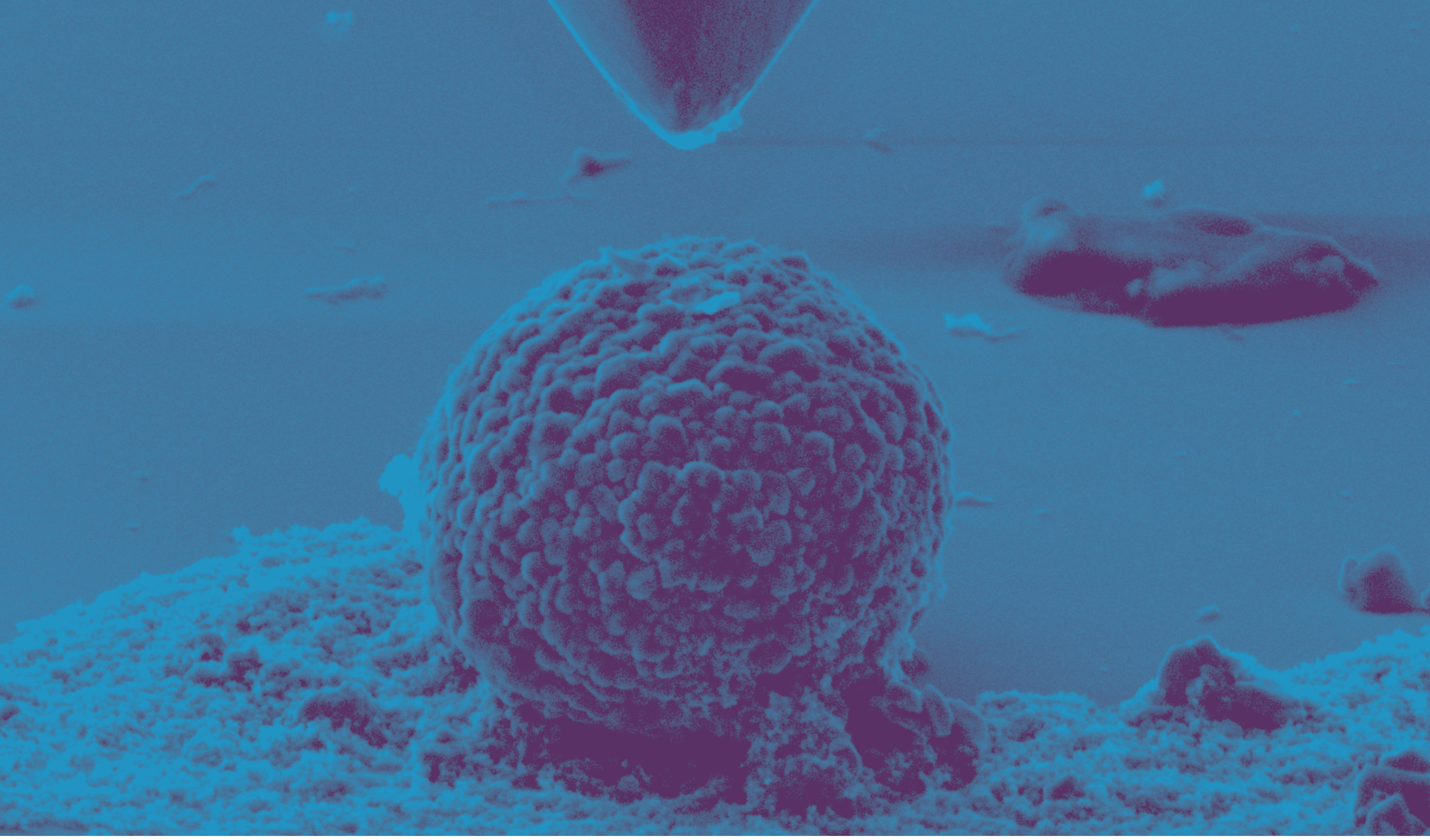
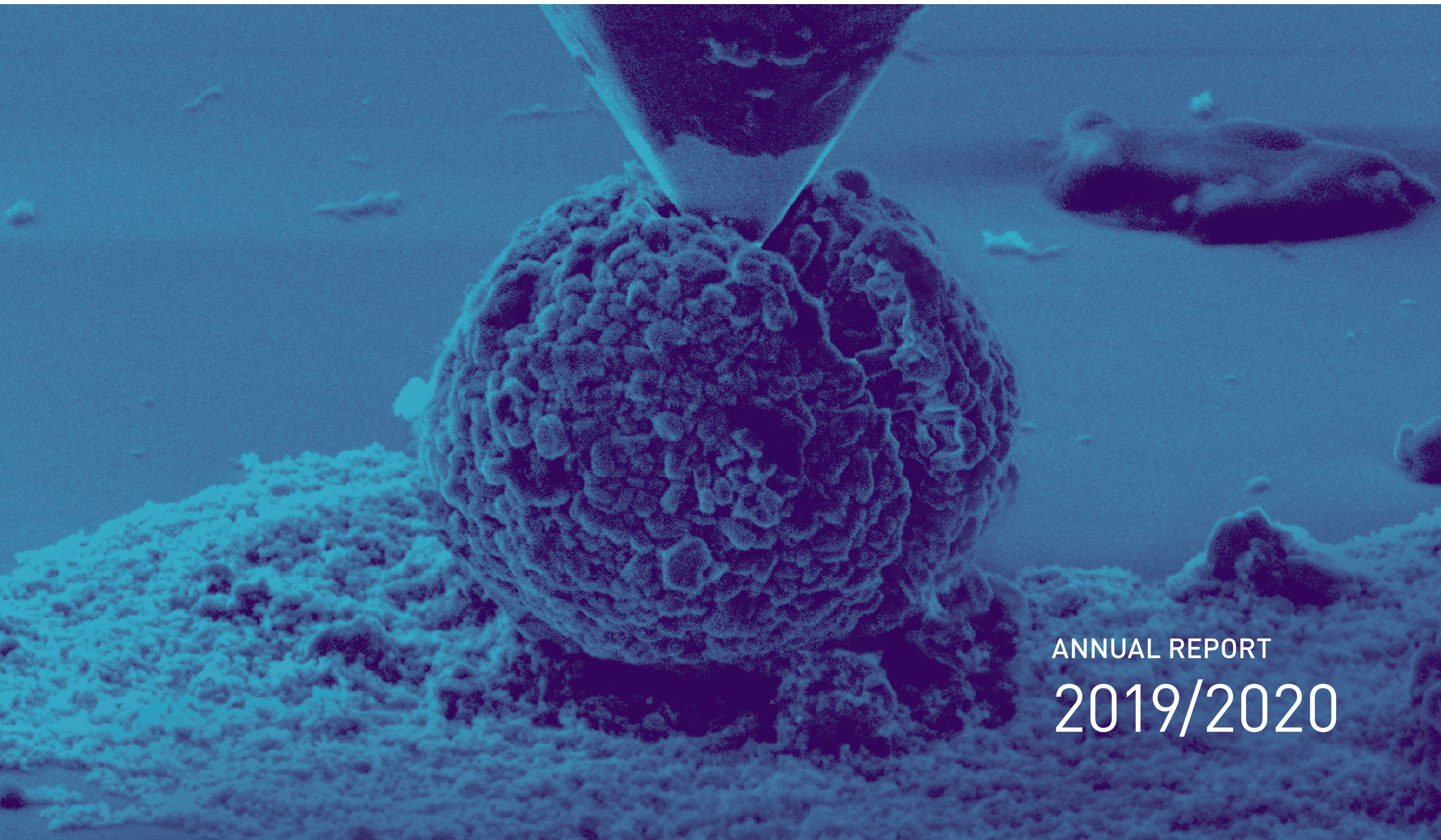


