Faraday Battery Challenge

Research activities

September 2024

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What is the Faraday Battery Challenge?

The world is undergoing a transition to a low-carbon future, but transport remains the largest source of carbon dioxide emissions in the UK, accounting for 29% of emissions[1]. Developing low-cost, reliable and long-range electric vehicles is the key to reducing these emissions, with batteries playing a crucial role, not only in the automotive sector but in applications across aerospace, rail, marine, off-highway vehicles and static storage. The UK and the EU have established clear end dates for the sale of petrol and diesel vehicles, which is driving the demand for battery-powered electric vehicles. This transition to an electrified future will require many types of batteries, with some yet to be imagined. Therefore, the next generation of battery technology must be developed, along with exploration and de-risking of new production processes that ensure long-term UK success in battery manufacturing and car-making.

This is the reason the Faraday Battery Challenge exists. It is a £610 million investment from the UK government in battery technology. The mission-led programme coordinates and manages applied research, business-led innovation and national scale-up infrastructure in support of the UK's transition to electrification. Delivered by Innovate UK, on behalf of UK Research and Innovation (UKRI), the Faraday Battery Challenge supports the development of sustainable batteries that are cost- effective, high -performance, durable, safe and recyclable.

The Challenge has positioned the UK as a leading scientific, technological, and industrial player in the development of batteries. The significant investment has not only contributed to the growth of UK companies, but also signaled to investors that the UK is an attractive opportunity for innovation and production in the battery sector. This initiative has promoted innovation and collaboration among researchers, businesses, and other stakeholders, which has enhanced the UK's credibility in this sector. The support provided by the Faraday Battery Challenge extends far beyond the automotive industry and encompasses cross-sector activities in skills development, policy, regulations, and more.

The Challenge is designed to support innovation from early-stage, university-led research through to near-commercial scale facilities to test manufacturing, providing the UK with a world-beating innovation landscape to commercialise battery technology. It is focused on three pillars: research, business-led innovation and scale-up. The Challenge draws together these pillars to accelerate the delivery of a pipeline of activity, and has built a globally competitive scientific capability at scale, harnessing our best talent toward solving the challenges for battery technology.

This document highlights the UK's battery electric transition in action, with the cutting-edge projects of the Faraday Battery Challenge. These projects are blazing a trail towards a cleaner, more sustainable future, backed by groundbreaking research and innovative technology that are the driving force behind the UK's electrifying transition to a battery-powered future. As you will see through these projects, the UK is well -positioned to thrive in the emerging low-carbon economy, with robust infrastructure, a skilled workforce, and a strong innovation ecosystem in place to drive the transition to electrification.

Tony Harper, Faraday Battery Challenge Director

"The Faraday Battery Challenge is a pioneering 'lab to factory' programme focused on delivering the research, business-led innovation, infrastructure and people required for the UK to prosper from the unprecedented opportunities arising from the mass transition to electrification.

Just over six years into the programme, this brochure illustrates the breadth and depth of cutting-edge capability that has been built and reinforces why the UK is amongst the very best in the world in battery technology development."

1 Transport and Environment Statistics 2021 Annual report.

Faraday Battery Challenge

Innovate UK | THE FARADAY INSTITUTION | UK BATTERY INDUSTRIALISATION CENTRE

Scaling high tech business ↔ **Building a Science Superpower** ↔ **Open access scale up with Gigafactory capability**

Research

The Faraday Institution is the UK's independent institute for electrochemical energy storage research, skills development, market analysis and early-stage commercialisation.

It brings together research scientists and industry partners on projects with commercial potential that will reduce battery cost, weight, and volume, improve performance and reliability, and develop whole-life strategies, including recycling and reuse.

Business-led Innovation

The Faraday Battery Challenge Innovation programme is supporting UK businesses to push the boundaries of battery innovation and grow the UK battery supply chain. £130m of funding from Innovate UK for UKRI has been invested for businesses to lead feasibility studies, and collaborative research and development projects across the battery value chain, in collaboration with the UK's world leading academics and research technology organisations.

Scale-up

The UK Battery Industrialisation Centre (UKBIC), the first facility of its kind in Europe, opened in 2021 and enables companies of all sizes to develop manufacturing capabilities for battery technologies to get them to market quickly.

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6 years of high-quality impacts in energy storage

The Faraday Institution has generated a great return on the UK's investment from a standing start in 2018

10
major research programmes, lead across 27 UK universities and research partners and 120+ industrial partners

777+
scientific papers published, 64.6% in top 10% journals, 47.5% in top 10% most cited, 44.1% with international collaborators

40
inventions identified, 18 patents filed and 7 published

500+
researchers united in a community, 45% new to field, to solve battery challenges through breakthrough science

14
entrepreneurial spin-outs, supported 17 industry fellows and 17 industry sprints

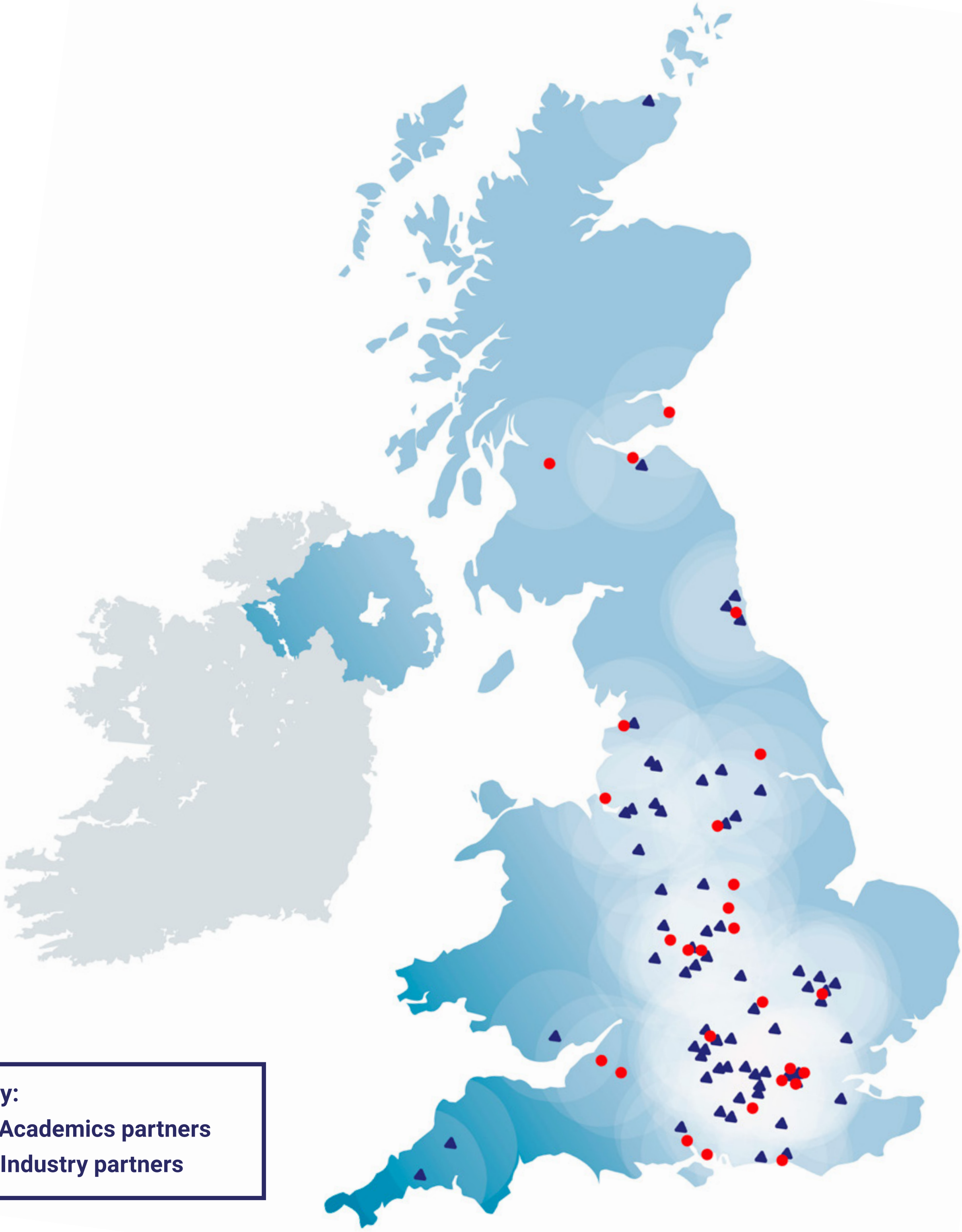
20
Faraday insights, 13 major reports, 12 national consultations, numerous briefings including House of Commons and House of Lord enquiries

