Birmingham

University of Oxford

University of Sheffield

Warwick Manufacturing Group (WMG)

Williams Advanced Engineering

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6. https://www.energy.gov/bil/battery-and-critical-mineral-recycling
7. https://www.energy.gov/bil/electric-drive-vehicle-battery-recycling-and-2nd-life-apps
8. https://www.energy.gov/sites/default/files/2021-06/FCAB%20National%20Blueprint%20Lithium%20Batteries%200621_0.pdf
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Acronyms

AI	Artificial intelligence
CAGR	Compound Annual Growth Rate
CAPEX	Capital expenditure
EOL	End of life
EV	Electric vehicle
GHG	Greenhouse gas
HGV	Heavy goods vehicle
IP	Intellectual property
IoT	Internet of Things
LCA	Life cycle assessment
LFP	Lithium Iron Phosphate (a type of cathode chemistry)
Li-ion	Lithium Ion
LTO	Lithium Titanate (a type of anode chemistry)
ML	Machine learning
NMC	Nickel-Manganese-Cobalt-Oxide (widespread lithium-ion cathode chemistry)
OEM	Original equipment manufacturer
PI	Principal investigator
PPP	Public private partnership
SaaS	Software-as-a-Service
SotA	State of the art
TCO	Total cost of ownership
TRL	Technology readiness level

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