Powering Britain's Battery Revolution

THE FARADAY INSTITUTION



ANNUAL REPORT
2019/2020

THE FARADAY INSTITUTION

Powering Britain's Battery Revolution

Annual Report 2019/2020

*Cover image: In-situ SEM compression testing of NMC particles – investigating the mechanical integrity of future cathode materials.
From research by Arron Bird and Laura Wheatcroft at the Sheffield NanoLAB for the Faraday Institution FutureCat project.*

Contents

The trustees and strategic report and the statement of financial activities including the income and expenditure account can be found at www.faraday.ac.uk/2019-20-annual-report

Outcomes and Impacts

An internationally recognised **research powerhouse**

450 researchers across **21 UK universities**

Committed over £100m to energy storage research

9 large-scale research projects and
3 characterisation projects

150+ high-quality scientific publications to date

91% in the top quartile journals

66% in the top 10% of journals

44% in the top 10% most cited papers worldwide between 2017 and 2020

50% include international collaborators

Across 122 institutions and 5 continents

Commercially relevant impacts

50+ industrial partners
5 spin-out companies
4 Industrial Sprints
4 IP disclosures
3 copyrighted tools
2 patents

Energy access

Member of
3 international consortiums

Producing
2 major reports

Impact to policy makers

10 Faraday Insights

Participation in **3 policy consultations**

3 presentations to All Party Parliamentary Groups

1 House of Commons adjournment debate

Public engagement

100+ pieces of press coverage

over 40 in top-tier nationals, trade publications, radio and television – since November 2019

Over 200k online views from the Royal Institution series of lectures on batteries

Next generation of talent

44 PhD researchers in doctoral training programme

100 undergraduate interns and **10 Faraday Scholars**

19 Faraday Masterclasses and 6 Faraday TECH workshops, providing 200+ early career researchers with 2,800 hours of training

7,500+ young people engaged through the Fully Charged Battery Box programme, spanning all parts of the UK

We have held to our vision of bringing together four pillars for economic success: research, training, analysis, and commercialisation.

Statement from the Chair

This has been a decisive year for the Faraday Institution. The organisation has raised itself remarkably quickly from a bold idea in the heads of a number of key experts in battery science and technology to a highly credible, impactful and internationally recognised voice on the global stage.

In this Annual Report you will read about how we have hit our stride and set the pace for delivery. Our research programmes have matured to include nine major projects spanning both lithium-ion and beyond lithium technologies as well as three characterisation projects. Scientific discoveries have led to highly cited publications, a suite of patents, and commercial spin outs. This is growing evidence that the work we are doing is hitting its mark. The next generation of battery researchers have found their footing through a range of innovative training programmes. And as a community, we have held to our vision of bringing together four pillars for economic success: research, training, analysis, and commercialisation.

In September, we welcomed our new CEO, Professor Pam Thomas, to lead the organisation to drive forward commercially relevant energy storage research for the benefit of the UK. In Pam Thomas we have found a passionate leader and excellent scientist who knows first-hand what it takes to translate research into commercial value.

This year ushered in a new reality in the form of the pandemic that has altered our world in profound ways, affecting us all both personally and professionally.

A steadfast commitment of the Faraday Institution research community was demonstrated when research plans were disrupted by coronavirus. This included an unprecedented shift to remote working, quick development of screening protocols and other safety measures and the detailed efforts to reopen science laboratory facilities in early summer. It is a testament to the determination, resilience and collective efforts of our community and our university partners that workplans were reprioritised and redefined to keep research progressing to the greatest extent possible.

Even amid this crisis, as a community of researchers, we stand at a unique moment in the UK's quest towards Net Zero and to place energy storage technologies centre stage to deliver a green recovery and to reinvent sectors from road transport and aviation to power generation and distribution. Energy storage has the great potential to rapidly transform society, be commercially disruptive, and provide significant economic and environmental benefit to the UK and beyond.

I would like to acknowledge the commitment and dedication of our executive team and staff, our trustees, the Faraday Institution research community, our supporters and advisers in government, and our many new partners as we continue with our important work.

Peter B. Littlewood
Chair

We are living through a special time when research and development will transform radically how energy is stored and deployed.

Statement from the CEO

I am pleased to share the Faraday Institution's 2019-2020 annual trustees' report, which outlines the progress we have made in energy storage research, education, commercialisation and analysis, our achievements and milestones. We are happy to acknowledge support from EPSRC-UKRI and the Faraday Battery Challenge that makes such achievements possible. The report also provides an update on the status of our funding and our financial results for the 2020 fiscal year.

This is an exciting time for battery research. We are living through a special time when research and development will transform radically how energy is stored and deployed – not only for transport, but also for capturing wind and solar energy for use on the grid. The commitments across the globe to decarbonisation and 'Net Zero' have never been more powerful and the context for battery research never more relevant.

The Faraday Institution set out from its inception to define itself by a commitment to being pioneering, visionary and resilient, and this year these values have been thoroughly tested. Our community, like so many others, has been strongly impacted by the coronavirus pandemic, but together with our partners, we have persevered and achieved much during lockdown. In some cases, research groups were able to keep labs running or ensured that labs were amongst the first to reopen. Projects reprioritised activities and set up new ways of working to maintain productivity with reduced lab capacities. We thank them for their tremendous efforts.

As incoming CEO, I can attest to my confidence in our ability to build an innovative and inclusive community with an enduring impact. I recognise, of course, that there is much important work yet for us to do to make these things happen. This is a critical moment for the Faraday Institution to give strong focus and support to those research areas where significant commercial impact for the UK shows the most promise.

In these pages, we highlight that Faraday Institution research discoveries are being patented and put on the path to commercialisation. These include a new type of sensor that can take samples of material from inside an operational battery, a novel solid-state electrolyte material, and a rapid recycling method that enables electrode materials to be stripped up to 100 times faster than alternative methods. With support from the Faraday Institution, five spin-outs have been launched and hired teams - in some cases, they have also taken on their first customers. Industrial engagement is deepening, and we are looking forward to the launch of our new Commercialisation Strategy pending early in the New Year.

Internationally, the Faraday Institution is committed to ensuring that energy storage technologies can be brought to bear on the complex energy challenges facing society. We are thankful for the additional support from UK Aid and the Foreign, Commonwealth and Development Office that is enabling us to advance the use of batteries to provide access to cheap, sustainable and reliable energy in emerging economies.

Our successful progress towards our goals continue to build upon the solid foundation provided by the UK Research and Innovation ecosystem – such as the world-class STFC-UKRI national facilities of which our work takes full advantage. Our achievements are made in partnership with government, universities, research organisations and businesses. We benefit from this support as we seize upon the potential of our research programmes to deliver value for the UK.