85
PhDs receiving bespoke training for UK industrial and academic careers, and an additional 100+ affiliated with our projects

International collaboration
DSIT funded US UK joint battery research on recycling and cathole materials

6
Royal Institution events hosted, attracting 300,000+ online viewers

Faraday Institution academic and industry partners



Key:
- ● Academics partners
- ▲ Industry partners

Research

In the near term, accelerating the drive towards electric vehicles (EVs) requires the optimisation of lithium-ion (Li-ion) battery technology. While there is still room for improvements to Li-ion, there are fundamental limits to the performance improvements that can be expected from its deployment. So, in the medium to long term, step changes in EV cost, range and safety will have to rely on the research, development and commercialisation of new battery chemistries.

Because of the current level of commercialisation of different technologies and the UK's need to deliver improvements in EVs over a range of timescales, the Faraday Institution is pursuing a portfolio of 10 major research projects:

- Seven projects aim to optimise current generation Li-ion based batteries where there are still considerable gains to be made and where research breakthroughs could start to be realised in commercial batteries within three to four years.
- Three focus on building core knowledge, understanding and capability in battery degradation, modelling and safety.
- Two on processing, electrode manufacturing and recycling.
- Two on next-generation cathode materials.
- The remaining three projects' focus areas are higher risk, higher reward, and could facilitate the long-term commercialisation of next-generation battery technology that still requires considerable research in the areas of materials discovery and optimisation in solid-state, sodium-ion and lithium-sulfur batteries.

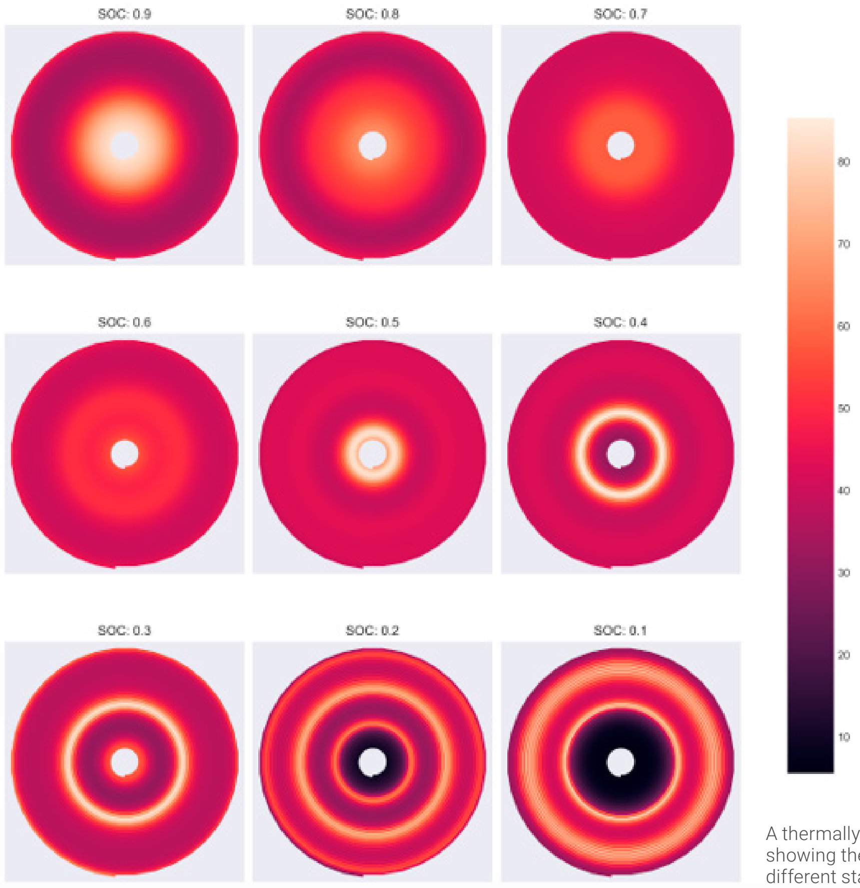
THE FARADAY INSTITUTION

This large-scale research programme is multidisciplinary, highly collaborative, and draws together the best of UK university research groups and industrial partners. Research topics are selected after consultation with academic and industrial stakeholders across the country, with due consideration of the potential impact they could make to the UK.

Research Excellence

Research from the Faraday Institution's programme is internationally recognised as a mark of excellence. Scientific discoveries have led to highly cited publications, a suite of patents, and commercial spin outs. To October 2023 the Faraday Institution has contributed over 777 publications to the scientific literature, more than 85 of which represent collaborative work across its research projects.

The following statistical data derives from the SciVal record from April 2018 to October 2023, which recognises 733 papers and 2,228 authors. 90.2% of publications are in open access journals, with 17.3% categorised as gold open access. 45 papers were published in collaboration with an industry partner. Almost half (44.1%) of the published research coming out of the Faraday Institution has international collaborators, spanning over 391 institutions, 39 countries and six continents. Key countries that collaborate most frequently with the Faraday Institution include the USA, China, Germany, France, Sweden, South Korea and Spain in that order.

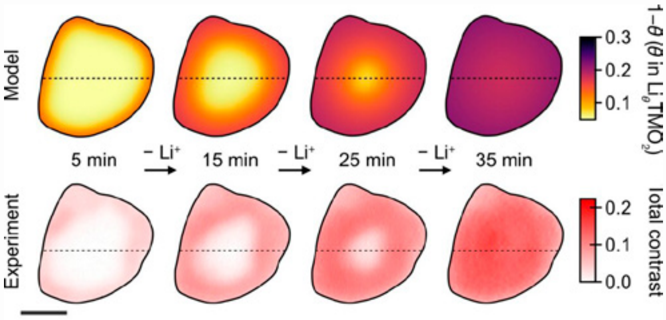


A thermally coupled electrochemical model produced in PyBaMM, showing the density variations that develop in a cylindrical cell at different states of charge.

Extending battery life

Understanding the mechanisms of degradation of lithium-ion batteries.