I would like to thank our research community for the resilience, commitment and dedication they demonstrated this year, as they have continued to progress during these turbulent and uncertain times. I also thank our staff in headquarters, our trustees and our funders in the Faraday Battery Challenge and EPSRC-UKRI for their ongoing support and accomplishments.

I am both excited and proud to have joined the leadership team of the organisation and look forward to working with the whole Faraday Institution community.

Pam Thomas
Chief Executive Officer

About the Faraday Institution

The Faraday Institution is powering one of the most exciting technological developments of the 21st century – Britain's battery revolution. As the world competes to define the future of energy and automation, the Faraday Institution is accelerating commercially relevant research needed for future battery development to power the transport and energy revolution for the UK.

Engineering and Physical Sciences Research Council

Faraday Battery Challenge

THE FARADAY INSTITUTION

The UK Government has entrusted the Faraday Institution as a key delivery partner for the Faraday Battery Challenge to bring forward bold and transformational change in mission-inspired energy storage research.

The Faraday Institution was designed to be the national focus for energy storage research, analysis, commercialisation and training. Funded through EPSRC-UKRI, it serves as the UK's flagship battery research programme to build and manage focused, substantial and impactful research projects in areas of fundamental science and engineering that have significant commercial relevance and potential, defined at a high level by industry and delivered by a consortium of universities and businesses. The Faraday Institution delivers training to the next generation of battery scientists and engineers, who will go on to work in both academia and industry and be responsible for facilitating the transition of new technologies to market.

Headquartered at the Harwell Science and Innovation Campus, the Faraday Institution is a registered charity with an independent board of trustees.

Our Mission

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 to work 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.

Our Research Community

In 2018, the Faraday Institution embarked on assembling a unique community – dedicated university researchers from a multitude of fields and UK universities, 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 efforts to overcome tough scientific challenges: to reduce battery cost, weight, and volume; improve performance, efficiency, and reliability; develop scalable designs; improve manufacturing abilities; develop whole-life strategies; and accelerate the outputs towards commercial outcomes.

Today this research community is a powerhouse – 450-strong from across 21 universities – working with the direction and guidance of UK industrial partners. The Faraday Institution has combined the strengths of highly competitive university research groups across the UK to work as active collaborators, marking a sea change for the research community and representing a new model for conducting commercially relevant research. The Faraday Institution's long-term vision to develop future generations of energy storage scientists and engineers is coming to fruition. To date, 44 PhD researchers are directly supported through the Faraday Institution's doctoral training programme.

Promoting Equality, Diversity and Inclusion (EDI)

To build and support a world-class energy storage research community, the Faraday Institution is committed to creating and sustaining a safe, welcoming, diverse and inclusive environment. Today this research community is brought together by a shared value that through interdisciplinary collaboration and by celebrating a diversity of ideas, opinions, knowledge and people, research excellence will follow. Beyond research disciplines, diversity within this community takes many other forms including age, race, ethnicity, gender, sexual orientation, gender identity, disability, national origin and religion. In recognition of this, the Faraday Institution aspires to maintain an inclusive environment where all individuals can thrive, feel they belong and have a voice.

An Equality, Diversity and Inclusion working group, comprising researchers from the community, advises the Faraday Institution to ensure best practices are put into place and opportunities made fully available. As approximately 30% of the research community are women, gender diversity has been an important focus for 2020. Improvements in recruitment process guidance and reporting for both FUSE intern and doctoral programmes led to a marked increase in candidate and cohort diversity. In particular, the 2020 PhD cohort reached gender balance with an equal number of women and men entering the programme. Challenges exist for our diverse and geographically distanced research community, especially during a period of lockdown and uncertainty as referenced in the EDI blog. Community training on inclusion, behaviour, intersectionality and wellbeing sought to focus on actions that individuals could take to apply best practice to their own situations. The Faraday Institution has launched an *EMPOWER* programme for women led by Skills4, as part of its 2020 focus on gender diversity priorities in the community and will continue in the coming year. Its membership in WISE, a campaign for gender balance in science, technology and engineering, enables collaboration with a wider network of experts who are championing best practice in this area. The momentum built from these efforts will carry the community forward and will make us collectively stronger.

Building a new community

Over half of the scientists engaged as co-investigators on the Faraday Institution's projects are new to battery science, having transferred their expertise from other areas of chemistry, materials science, physics and computing.

Our Partners

From industry to academia, from regional government to international partnerships, the Faraday Institution is part of a growing innovation network that seeks to transform the world we live in through electrification and energy storage. To successfully deliver the UK's mission for a fully electrified economy the Faraday Institution is convening a range of UK and international organisations to engage with one another, efficiently collaborate and effectively partner.

Multidisciplinary Power from the UK's World-Class Universities

To solve battery challenges that industry faces, the Faraday Institution brings together:

50+ industry partners

21 universities

With 4 ranked in the top 20 in the Times Higher Education World Rankings 2020

University of Oxford (no. 1)
University of Cambridge (no. 3)
Imperial College London (no. 10)
UCL (no. 15)

450+ researchers

Across multiple disciplines including chemical engineering, chemistry, data and computer science, mechanical engineering, electrical engineering, law, materials science, maths and physics

Cardiff University / Prifysgol Caerdydd — Imperial College London — Lancaster University — Newcastle University
Oxford Brookes University — UCL — University of Bath — University of Birmingham
University of Cambridge — The University of Edinburgh — University of Leicester — University of Liverpool
Manchester 1824 — University of Nottingham UK | China | Malaysia — University of Oxford — University of Portsmouth
The University Of Sheffield. — University of Southampton — University of St Andrews — University of Surrey — Warwick The University of Warwick

University Partners

A large-scale endeavour of this significance necessitates an extensive national reach. The Faraday Institution draws its strength from 21 UK universities, from St Andrews to Southampton, including world-leading universities Oxford, Cambridge, Imperial and University College London.

Government Partners

Across the UK Government, the Faraday Institution regularly provides evidence-based insights into topics related to energy storage, electric vehicles, materials supply chain and recycling. It participates in both formal and informal knowledge exchanges with Number 10, Department for Business, Energy & Industrial Strategy (BEIS), Foreign, Commonwealth and Development Office, Department for International Trade, UK Research and Innovation, the Office for Low Emissions Vehicles, and both Houses of Parliament.

UKRI

The Faraday Institution engages across the most relevant parts of the UKRI research and innovation landscape to accelerate its mission, ensuring access to world-class facilities and building beneficial partnerships with other institutes and challenges. The Henry Royce Institute, for example, has provided state-of-the-art equipment and training to Faraday Institution research teams, including those at Oxford, Manchester and Cambridge. The National Physical Laboratory (NPL) directly supports four of the Faraday Institution research projects through materials and cell testing.

The Faraday research community actively benefits from access to the nation's world-class STFC-UKRI facilities at Harwell Science and Innovation Campus, such as Diamond Light Source and ISIS Neutron and Muon Source as well as from active engagement with other delivery partners from the Faraday Battery Challenge. Discoveries from the Faraday Institution's research programmes have led to numerous applications into Innovate UK for collaborative research and development follow-on work.

'The Faraday Institution report on UK battery demand was used extensively to evidence the requirement for UK based automotive battery gigafactories and therefore the need for the Automotive Transformation Fund (ATF) to support establishing them. The report underpins a significant element of the business case for the ATF and has therefore been instrumental in communicating the urgency around the need for automotive supply chain transformation. The UK demand for batteries and other key elements from the report are also extensively used in discussions with potential inward investors to the UK and have been cited in the official UK government prospectus to help attract these investors to the UK.'

Ian Constance, Chief Executive Officer at the Advanced Propulsion Centre UK

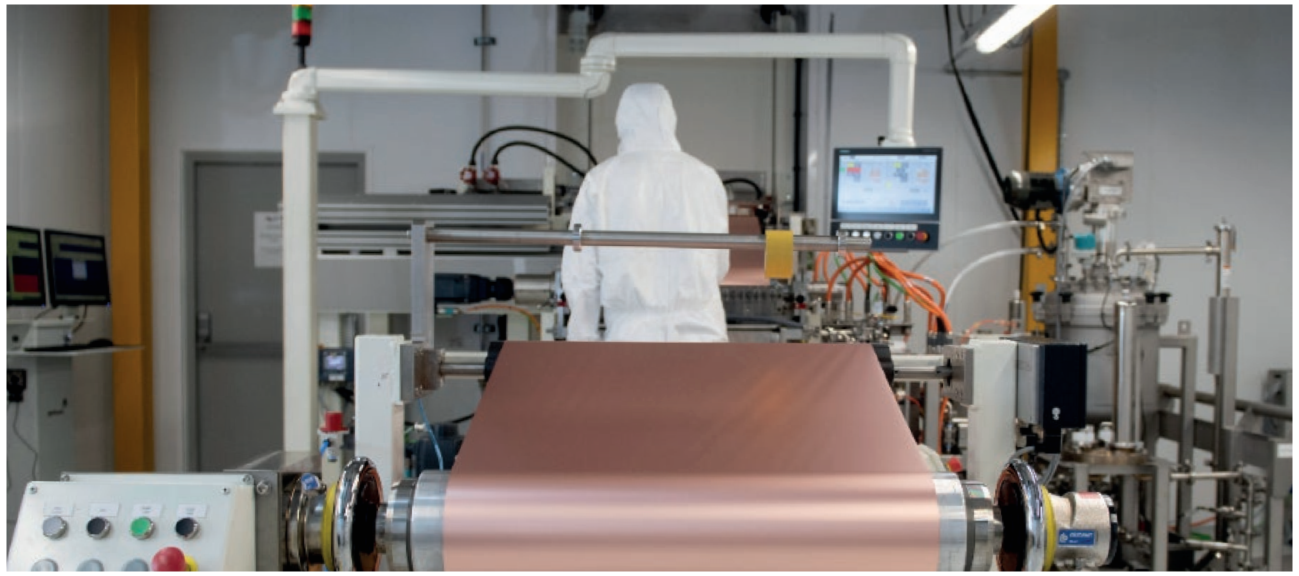
Industrial Partners

The Faraday Institution has developed strong and significant collaborative links with a wide range of industrial partners, including both established and emerging volume and specialist vehicle manufacturers, automotive and aerospace engineering companies and suppliers, battery manufacturers and the companies in the chemicals and materials sector.

This engagement continues to both grow and deepen as Faraday Institution research matures, ensuring research directions remain commercially relevant and to increase probabilities of success. Industrial Sprints, Industry Fellowships, and other collaborative opportunities are flourishing and demonstrating value.

The Faraday Institution's membership on the Automotive Council Skills Working Group is enabling the sector to anticipate and deliver the skills needed to fully electrify auto production and serves as a model for other sectors, such as aero and grid. The role of the Faraday Institution, working with the Automotive Council, WMG and the High Value Manufacturing Catapult, in developing a National Skills Framework for electrification of the auto sector will be essential to meet this need. Phase one of this effort concluded in 2020.

AGM Batteries
Arcola Energy
Axion Group
BBOXX
Benchmark Mineral Intelligence
BenevolentAI
BMW Group
British Metal Recycling Association
cap hpi
Carl Zeiss Microscopy
Caterpillar
Claytex Services
Continental
CPI
Denchi Power
Deregallera
Echion Technologies
Eco-bat Technologies
Envision AESC
Exawatt
Faradion
Horiba Mira
Huntsman Corporation
Ilika Technologies
Imerys Minerals
Intelligens
Johnson Matthey
KU Leuven
KUKA Robotics
Lancaster Materials Analysis Ltd
Less Common Metals
LG Chemical Investment
Lianhetech
McLaren Automotive
Morgan Advanced Materials
Nexeon
nVIDIA
Omicron Nano Technology
Oxis Energy
Potenza Technology
PV3 Technologies
QinetiQ
Rolls-Royce
Samsung
Shell International Exploration and Production
Shell Research UK
SHIELD Investment Management
Siemens
Silson
Talga Technologies
Thatcham Research
Thermo Fisher Scientific
Toyota Motor Europe
William Blythe
Williams Advanced Engineering



The newly opened UK Battery Industrialisation Centre. UKBIC is a pioneering facility that bridges the gap from laboratory or prototype scale battery technology and mass production. When fully operational, it will provide the Faraday Institution research community with a new tool in its arsenal to pull research out of the lab and into production.

International Partners

The Faraday Institution benefits from formal relationships with US research organisations like the Joint Centre for Energy Storage Research, Argonne National Laboratory, and the National Renewable Energy Laboratory. In Canada, it is forging ties with centres of excellence and councils such as the National Research Council Canada. In Europe, the Faraday Institution has joined Battery 2030+, a large-scale and long-term European research initiative with the vision of inventing the sustainable batteries of the future, and the Interreg North-West Europe (NWE) STEPS programme of the European Regional Development Fund to strengthen the competitiveness of NWE innovative storage providers.

To transform energy access across the world and to ensure sustainable practices are in place across the battery value chain, the Faraday Institution participates in the Global Battery Alliance of the World Economic Forum and the Energy Storage Partnership of the World Bank Group. It also contributes to a consortium effort with the Shell Foundation to trial micro-grid technology in Nigeria. This work is supported by UK Aid and the Foreign Commonwealth & Development Office.

STEM and Outreach Partners

To ensure the public has the best information on the opportunities and challenges of energy storage, and that future generations of scientists and engineers from all backgrounds are inspired to pursue promising STEM careers, the Faraday Institution has engaged delivery partners including the Royal Institution, SEO London, WISE, The Curiosity Box and the Primary Science Teaching Trust (PSTT).

Company support

More than 50 companies from the UK – including leading corporations in the FTSE 100 index – along with several international research organisations provide financial and non-financial support to the Faraday Institution's research programmes.

Indistrial Sprint: Thermally OPtimised BATtery system (TOPBAT)

Launched in July 2020, an Industrial Sprint project with AMTE Power and researchers from the Multi-Scale Modelling project is seeking to identify improvements in battery pack and cell design to better control cooling at the cell, module and pack level. Improvements in useable energy at the pack level of 10-20% or more are expected, translating into either a longer driving range for electric vehicles or cheaper battery packs. Improvements in lifetime at the pack level of 100-200% are also expected, significantly reducing the cost of ownership and increasing opportunities for second life applications of batteries.