Grant contribution: £22,700,000



Comparison of simulation and experimental imaging results, both conducted at a delithiation rate of C/3. The predicted degree of delithiation (1-θ) on the basal plane of the particle at various times during the charge.

Executive summary

Using a suite of advanced modelling and characterisation techniques, the project aims to understand the mechanisms of degradation of lithium-ion batteries containing high Ni-content NMC, cobalt-free cathodes and a range of anode chemistries from graphite, graphite/SiOx composites and anode-free.

This project is examining how environmental and internal battery stresses (such as high temperatures, charging and discharging rates) degrade electric vehicle (EV) batteries over time. Results will include the optimisation of battery materials and cells to extend battery life (and hence EV range) and reduce battery costs.

Despite the recent reduction in the cost of lithium-ion batteries driven by mass manufacture, the widespread adoption of battery EVs is still hindered by cost and durability, with the lifetimes of the batteries falling below the consumer expectation for long-term applications such as transport.

Additionally, fast charging of battery EVs is crucial to help assuage range anxiety and provide the operational convenience required for mass adoption of the technology. Fast charging, however, can rapidly accelerate degradation and even trigger degradation mechanisms that are not present in ‘normal’ operating conditions. A key goal for the automotive industry is to understand more fully the causes and mechanisms of degradation to enable improved control and prediction of the state-of-health of battery systems.

The goal of the project is to create accurate models for use by the automotive industry to extend lifetime and performance.

Timeline with milestone/deliverables (March 2025)

- Identify the key stress-induced degradation processes and kinetics that occur in cells.
- Link the electrical signatures of degradation with specific chemical and materials processes so that they can be identified in an operating battery pack.
- Examine and understand the physicochemical mechanisms of degradation in high-nickel and colbalt-free positive electrode materials.
- Examine and understand the physicochemical mechanisms of degradation of graphite and anode free electrode materials. Emphasis is being placed on the interaction, or ‘cross-talk’, effects of positive electrode materials on causing or accelerating these pathways at the electrode-electrolyte interface.

Project innovations

This project will provide a more complete understanding of the signatures of degradation, lead to increased lifetime and better prediction of failure, and accelerate the development of new battery chemistries through the holistic and coordinated efforts of the research. An ability to fully understand the causes of limited lifetime of lithium-ion batteries will place the UK at the forefront of the next generation of battery EV technology.

Partners

University of Cambridge (co- lead)
University of Warwick (co-lead)
Imperial College London
Newcastle University
University College London
University of Birmingham
University of Oxford
University of Sheffield
University of Southampton
National Physical Laboratory (NPL)
+ 8 Industrial Partners

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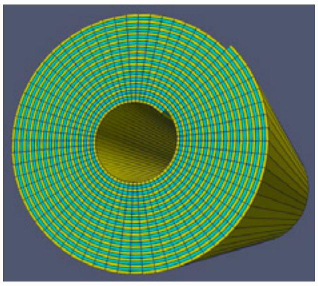
Multi-scale Modelling

Bringing together a multidisciplinary team to develop fast, highly accurate models to speed up battery development and ensure safe operation for longer battery life.

Grant contribution: £22,900,000



Cylindrical cell geometry discretisation example in 2D (approximately 2000 modelling cells). Each finite volume is simulated as an individual Newman model.

Executive summary

Accurate simulations of batteries will enable battery makers to improve designs and performance without creating expensive prototypes to test every new material, or new type or configuration of cells. The project considers a range of length scales, from the nanoscale – where atoms interact – up to the macroscale of a complete pack and its electronic control systems. A range of timescales are also considered from the movements of atoms at the nanosecond, through to long-term degradation occurring over years. Battery simulations and design tools exist at each length and timescale, but they have previously lacked the accuracy required for understanding the phenomena occurring within batteries.

The project's world-leading research bridges science and engineering, working innovatively alongside UK industry to deliver impact. Its internationally recognised experts are developing new digital and experimental techniques for understanding battery behaviour at the atomistic, continuum and system scales. Fast, accurate models, incorporating the most complete physics and advanced mathematical techniques, are being developed to be directly usable for industry, enabling digital twinning of whole cells and packs. Atomistic accuracy will parameterise higher level models and tackle key challenges, such as the complex interactions and activity at the electrolyte-electrode interface. Rapid experimental parameterisation methods are being developed, greatly reducing the time and cost of customising models for specific applications.

Timeline with milestone/deliverables (March 2025)

- Expand on the physics and degradation models in PyBaMM (Python Battery Mathematical Modelling).
- Establish a similar common code base for equivalent circuit models (ECMs), called PRISM.
- Examine the processes that occur during the formation cycles of a newly manufactured battery and how this can set the trajectory for its performance and lifetime.
- Develop physics-based models for lithium iron phosphate (LFP) battery chemistries.
- Develop a data set on long-term cell ageing, using rigorously controlled experiments.
- Implement models for advanced state estimation and control.
- Develop digital twins as design tools for new cell and pack configurations.

Project innovations

A common coding framework – PyBaMM – has been established and multiple degradation mechanisms added. It is an open-source model, which is easy to use and provides a high-quality resource for the battery community to explore the mathematical theories with a minimum of coding effort. The PyBaMM community continues to grow, with users and developers from industry and academia around the world.

Rigorous, standardised parameterisation techniques have been developed and the spin-out About:Energy was formed to provide parameterised models as a service to increase access for industry.

Improvements to atomistic modelling were released as part of ONETEP and an ultrafast solver, DandeLiion, has also been developed, which is optimised for speed. The physical models in both PyBaMM and DandeLiion now incorporate thermodynamics, mechanics and long-term ageing.

Partners

Imperial College London (Lead)
University of Birmingham
University of Oxford
University of Bristol
University of Portsmouth
University of Southampton
University of Warwick
UK Battery Industrialisation Centre (UKBIC)
+ 17 Industrial Partners

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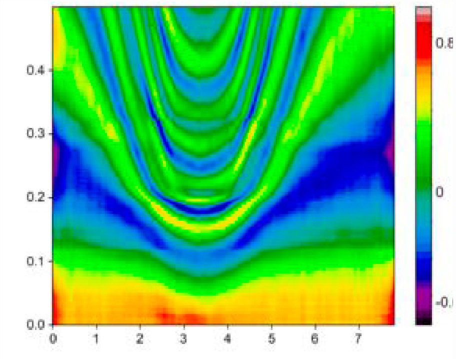
SafeBatt – the science of battery safety

Improving the fundamental understanding of the root causes of cell failure, mechanisms of failure propagation, and processes occurring during real world failure.

Grant contribution: £4,300,000



2D spatiotemporal cross-correlation mapping as a quantitative technique to track failure propagation; this image shows the spatiotemporal map where a ball compresses the electrode structure. The map indicates that the centre of the ball, x ≈ 3.45 mm, starts displacing the electrodes from t ≈ 0.04 s, where the extent of displacement reduces radially due to the circular profile of the ball.

Executive summary

While lithium-ion cell fires are rare, they can occur under various conditions of mechanical, thermal or electrical stress or abuse. As the use of lithium-ion batteries expands into automotive, stationary storage, aerospace and other sectors, there is a need to further decrease the risk associated with battery usage to enable the optimisation of safety systems.