Board of Trustees

Our Board of Trustees brings multifaceted perspectives and experiences from academia, industry and public service to the role of advising the Faraday Institution. Board members serve as ambassadors and advisers in support of the Faraday Institution's aims.

Chair
Professor Peter B. Littlewood
Professor of Physics
The University of Chicago

Vice Chair
Stephen Heidari-Robinson
Co-founder and
Managing Director
Quartz Associates

Dr Jeff Chamberlain
CEO
Volta Energy Technologies

Dr Andreas Docter
Director of Electric Powertrain
Jaguar Land Rover

Professor Kristina Edström
Director, Ångström Advanced
Battery Centre (ÅABC)
Uppsala University, Sweden

Dr Johney Green Jr.
Associate Laboratory Director
US National Renewable Energy
Laboratory (NREL)

Dr Julie Maxton
Executive Director
The Royal Society

Dr Jorge Pikunic
Managing Director
Distributed Energy
and Power Centrica

Professor Mark Spearing
Vice President
Research and Enterprise
University of Southampton

Dr Maurits van Tol
Chief Technology Officer
Johnson Matthey

Sir Oliver Letwin
Senior Advisor to
the Board of Trustees

Executive Team

Pam Thomas
Chief Executive Officer
Professor of Physics
University of Warwick

Susan Robertson
Chief Financial Officer

Peter G Bruce
Chief Scientist
Wolfson Professor of Materials
University of Oxford

Stephen Gifford
Chief Economist

Ian Ellerington
Head of Technology Transfer

Matthew Howard
Head of Engagement and Education

For complete biographies, see Appendices.

About the Faraday Battery Challenge

The Faraday Battery Challenge is part of the Industrial Strategy Challenge Fund, overseen by the Department for Business, Energy and Industrial Strategy (BEIS), which is designed to ensure that research and innovation take centre stage in the government's Industrial Strategy.

With investment into the Faraday Battery Challenge of £318 million between 2017 and 2022, the challenge aims to support a world-class scientific, technology development and manufacturing scale-up capability for batteries in the UK. The challenge is focused on developing cost-effective, high-performance, durable, safe and recyclable batteries to capture a growing market through three key elements:

Research

Funded through the Engineering and Physical Sciences Research Council (EPSRC), part of UK Research and Innovation, the Faraday Institution is a £100 million research institute that is accelerating the fundamental research needed for future battery development.

Innovation

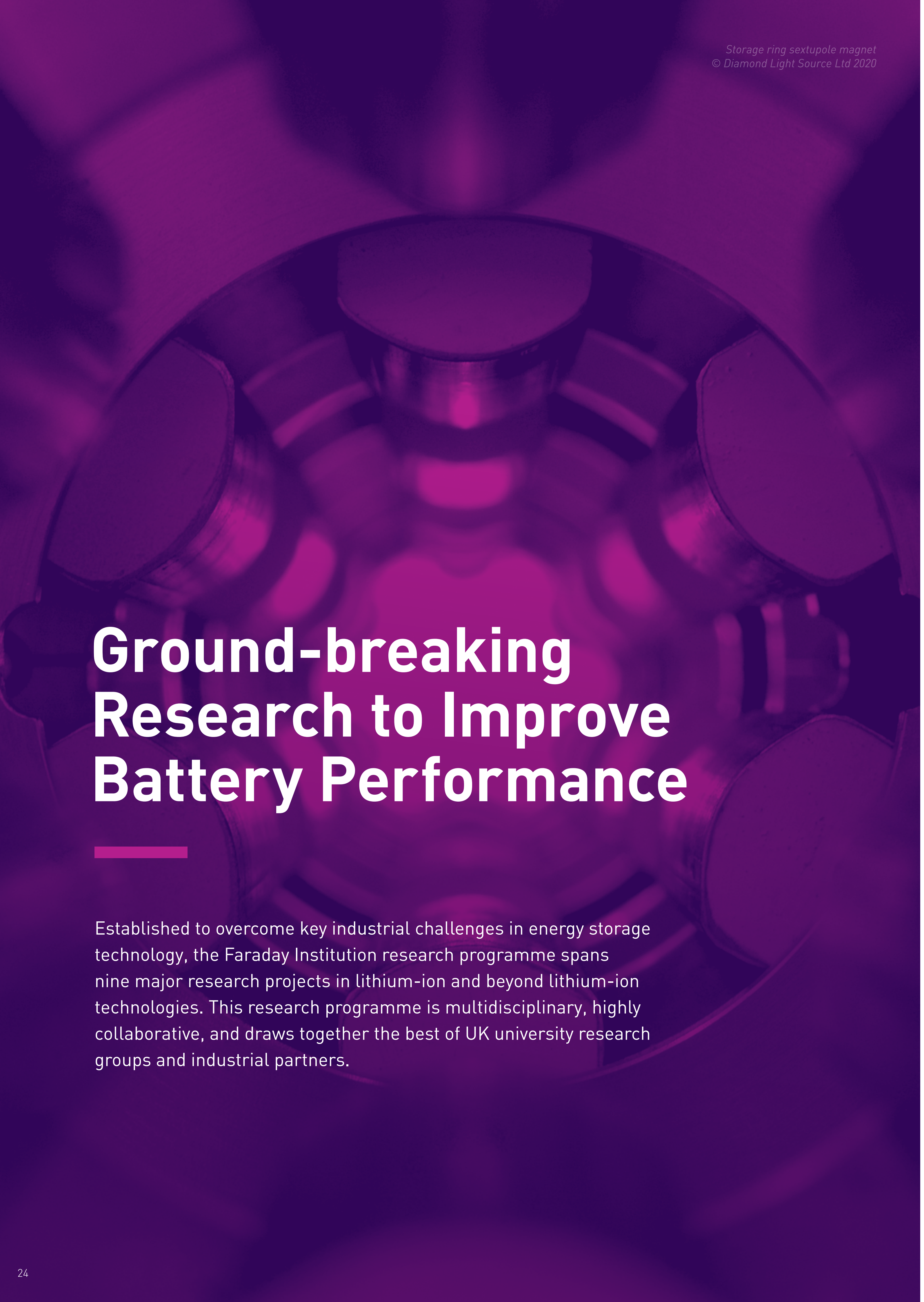
Delivered by Innovate UK, part of UK Research & Innovation, over £90 million of funding is available for businesses to lead feasibility studies and collaborative research and development projects in battery technology.

Scale-up

Delivered by the Advanced Propulsion Centre (APC), the £130 million UK Battery Industrialisation Centre (UKBIC) will enable companies of all sizes to develop manufacturing capabilities for battery technologies to get them to market quickly.

'A vital part of the Government's industrial strategy, the Faraday Battery Challenge is creating the research, innovation and commercialisation pathways and ecosystem that is establishing the UK as a battery science superpower, growing innovative companies and attracting large scale battery manufacturing to the UK. This continuing effort will play a significant part in meeting the UK's Net Zero agenda to combat both poor air quality and climate change.'

Tony Harper, Faraday Battery Challenge Director



Storage ring sextupole magnet
© Diamond Light Source Ltd 2020

Ground-breaking Research to Improve Battery Performance

Established to overcome key industrial challenges in energy storage technology, the Faraday Institution research programme spans nine major research projects in lithium-ion and beyond lithium-ion technologies. This research programme is multidisciplinary, highly collaborative, and draws together the best of UK university research groups and industrial partners.

RESEARCH STREAMS 1-3

RESEARCH STREAM 1 **Lithium-ion**	Projects optimising the current generation lithium-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 3-4 years. In addition, one of our projects is focussed on the recycling and reuse of batteries and supporting the principles of the circular economy.
RESEARCH STREAM 2 **Beyond Lithium-ion**	Projects that are higher risk, higher reward and could facilitate the long-term commercialisation of next-generation battery technology that still require considerable research in the areas of materials discovery and optimisation.
RESEARCH STREAM 3 **Battery Characterisation**	Additionally, three shorter-term projects to develop battery-focused characterisation and analytical techniques will provide UK researchers with world-leading tools to accelerate their understanding of battery materials and their performance.

The Faraday Institution benefits from the UK's world-class research and innovation infrastructure, capabilities and facilities, primarily in the physical sciences and engineering sector, the energy sector, and large-scale multi-sector facilities. These include world-class STFC-UKRI facilities at Harwell Science and Innovation Campus, such as Diamond Light Source pictured and ISIS Neutron and Muon Source.

Battery Degradation

Although mass manufacture has made lithium-ion batteries cheaper, cost and durability remain obstacles to the widespread adoption of battery electric vehicles. The lifetime of the batteries falls well below the consumer expectation for long-term applications such as transport. The automotive industry wants to better understand the causes and mechanisms of degradation to enable improved control and prediction of the state of health of battery systems.

Degradation mechanisms can occur on length-scales from the nano to the macroscopic, and timescales from seconds up to years. A full understanding of the causes and effects of degradation of lithium-ion batteries for automotive applications therefore requires synergistic investigation across these length and time scales and with the combination of many experimental techniques.

This project has created a cross-disciplinary consortium of researchers and industry partners to develop a comprehensive mechanistic understanding of the relationship between external stimuli (such as temperature and cycling rate) and the physical and chemical processes occurring inside the battery that lead to degradation.

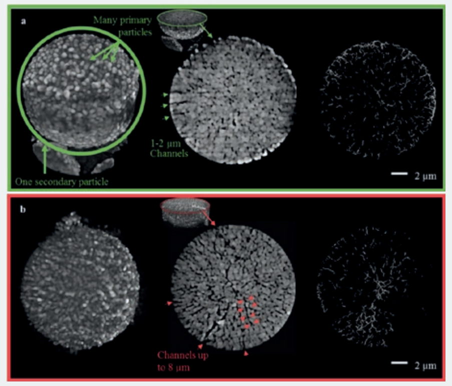
Objectives

- Build a significantly enhanced scientific understanding of the fundamental degradation mechanisms in modern, nickel-rich Li-ion battery chemistries.
- Develop the capabilities, tools, and techniques required to fully characterise/quantify the chemical and physical degradation mechanisms within nickel-rich Li-ion batteries, including the complex interplay between individual mechanisms.
- Develop top-down understanding of correlation between electrical signatures and state-of-health (SoH) sufficient to support responsive battery management system implementation where machine learning and cloud computing are used to mitigate lack of board computing capability.
- Work with industry partners to translate and commercially exploit the knowledge, understanding and potential intellectual property generated.

Outcomes

The knowledge and understanding gained by the project thus far have led to a significant number of high-profile scientific papers on the mechanisms of degradation (see Appendix: Scientific Publications), the filing of patents in novel characterisation techniques, and new material preparation methods. The consortium is now well equipped to progress the understanding of degradation in high nickel manganese cobalt (NMC)-graphite cells following a holistic approach that is delivering results beyond what would be achieved by smaller projects working on different techniques in isolation.

With the support of Cambridge Enterprise and the Faraday Institution, the consortium has identified two opportunities for IP protection this year and are engaging appropriate partners for commercialisation. The first of these relates to a new sensor that has the potential to be a powerful tool for researchers, in academia and industry, as they further develop new battery technologies.



Newly developed X-ray micro computed tomography (micro-CT) image acquisition and data processing methods are being used to measure and quantify three-dimensional cracking behaviour in NMC811 as a function of cell voltage and cycling history.

1

RESEARCH STREAM 1

Lithium-ion

Project Duration

1 March 2018 – 30 June 2021

Principal Investigator

Professor Clare Grey
University of Cambridge

Project Leaders

Dr Rhodri Jervis
University College London

Dr David Hall
University of Cambridge

University Partners

University of Cambridge (Lead)
Newcastle University
University College London
Imperial College London
University of Liverpool
University of Manchester
University of Oxford
University of Sheffield
University of Southampton
University of Warwick

Research Organisations, Facilities and Institutes

National Physical Laboratory (NPL)

+ 8 Industrial Partners

£12m investment

Lead Institution

University of Cambridge

Case Study: Forecasting State of Health

Forecasting the state of health and remaining useful life of Li-ion batteries is an unsolved challenge that limits technologies such as consumer electronics and electric vehicles.

The Degradation team has built an accurate battery forecasting system by combining electrochemical impedance spectroscopy (EIS) – a real-time, non-invasive, and information-rich measurement that is previously underused in battery diagnosis – with Gaussian process machine learning. Over 20,000 EIS spectra of commercial Li-ion batteries were collected at different states of health, states of charge and temperatures – the largest dataset to our knowledge of its kind. The Gaussian process model takes the entire spectrum as input, without further feature engineering, and automatically determines which spectral features predict degradation. This model accurately predicts the remaining useful life, even without complete knowledge of past operating conditions of the battery. The results demonstrate the value of EIS signals in battery management systems. This has multiple potential benefits, such as improving the economics of grid-based storage, assessing the length of second life batteries and measuring the wear and tear on electric vehicles.

Multi-Scale Modelling

The performance and lifetime of a battery depends on how the cells are combined into a pack large enough to power an electric vehicle (EV), an aeroplane or even an electricity grid. The mechanism controlling the local environment of each cell within that pack also influences lifetime and performance.

Accurate simulations of batteries will provide battery makers with the ability to design advanced batteries without incurring the costs of creating numerous prototypes to test every new material, or new type and configuration of the cells which make up a pack.

To simulate an EV battery pack, 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 mechanisms. A variety of timescales have also been considered to assess atomic processes at the nanosecond through to long-term degradation occurring over years. Battery simulations and design tools exist at each length- and timescale, but they were previously not linked together and often lacked the accuracy required for understanding the unique phenomena occurring within batteries.

This project brings together world-leading battery experts with a broad set of skills to build the critical bridge between science and engineering, working innovatively alongside UK industry to deliver impact. The team is creating new methodologies and techniques to measure electrolyte properties, characterise the 3D structure of cells and parameterise models. The project is delivering a portfolio of exceptional, world-leading research of strategic importance for the UK. The first challenges to be tackled include fast charging of batteries, low temperature operation and thermal management of cells within battery packs.

Objectives

- Validate new, more complete battery physics, including coupled degradation mechanisms, to develop degradation diagnostic tools and predict end-of-life.
- Exploit novel multiscale/multi-physics methods to design better devices, including designing new cells and establishing new standards for thermal characterisation.
- Integrate research communities across scales and approaches, enabling them to work together to bring atomistic accuracy into battery simulations.
- Develop a common modelling framework: the project's software, including PyBaMM, DandeLiion and ONETEP, is creating a global community of collaborators enabling the team to tackle the biggest problems in modelling.
- Make trusted models, usable by industry: companies are eager to use the project's software, showing that its work is industrially competitive and reflects a world-leading body of knowledge and understanding.