This project is improving the fundamental understanding of the root causes of cell failure and the mechanisms of failure propagation. Working closely with industry partners, a multi-scale approach is being taken, from the material to the cell and module scale. Whilst the nucleation of failure may be a microscopic event, the propagation of failure, in particular cell-to-cell propagation, is macroscopic. Research spans time frames from the degradation of materials over hundreds of charging cycles, down to the nucleation and propagation of thermal runaway with characteristically sub-second events.

The project is also developing an improved understanding of processes occurring during real world failure, including the environmental consequences of lithium-ion battery fires. This will inform the further development of fire sensing and protection systems for lithium-ion battery energy storage systems and help inform first responders.

Timeline with milestone/deliverables (March 2025)

- Investigate materials driven safety issues, detecting early signatures of failure and how these may change as the cell ages.
- Investigate the effect of fast charging and operation under extreme conditions on the safety response at a cell level.
- Understand cell failure modes and how they translate to multi-cell clusters and modules, using advanced instrumentation and high-speed characterisation and imaging techniques.
- Develop and demonstrate detection methods and mitigation strategies to prevent thermal runaway and propagation.
- Develop a model to infer reaction kinetics and predict thermal runaway, simulating the external flow of gas, heat and ejecta during failure.
- Conduct tests in larger format cells and at module level to help industry and other stakeholders understand how EV and micro-mobility battery packs and static energy storage systems fail in real-world scenarios.
- Continue international dissemination activities, providing a central point of access for industry, government bodies and fire services seeking knowledge on safety related battery issues.

Project innovations

Large scale experiments at module level include further investigating fire extinguisher efficacy and the toxicity of fumes and run-off. Previous large-scale work has been instrumental in highlighting the potential explosion hazard of the vapour cloud, which is produced by cells under certain failure conditions. This ground-breaking work is informing best practice and providing knowledge to numerous stakeholders internationally (including first responders and government working groups) on real-world lithium-ion battery failure hazards in EVs and micro-mobility devices, recycling facilities, and domestic and industrial energy storage facilities. This knowledge is being used to influence British and international standards, and produce safe practices for storing and charging devices such as e-scooters and e-bikes.

Partners

University College London (Lead)
University of Oxford
University of Cambridge
King's College London
Newcastle University
University of Sheffield
University of Warwick
+ 2 Industry Partners

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ReLiB – recycling and reuse of EV lithium-ion batteries

Providing a UK EV battery recycling industry with a pipeline of scalable technologies.

Grant contribution: £18,500,000

Coins cells being tested to understand their performance after remanufacture from recycled material via the organic selective phased leaching technology.

Executive summary

The transition to electric vehicles (EVs) brings challenges and opportunities associated with the need to manage projected volumes of around 28,000 tonnes of EV lithium-ion batteries needing recycling by 2030, rising to 235,500 tonnes in 2040. To cope effectively with these volumes, vast improvements in the speed, environmental footprint and the economics of recycling processes will be required, not least as the security of supply of critical materials is becoming an ever-increasing priority for Government. To this end ReLiB is developing recycling technologies that will put the UK at the cutting edge of research & development whilst also building the industrial capacity to underpin the transition to EVs.

ReLiB's vision is to provide a UK EV battery recycling industry with a pipeline of scalable technologies that are responsive to regulatory drivers, new battery designs and chemistries, and the opportunities afforded by Industry 4.0.

Over the next two years to March 2025 the project aims to develop – and scale – the following technologies:

- Cathode leaching to industrial level;
- Upcycled electrode materials used in new cells;
- Binder recovery (where there is an economic or regulatory rationale to do so);
- Biorecovery of materials, e.g., metals from plastic EV battery waste, from secondary waste solutions – 'zero waste' concept;
- Data informed recycling routes based on digital diagnostic tools that can interface seamlessly with battery data passports to assess the batteries key recycling indicators;
- Batteries designed and manufactured with consideration for recycling;

and

- Identification of new research topics that fit with changing battery design and chemistry systems and regulatory drivers.

Timeline with milestone/deliverables (March 2025)

- Demonstration of effective leaching from generation one end-of-life EV batteries.
- Development of a cell-dismantling route for recovery of materials from end-of-life battery cells as an alternative to shred and sort.
- Routes for short loop and/or direct recycling of common cathode materials, including upcycling.
- Evaluation of optimum methodology for recovery and reconditioning of current and future anode materials.
- Scale up of selective metal bioleaching processes using natural and bioengineered bacterial strains.
- Production of remanufactured cells from recycled materials for long-term cycling and investigation of causes of failure.

Project innovations

Unlocking safe, cheap and environmentally benign routes for the separation, recovery, remanufacture and recycling of materials contained within EV batteries is critical to the success of the EV revolution and the sustainability of manufacturing supply chains. The project will achieve this through direct targeting of fast, efficient dismantling processes to boost productivity and safety within the waste and recycling sector. This will provide high-purity and high-value recovered material streams, maximising the environmental gains of the transition to EVs.

Partners

University of Birmingham (Lead)
University College London
University of Edinburgh
University of Leicester
Newcastle University
Imperial College London
+20 Industry Partners

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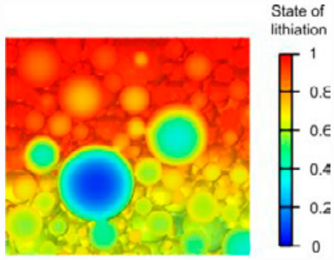
Nextrode – next generation electrode manufacturing

Battery performance improvements through smarter electrode manufacturing.

Grant contribution: £17,900,000



An electrochemical simulation of active material utilisation within a realistic, X-ray CT-based, NMC622 electrode microstructure

Executive summary

Substantial benefits in battery performance can be realised by smarter assembly of the different materials that comprise the electrodes used in rechargeable batteries. These benefits apply equally to mature material systems already used commercially and to new emerging high performance battery systems. Nextrode is focused on researching, understanding and quantifying the potential of smart electrodes to improve energy storage devices, and developing new practical manufacturing innovations that can scale smart electrode benefits to the industrial scale.

Nextrode is investigating how to engineer a new generation of battery electrode structures in both traditional slurry cast electrodes and novel low or no solvent electrodes.

The project is:

- Exploring and exploiting sensor integration and metrology, modelling and data analytics at all stages of electrode manufacture to lay the foundations for future closed loop process control, leading to higher yield, higher productivity and greater flexibility.
- Developing new models and using predictive simulations to suggest the optimum arrangement of materials in electrodes and realising these in practice through prototypes.
- Expanding its research on low and no solvent processing End investigating smart anodes and manufacturing scale-up as well as continuing work on smart cathodes.
- Using 3D characterisation techniques to quantify and assure our bespoke designs and to relate electrode structural features to electrochemical performance.

Nextrode aims to support UK manufacturers and energy storage supply chain companies by showing how to increase cell performance, add value in electrode processing, and improve safety and sustainability.

Timeline with milestone/deliverables (September 2025)

- Provide the critical underpinning manufacturing science to alleviate constraints in electrode manufacturing through engineering particle design and improved understanding of the relationship between powder properties and deposition/calendering techniques.
- Design manufacturing process steps and utilise advanced in-line measurements to enable slurry casting to produce more reproducible electrodes with improved property balance.
- Manufacture new arrangements of anode and cathode materials and identify conditions where benefits are maximised and develop cells that expand the energy-power-lifetime design space.
- Link correlative imaging, quantification and image-based modelling to design optimal microstructures to inform manufacturing development.
- Create and validate data-driven predictive models of electrode manufacturing driving improvements in production efficiency and flexibility.