Outcomes

The fundamental modelling work has led to significant scientific breakthroughs in the understanding of lithium plating, stresses within particles leading to cracking, and intercalation in graphite; the development of new approaches to model charged interfaces; the modelling of cathode degradation in a continuum model for the first time; and new approaches to modelling nickel rich cathode materials. (See Appendix: Scientific Publications).

The experimental workstream has published a complete parameter set for a cell with the most advanced commercially available cathode and anode materials, measured the complete set of lithium-ion electrolyte properties for the first time, and delivered significant advances in linking 3D modelling with microstructural imaging.

1

RESEARCH STREAM 1

Lithium-ion

Project Duration
1 March 2018 - 30 June 2021

Principal Investigator
Dr Gregory Offer
Imperial College London

Project Leader
Dr Jacqueline Edge
Imperial College London

University Partners
Imperial College London (Lead)
University of Birmingham
University of Bath
University College London
Lancaster University
University of Oxford
University of Portsmouth
University of Southampton
University of Warwick

Research Organisations, Facilities and Institutes
UK Battery Industrialisation Centre (UKBIC)

+ 14 Industrial Partners

Project website

£11.5m
investment

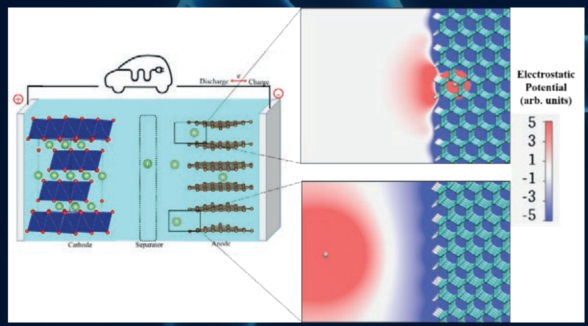
Lead Institution

Imperial College London

Case Study: Building Businesses and Community

The Multi-Scale Modelling project has supported UK industry through direct collaborations and through the many Innovate UK & consultations built through sharing data and experimental techniques. It has supported three start-up companies – Cognition Energy, Breathe Battery Technologies and Altelium – and expects more in future years.

The Multi-Scale Modelling Project is helping create global collaborative communities, such as PyBaMM and the future battery database, the development of new methods for simulating materials, cells and packs and bridging the atomistic and continuum scales. There are several opportunities for licensing its software, for example atomistic simulations of interfaces and inhomogeneities through ONETEP, experimental protocols, electrode microstructure models and reduced order models for control. The project's fast battery modelling platform, DandeLiion, has now been launched as a PAYG cloud-based service. The protection of the IP developed is always actively considered, including research cell specifications, parameterisation and validation protocols, health and lifetime prediction techniques and control algorithms.



ONETEP software: new tools for hybrid quantum atomistic/ continuum electrochemical simulations of batteries.

ReLiB: Recycling and Reuse of EV Lithium-ion Batteries

Transport is currently the largest source of greenhouse gas emissions in the UK. To meet legal commitments to reduce emissions to Net Zero by 2050, major reductions are required. To meet government's aim of moving towards a more circular economy, keeping resources in use as long as possible, minimising waste and promoting resource efficiency, the infrastructure for managing lithium-ion batteries when they are removed from electric vehicles (EVs) must be developed. The project aims to ensure that the UK has the facilities and regulations required for the safe, economic and environmentally sound management of the materials contained in lithium-ion batteries at the end of their first life and so enhance the overall efficiency of the raw materials supply chain.

Objectives

ReLiB aims to devise and develop alternative recycling routes that could provide UK businesses with a competitive advantage. The project is using a range of physical, chemical and biological techniques to separate and recover the materials contained in the full range of battery compositions currently in use.

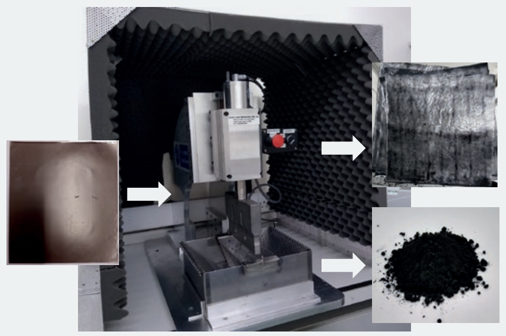
Success will be demonstrated by the construction (through a collaboration between the partner universities, local authorities and industrial partners) and patenting of demonstrator plants that can:

- Strip down the whole battery more safely and much faster than present techniques allow.
- Reduce environmental impact by minimising the use of chemicals.
- Minimise human intervention by using advanced robotics to automate most processes.
- Recover a high proportion of the original materials in a reusable form.
- Maintain high value materials streams to improve the economics of recycling.

Outcomes

The project has filed a patent application for a rapid delamination process that enables the electrode materials to be stripped from the metal foils on which they are mounted up to 100 times faster than alternative methods. Further patents relating to selective material separation and low temperature electrode regeneration, are being drafted.

Spatially resolved synchrotron X-ray diffraction data have been collected on the heavily cycled ex-Leaf cells at Diamond Light Source to cross-reference with electrochemical impedance spectroscopy (EIS) and thermal imaging studies in order to explore correlations between the chemical and electrical characteristics of the cells.



ReLiB has developed a demonstrator which can delaminate electrodes in seconds to produce clean foils and active material

1

RESEARCH STREAM 1

Lithium-ion

Project Duration

1 March 2018 - 30 June 2021

Principal Investigator

Dr Paul Anderson
University of Birmingham

Project Leader

Mr Anthony Hartwell
University of Birmingham

University Partners

University of Birmingham (Lead)
Cardiff University
University of Edinburgh
University of Leicester
University of Liverpool
Oxford Brookes University
Newcastle University

Research Organisations, Facilities and Institutes

Diamond Light Source (STFC)
UK Battery Industrialisation Centre (UKBIC)

+ 15 Industrial Partners

Project website

£10.1m
investment

Lead Institution

UNIVERSITY OF BIRMINGHAM

Case Study: Tech for End of Life

For maximum impact against the uncertainty of a rapidly changing landscape, ReLiB has targeted technologies in testing, triage and recycling functions that offer large improvements in the throughput and safety of end-of-life (EoL) processes – essential to cope with projected volumes. Results demonstrate that this is feasible, and the project is seeking IP protection for significant advances in these areas. ReLiB's approach is directly targeted at delivering EV lithium-ion battery EoL management at economically viable cost, even for low value cathode chemistries such as lithium iron phosphate (LFP).

In collaboration with industrial partners and the Faraday Institution, the project is drawing up a full roadmap for the primary pathways for commercialisation. Key to the approach will be strengthening links by demonstrating and embedding technology such as automation of advanced testing protocols integrated with robotic disassembly, and fast delamination. The project's delamination technology is already of interest to industry partners.