Project innovations

The project's industry partners, including UKBIC, major players in the materials supply chain and the automotive industry, and organisations involved in R&D/niche volume electrode manufacturing, are focusing the project towards developments that have the most potential for industrial impact (at a low volume/niche through to gigafactory scale). They are taking an active role in discovery exploitation and dissemination. Where distinct and protectable research breakthroughs occur, the project will secure intellectual property and look for opportunities to form spin-out companies.

Partners

University of Oxford (Lead)
Imperial College London
University of Birmingham
University College London
University of Sheffield
University of Southampton
University of Warwick
UK Battery Industrialisation Centre (UKBIC)
+ 14 Industry Partners

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FutureCat – high nickel content, high performance cathode materials

Grant contribution: £13,400,000

FutureCat researcher loading a coin cell onto an instrument for electrochemical characterisation.

Executive summary

Delivering improved EV performance demands high energy density batteries to improve range, high power densities for fast charging, longer lifetimes, and lower cost through reduced reliance on expensive metals. This requires fundamental materials discovery and characterisation to deepen researcher's understanding of the underpinning mechanisms and mechanics, and push performance limits in a sustainable manner.

FutureCat addresses these challenges through three integrated research themes for designing and developing near- and next-generation cathodes, with a focus on high-capacity, high-performance Ni-rich oxide cathodes, but also considering sustainable alternatives that avoid supply-chain at-risk elements.

The advances the project is targeting represent significant commercial opportunities. FutureCat, in collaboration with WMG, University of Warwick, is well positioned to develop scalable solutions for next-generation cathodes towards industry relevant battery formats such as pouch cells. The project is joined by industry partners across the battery supply chain. Three new partners join the consortium in Phase Two working on material lifetime extension via atomic layer coatings, new advanced electrolytes to maximise cathode performance, and advanced X-ray tomography characterisation methods to look inside batteries as they operate.

Timeline with milestone/deliverables (September 2025)

- FutureCat is targeting three transformative step-changes:
- Novel redox processes: understanding novel redox processes and delivering new high-energy/power cathodes exploiting new knowledge.
- Scalable designer morphologies: longer lifetime, high-energy/power through concentration gradient, single crystal and thin coatings.
- Materials delivery: scaling-up industrially relevant Ni-rich and down-selected active materials based on earth-abundant elements.
- FutureCat will deliver cathode materials and fabrication methodologies that provide enhanced energy density, cycle-life, power output and reduced costs, empowering UK battery manufacturing.

Project innovations

FutureCat sets ambitious targets to make fundamental cathode breakthroughs that deliver significant improvements in energy/power density, cost and first life:

- Electrochemical step-changes through strategic synthesis of doped-cathode variants exhibiting controlled morphology, where novel additives/interfaces promote fast ion conduction; including cation-plus-anion redox active materials, gaining a fundamental understanding of anion redox processes to harness and stabilise additional capacity; fundamental scientific enquiry of the underpinning synthesis–structure–property relationship governing performance.
- Establishing design principles for durable cathodes informed by mechanochemical properties; developing new mechanical-testing methods informing the synthetic design process.
- Determining new methodologies for assessing disorder in high-capacity cathodes, fast-tracking theory-meeting-experiment to inform then realise new target chemistries.

This innovation pathway also considers material/method scalability and lean-manufacturing techniques to smooth the path from laboratory to commercialisation.

Partners

University of Warwick (Lead)
University of Sheffield
University of Cambridge
Lancaster University
Imperial College London
University of Birmingham
University of Nottingham
Diamond Light Source
ISIS Neutron and Muon Source
+ 8 Industry Partners

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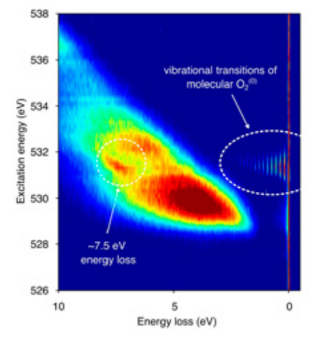
CATMAT – High energy-density, sustainable cathode materials

Grant contribution: £14,300,000



High-resolution resonant inelastic X-ray scattering (RIXS) map of $Li_{2-x}MnO_2F$ charged to 5.0 V, showing the vibrational features corresponding to molecular O2 only, and an energy loss feature at ~7.5 eV (McColl, House, Islam et al., Nature Comms, 2022).

Executive summary

The CATMAT project is focused on targeting improvements in lithium-ion battery energy density and electric vehicle (EV) range through an understanding of the critical properties and limitations of lithium-rich oxygen-redox cathodes and novel anion-chemistry cathodes, and developing scalable synthesis routes for these materials.

The cathode represents one of the greatest barriers to increasing the energy density of lithium-ion batteries for EV applications. Changes to the chemistry of the cathode are likely to give the greatest improvements in future battery performance: by boosting battery life, storing greater energy to improve range, by reducing battery cost and increasing the power available to the EV during acceleration. Developing a new generation of lithium-ion cathodes is therefore a major scientific and commercial challenge as well as a huge opportunity.

The CATMAT project is focussed on understanding and mitigating the current limitations lithium-rich oxygen redox cathodes, and of developing cathodes with novel or complex anion chemistries. Alongside this progression in fundamental understanding of the electrochemistry of these cathodes, the project is developing scalable synthesis routes for the most promising identified materials. Once synthesised at larger scale, these materials will then be integrated in full battery cells to demonstrate practical performance.

This project will support the accelerated development of new cathode materials and will build on industrial partnerships to deliver technological applications.

Timeline with milestone/deliverables (September 2025)

- Develop a deeper understanding of lithium-rich cathode materials with high energy densities and develop solutions to issues hindering major advances.
- Exploit new knowledge to inform the discovery of novel cathode materials for high energy density batteries (to increase EV range) while reducing reliance on critical materials in the supply chain.
- Use experimental, modelling, and cell performance evaluation to down-select novel materials for further synthetic and scale-up work.
- Connect basic science to the manufacturing process, with promising cathodes taken forward to synthesis at scale and cell testing, thereby demonstrating their performance for applications.
- Build on industrial partnerships for pathways to deliver technological impact.

Project innovations

CATMAT is developing a substantial core of knowledge that will lead to the development of the lithium-ion cathode chemistries of the future. The project's advances in high performance cathodes will be taken forward to innovation and potential commercialisation through its industrial partners, which will provide important pathways to technological impact. Partners include leading players in the chemical, materials, cell manufacturing and automotive sectors. Their perspectives on commercialisation and technology transfer are being woven throughout the project.

As the UK establishes its own lithium-ion battery manufacturing base, the potential for CATMAT to bring important innovations in cathode chemistry to commercial fruition is increasing considerably while the importance of inventing chemistries that boost the resilience of an ethical supply chain and improve recyclability is paramount.

Partners

University of Oxford (Lead)
University of Bath
University of Birmingham
University of Cambridge
University of Liverpool
University College London
CPI
Diamond Light Source (STFC)
UK Battery Industrialisation Centre (UKBIC)
+ 12 Industrial Partners

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SOLBAT – all-solid-state lithium-metal anode batteries

Addressing fundamental research challenges facing the realisation of solid-state batteries in automotive applications.

Grant contribution: £21,800,000

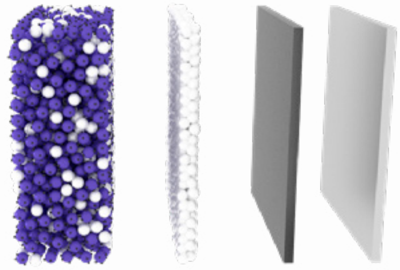

Image representation of solid-state battery structure

Executive summary

The ambition of SOLBAT is to demonstrate the feasibility of a solid-state battery with performance superior to lithium-ion in electric vehicle (EV) applications. An all-solid-state battery would revolutionise the EVs of the future and profoundly impact the consumer electronics and aerospace sectors. The successful implementation of a lithium metal negative electrode and the replacement of the flammable organic liquid electrolytes currently used in lithium-ion batteries with a solid would increase the range, decrease the charging time, and address safety concerns.

SOLBAT was established to address fundamental research challenges facing the realisation of solid-state batteries. Significant progress has been made including: understanding the role of voiding at the lithium-solid electrolyte interface on discharge, and the mechanism of lithium dendrite ingress and crack propagation/short circuit on charge; developing and implementing of a new method of solid electrolyte materials discovery; and understanding the effect of volume change in composite cathodes. SOLBAT is now using this fundamental understanding to provide solutions to these challenges.

Organised around three research areas, namely anode, cathode and electrolyte, with cross-cutting characterisation and modelling activities, the project aims to prevent dendrites and voiding, minimise operating pressure and facilitate scaling.

Timeline with milestone/deliverables

Anode

- Investigate structural changes during alloying and interfacial stability (March 2024).
- Understand the effect of interlayers on plating, stripping and critical current density (March 2024).
- Prepare and test new alloys and interlayers (March 2025).
- Clarify the effect of the current collector, interlayers and formation cycle in Li-less cells (March 2025).

Cathode (March 2025)

- Synthesise polymers with targeted electrochemo-mechanical properties for use as binders and coatings for use in composite cathodes.
- Demonstrate effect of composite cathode microstructure on performance and optimisation.

Electrolyte (March 2025)

- Investigate effect of particle size, processing and secondary phases on densification, microstructure, mechanical properties and supressing dendrites.
- Understand how the ceramic microstructure, density, grain size, shape, and particle surface composition affect the grain boundary resistances.
- Determine degradation mechanism of sulfide solid electrolytes in air and develop mitigation strategies to reduce moisture sensitivity.
- Develop models at the particle, component and cell level to guide materials research and microstructural design.

Project innovations

SOLBAT will tackle the barriers to realising solid-state batteries that are at the research level. New intellectual property will be developed and ideally converted into viable businesses by industrial partners and/or newly created commercialisation vehicles. Ultimately, a long-term effort in developing a strong and substantial core knowledge will provide a strong foundation for the commercialisation of this technology.

Partners

University of Oxford (Lead)
Newcastle University
Diamond Light Source
+ 3 Industry Partners

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NEXGENNA – sodium-ion batteries

Improving the energy storage, power and lifetime of sodium-ion batteries while maintaining sustainability, safety and cost advantages

Grant contribution: £13,900,000

St Andrews facility

Executive summary

NEXGENNA will develop the NEXt GENeration of Na-ion batteries. Its mission is to surpass LFP-graphite by improving the energy storage, power, and lifetime of sodium-ion while maintaining sustainability, safety, and cost advantages.

Sodium-ion batteries (NIBs) are an emerging battery technology, on the cusp of commercialisation, with promising cost, safety, sustainability and performance benefits when compared to lithium-ion batteries. They use widely available and inexpensive raw materials and existing lithium-ion production methods, promising rapid scalability. NIBs are an attractive prospect in meeting global demand for carbon-neutral energy storage, where lifetime operational cost, not weight or volume, is the overriding factor. Increasingly NIBs have characteristics comparable to lithium iron phosphate (LFP), suggesting that even mid-range automotive applications are possible.

NEXGENNA is taking a multi-disciplinary approach incorporating fundamental chemistry through scale-up and cell manufacturing. Many models of future renewable networks encompass storage for increased network resilience and to ensure the efficiency of small-scale renewable sources. The widespread use of commercial NIBs, that this project will facilitate, would aid the realisation of these models, and fulfil the need for low-cost electric transport options in the densely populated and polluted conurbations of developing economies.

Timeline with milestone/deliverables (September 2025)

- Discover and develop innovative electrode materials for higher performance, lower cost NIBs.
- Discover and develop next-generation electrolyte materials, giving higher sodium mobility and therefore higher power.
- Develop the understanding of interface formation and cell degradation to extend cycle life.
- Optimise key industry-relevant materials for scale-up.
- Demonstrate nascent NEXGENNA technology in pouch cells.
- Improve the industrial state-of-the-art by delivering a novel medium power, lost-cost sustainable or energy pouch-cell design.

Project innovations

The project benefits from strong academic-industrial links across the value chain, where industry partners bring strengths in terms of materials, cell fabrication and electrode manufacturing. By working closely with these partners, the project team will ensure that it readily exploits and successfully deploys cutting-edge science, making the UK a leader in this technology for stationary and low-cost batteries for transportation applications.

Partners

University of St Andrews (Lead)
Imperial College London
University of Cambridge
Imperial College London
Lancaster University
University of Birmingham
ISIS Neutron and Muon Source(STFC)
+ 3 Industry Partners

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LiSTAR – the lithium-sulfur technology accelerator

Developing commercially relevant lithium-sulfur batteries that surpass the capabilities of existing Li-ion technology.

An optical microscope image showing the formation of Li-metal dendrites during Li-S cell cycling captured by Faraday Institution Research Fellow Rhodri Owen, UCL

Grant contribution: £12,900,000

Executive summary

There is a need to develop batteries which supersede the practical capabilities of lithium-ion batteries to enable the electrification of applications including aerospace and heavier electric vehicles (EVs). While there are several realistic candidates, the Li-S chemistry combines relative technical maturity with a practical limit that places the technology in a unique position to facilitate commercialisation.

Compared with conventional Li-ion batteries, Li-S cells store more energy per unit weight and can operate in a wider operating temperature range. They may also offer safety and cost improvements. However, the widespread use of Li-S faces major hurdles that stem from sulfur's insulating nature, migration of discharge products leading to the loss of active material, and degradation of the metallic lithium anode. Scientists and engineers need to know more about how the system performs and degrades in order to overcome current limitations in the power density and lifespan of Li-S cells could unlock their use and see their translation from research into prototypes and industry.

LiSTAR is designed to address these challenges. The consortium is generating new knowledge, materials and engineering solutions, thanks to its application-guided approach, with dual focus on fundamental research at material and cell level, and an improved approach to system engineering. The project is addressing five key areas of research: cathodes and cathode interfaces; electrolytes and electrochemistry; anodes and new cell concepts; cell and system engineering; and Li-S characterisation. In doing so, the consortium is seeking to enable rapid improvements in Li-S technologies, with the aim of securing the UK as the global hub for the research, development and commercialisation of this emergent technology.

Timeline with milestone/deliverables (March 2025)

- Identify and develop routes for ultra-high energy cells and improve their durability.
- Improve safety via implementation of non-flammable electrolytes.
- Overcome key remaining commercialisation barriers for Li-S batteries, particularly the use of $LiNO_3$ to expand the operating temperature window.
- Demonstrate the scalability of components and feasibility of the technology at relevant scales.
- Understand and mitigate the anode-dominated degradation routes of Li-S cells.
- Demonstrate a battery management system to maximise performance.
- Develop bespoke advanced cell monitoring and diagnostic techniques from the outset of the chemistry's commercialisation.

The project aims to pave the way for multiple Li-S cell concepts: an 'energy' and 'lifetime' cell, with significantly improved operating temperature window, power and energy densities, and cycle life.

Project innovations

LiSTAR is tracking the technical requirements for Li-S batteries in strategic markets with near term opportunities such as aerospace applications. The project anticipates that the first viable commercial products will be for niche markets that place a premium on energy density, which will subsequently stimulate others (including automotive). Alongside the research partners, the consortium's industry partners have the capability to fast-track research to higher technology readiness levels and efficiently provide proof-of-concept manufacture of the new developments.

Partners

University of Oxford (Lead)
University College London
University of Cambridge
Coventry University
Cranfield University
University of Birmingham
Imperial College London
University of Nottingham
University of Southampton
University of Surrey
Aerospace Technology Institute
+ 5 Industry Partners

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Research Community

Convening the UK battery community at the Faraday Institution Conference 2023

Since its inception, the Faraday Institution has been actively building a unique and dedicated community. It consists of university researchers from various fields, committed industry partners, technology business development specialists, and a new generation of students. Together, they bring a diversity of perspectives and are united in their determination to overcome challenging scientific obstacles.

The research community is a powerhouse, comprising over 500 researchers from across 27 universities. Collaboration with international research groups and UK industrial partners ensures research directions remain commercially relevant and the likelihood of success is maximised. By combining the strengths of highly competitive university research groups across the UK, the Faraday Institution has marked a significant moment of change for the research community, establishing a new model for conducting nationally important strategic research.

Community building initiatives undertaken by the Faraday Institution, alongside training partner Skills 4, include the provision of Inclusion Ally workshops - providing practical ways for the community to improve inclusivity - and a THRIVE career development programme for a cohort of researchers who identify as being in a minority in their work environment. The Faraday Institution Community Awards are a way to celebrate successes and reward members of the community who demonstrate excellence and behaviours in line with the organisation's mission and values – and who go above and beyond what would normally be expected.

The Faraday Institution Conference, held in September 2023 with the theme of driving towards sustainable electrification of the UK, served as a resounding endorsement from the community. As part of the Institution's objectives of being the trusted national convener for battery science and building a broader community of battery researchers, the conference doors were opened to academics working within and beyond Faraday Institution projects, to UK industry and policy makers in the battery space, and to overseas partners. 52% of delegates were academics already working within the Faraday Institution community, 27% were from other UK academic institutions, 13% from industry and 7% from government. It was a pleasure to convene this thriving and diverse community for three days of science dissemination and networking. The buzz in the room and sense of community was palpable, and we look forward to creating a similar atmosphere at the 2024 Conference hosted by Newcastle University from 10-12 September.

2023 Conference success metrics:

- 530 delegates
- 71 speakers
- 9 themed sessions
- 160 posters
- 21 exhibiting companies
- 150 organisations represented of which 55 were industry or government
- 231 expressions of interest to speak or present posters

The thriving academic field of battery research and the collaborative community that is being built offer a wealth of opportunities for researchers at every level to grow their careers in the UK battery sector, be it in academia, industry or policy, with a significant proportion of the community receiving external recognition and promotions.

The 2023 Community Awards winners

Early-Stage Commercialisation

The Faraday Institution has a mission to not only sponsor fundamental, world-class battery research, but to develop resulting discoveries into technologies with significant impacts on the competitive advantage of the British manufacturing industry.

The Institution does this by actively promoting novel means of translating the results of university battery research into technological advancements, undertaking activities that go well beyond the remit of a standard research organisation. See, for example, the support for UK-based start-up OXLiD, which has led to a successful acquisition by Gelion, and retained a significant lithium-sulfur battery IP portfolio for the UK.

The Faraday Institution has developed collaborative links with more than 122 industrial partners in the automotive, aerospace, battery, and materials sectors, working in collaborative relationships that help to identify application needs as the organisation continues to reshape its research programmes.

TSCAN Methodology

The Faraday Institution has developed an analytical methodology to assess early-stage commercialisation potential for each of its research projects. The assessment results in a bespoke approach to commercialisation tailored to each project, the prioritisation of limited resources and the development of consortia that are investment ready. The process has substantial input and support of the academic research teams and industrial partners (where relevant). The assessment is made up of the five components: Technology, Significance, Competition, Action and Investment. The methodology continues to change and develop.

Commercialising Modelling Research

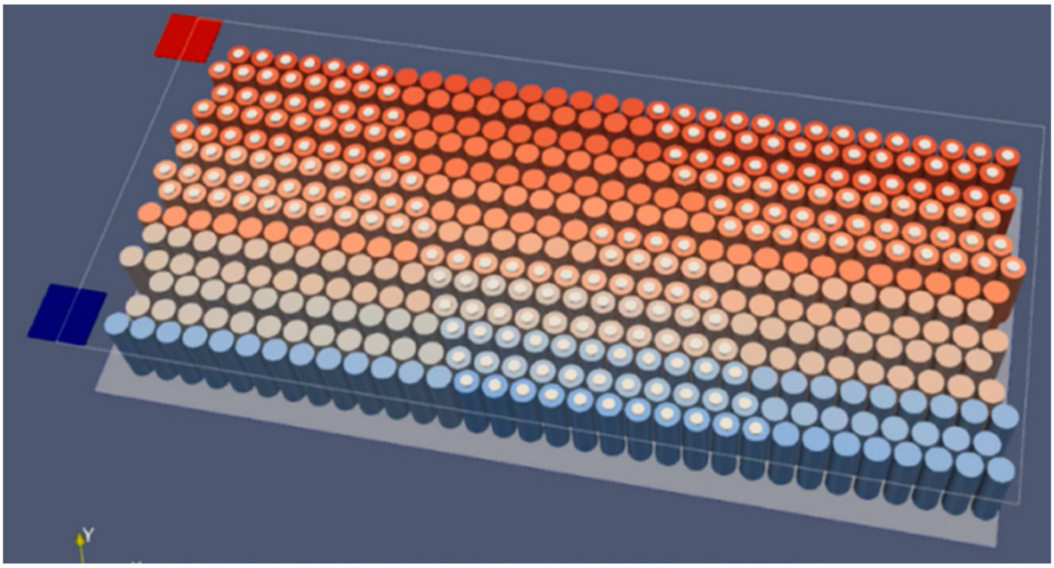
As an example of the innovative routes the commercialisation team is pursuing, the Faraday Institution has launched the Battery Parameter eXchange (BPX). It is an open standard to support the wider adoption of 'industrial strength' physics-based modelling by the battery industry globally. BPX is 'usage driven' and is delivering Faraday-funded research in a form directly useable day-to-day by engineers in industry organisations who are developing batteries.

The standard has been downloaded by over 100 organisations, with. 70% of these from industrial users across a range of battery industry sectors. The feedback from industry, especially OEMs, is that BPX has been very useful in stimulating thinking and discussion, and has helped to highlight many common challenges in industrial battery modelling. Industry organisations have provided strong encouragement to further develop the BPX standard, with various companies being collectively engaged in the process and with the Faraday Institution acting as the convening entity. The commercialisation team believes this standards-based approach of delivering research value directly to engineers based in industry is a valuable supplement to other Faraday Institution research dissemination paths, and one that is more immediately relevant and that can drive further industrial engagement.

Commercialisation project portfolio

The Faraday Institution's commercialisation portfolio also includes (as of March 2024):

- 16 Industry Sprints, comprising small, focused teams of researchers to solve a commercially relevant research opportunity identified from within the research programme and prioritised by an industrial partner.
- 14 Entrepreneurial Fellowships, supporting researchers across the UK looking to create new businesses and commercialise battery technologies.
- 18 Industry Fellowships, a programme to strengthen ties between battery researchers working in industry and academia.



Thermal modelling of a Tesla battery pack

Inspiring and Training the Next Generation

The growing national need for energy storage researchers is evident, in order to support research and development for a UK domestic battery manufacturing industry. Aware that next-generation energy storage technologies will come from future scientists and engineers, the Faraday Institution is committed to developing a dynamic and diverse pool of talent for the sector. The organisation plays an active role in inspiring, attracting and retaining young people, particularly those from groups historically underrepresented in STEM (science, technology, engineering and maths), to consider careers in the field. This involves nurturing a diverse talent pool at various stages.

Researcher Professional Development

With 75% of Faraday Institution researchers aged below 40, a significant portion of the battery community comprises early-career researchers who are actively seeking opportunities to advance their careers. The organisation provides a range of continuing professional development opportunities for early-career scientists and engineers as they build their researcher identities. The Early Career Researcher (ECR) Committee creates and delivers high-quality training opportunities and events, including the ECR Conference and Training Event and annual Faraday Career Week. Researchers and project managers receive a training budget of £2,000 each year dedicated to their professional development.

PhD Training Programme

Since its inception in 2018, the Faraday Institution PhD Training Programme has supported 85 studentships. Collaborating across partner universities to provide a bespoke curriculum that encompasses technical, commercial, and transferable skills, the programme's primary goal is to nurture the next generation of battery experts, empowering them to emerge as successful leaders in their respective fields.

To ensure the proficiency of PhD researchers, the programme offers networking opportunities and specialised battery-related courses taught by academic and industry experts. These equip researchers with comprehensive knowledge and essential skills to maximise the potential of their research projects. Moreover, the organisation partners with expert training providers to deliver sessions such as presentation skills, project management, negotiation skills, as well as thesis and grant writing workshops. 100% of the first cohort of researchers have now secured permanent positions in the battery sector.

A further 100+ affiliated PhD researchers are valued members of Faraday Institution research projects. The organisation encourages PhD researchers to undertake three-month internships to explore opportunities that further their skills, grow their networks and/or showcase future battery-related careers, and enhance their projects.

Undergraduate Attraction

A range of initiatives attract and inspire undergraduates toward energy storage careers and showcase the opportunities the battery sector has to offer. To date, the Faraday Institution has funded 300+ Faraday Undergraduate Summer Experience (FUSE) internships, giving undergraduate students the opportunity to undertake paid eight-week placements with battery researchers at member universities. Alongside the research, FUSE interns have a series of cohort calls. The FUSE internship programme is also proving an effective feeder programme for the organisation's PhD Training Programme, while other initiatives include careers webinars on Battery Day and sponsorship of Formula Student.

FUSE undergraduate interns at the University of Oxford

STEM Outreach

The Faraday Institution has trained over 85 PhD researchers as STEM Ambassadors who are now adept at delivering presentations about their research in a manner that is relatable, engaging, and creative, effectively reaching diverse audiences. The organisation makes available a wealth of battery-related STEM outreach resources and over 13,000 young people have had the opportunity to learn about batteries through engaging with the "Faraday Fully Charged Battery Box."

Faraday Institution PhD researchers at WMG Battery School 2023

Informing Policy

The Faraday Institution regularly advises a range of audiences on the UK's transition to energy storage technologies to ensure that members of the public, public bodies, policy makers and public institutions are well informed. Representing a national effort for energy storage, the Faraday Institution is committed to being a voice to help guide government and industrial communities.

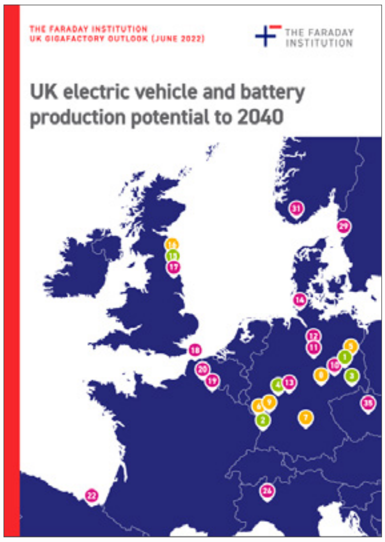
Faraday Insights

Through its concise "Faraday Insights" briefings, the Faraday Institution provides independent, evidence-based understanding of battery economics, societal issues, capabilities and competitive position. The organisation brings together industry, trade groups, government and academia, bridging knowledge gaps and informing policy makers and regulatory bodies on the energy transition.

19 Faraday Insights have been published, including most recently:

- Powering the Skies: The Rise of Electric and Low-Carbon Aircraft.
- Developments in Lithium-Ion Battery Cathodes.
- Improving the Safety of Lithium-ion Battery Cells.
- The Micromobility Revolution Gathers Momentum.
- The Value of Modelling for Battery Development and Use.
- The Importance of Charging Infrastructure to the Electric Vehicle Revolution.

Micromobility Insight report



EV report

Faraday Reports

The Faraday Institution's report 'UK Electric Vehicle and Battery Production Potential to 2040' continues to be the definitive resource on the demand for UK-based gigafactories. The Faraday Institution predicts that there will be demand for ten UK-based gigafactories by 2040, each producing 20 GWh per year of batteries. The report has had 250+ media citations since it was first published in 2019, and was cited in the UK Government's announcement in July 2023 that Tata Group is to invest over £4 billion in UK gigafactory, creating thousands of jobs.

As an example of another in-depth report commissioned by the Faraday Institution, a report was published in April 2023 analysing how hydrogen and battery technologies are likely to be used in different sectors within the UK, including transportation, manufacturing, the built environment, and power, to 2050. Both technologies are anticipated to play an increasingly vital role as the UK transitions to a low-carbon future to address critical concerns of climate change and energy security. Batteries and hydrogen have distinct characteristics and should largely be viewed as complementary rather than competing technologies. Both will require significant technological advance and extensive scale up of manufacturing and deployment if the UK is to meet its obligation to reach net zero by 2050.

Input into Inquiries and Consultations

The Faraday Institution provides detailed written and oral responses to government inquiries and consultations to inform the UK's transition to energy storage technologies.

Recent examples include:

- House of Commons Business and Trade Committee Inquiry into Batteries for EV Manufacturing.
- House of Lords Science and Technology Committee Inquiry into Long-duration Energy Storage for Net Zero.
- House of Lords Environment and Climate Change Committee Inquiry on Electric Vehicles.

About Innovate UK

Innovate UK, part of UK Research and Innovation, is the UK's innovation agency. It works to create a better future by inspiring, involving and investing in businesses developing life-changing innovations. Its mission is to help companies to grow through their development and commercialisation of new products, processes and services, supported by an outstanding innovation ecosystem that is agile, inclusive and easy to navigate.

For more information visit www.ukri.org

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