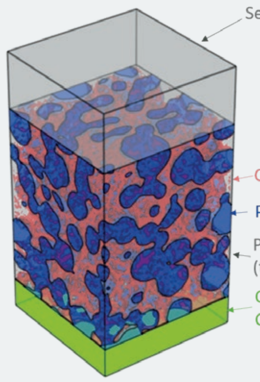
Nextrode – Electrode Manufacturing

Substantial benefits in battery performance can be realised by smarter assembly of the different materials that comprise the electrodes used in rechargeable ion batteries. Further, these benefits will apply equally to mature material systems already used in electrodes and to new systems. Launched in autumn of 2019, this project is focused on researching, understanding and quantifying the potential for smart electrodes to improve energy storage devices, and developing new practical manufacturing innovations that can scale smart electrode benefits to the industrial scale.

Nextrode focuses principally on manufacturing research into how to engineer a new generation of battery electrode structures. Novel developments in electrode structuring will be drawn from basic science understanding of the current slurry casting manufacture of Li-ion electrodes along with predictive modelling to suggest how control of electrode microstructure can deliver improved energy storage characteristics. Nextrode will support UK manufacturers and supply chain companies, draw on cutting edge scientific and technological knowledge to produce increased cell performance, add value in electrode processing, and improve safety and sustainability.

Objectives

- Support an agile electrode fabrication capability. The team aims to deliver insights that will reduce the time needed to re-optimise slurry casting parameters when electrode formulations are changed using a methodology that is validated at lab, intermediate and, with project partners, production scale.
- Enable the production of Li-ion batteries with smart electrodes that reduce degradation rates and increase energy density at high charge/discharge rates.
- Demonstrate smart electrode manufacturing technology and performance benefits in a scalable battery format.
- Provide a suite of modelling and characterisation tools that link microstructural features to electrochemical performance and which allow design-driven structural optimisation of battery structures, suitable for a broad range of battery formulations.



Outcomes

The Nextrode programme has been endorsed by its industrial consortium and their feedback has been incorporated into near-term plans, including validating near-term goals to inform baseline cell fabrication activities. This has progressed well, closely aligning with UKBIC so that knowledge transfer across the Faraday Battery Challenge will occur. Phase 1 of this experimental programme is underway, and the first large scale electrodes have been manufactured on the Warwick Manufacturing Group (WMG) battery pilot line, with cell assembly then occurring at WMG and at partner institutions.

A large number of electrodes have been manufactured at both laboratory and intermediate scale using a standardised approach, and electrodes are being characterised in detail and fabricated into pouch cells. Modelling research is developing tools that are allowing the team to explore the influence of detailed microstructural arrangements on electrochemical performance while 3D characterisation research is showing structural variations inside real electrodes and the extent to which they might be used to improve performance. Looking to the next generation of manufacturing processes, research investigations on smarter slurry formulation and deposition, process monitoring, and more controlled electrode fabrication techniques are underway.

The model geometry for a Nextrode NMC 622 electrode which has been built using data collected from X-ray CT measurements of real electrodes.

1

RESEARCH STREAM 1

Lithium-ion

Project Duration
1 October 2019 – 30 September 2023

Principal Investigator
Professor Patrick Grant
University of Oxford

Project Leader
Dr Denis Cumming
University of Sheffield

University Partners
University of Oxford (Lead)
University of Birmingham
University College London
University of Sheffield
University of Southampton
University of Warwick

Research Organisations, Facilities and Institutes
UK Battery Industrialisation Centre (UKBIC)

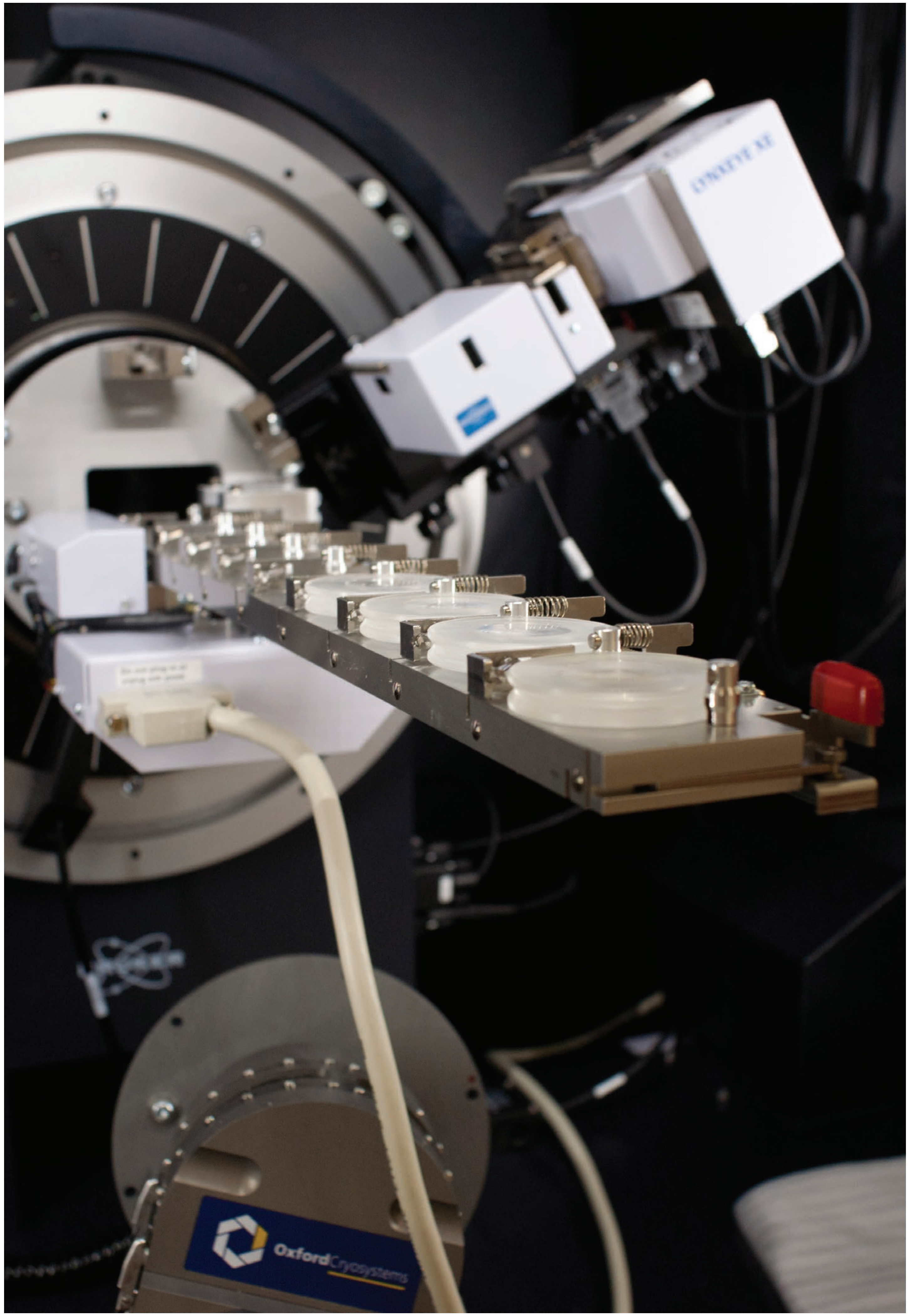
+ 12 Industrial Partners

Project website

£12m
investment

Lead Institution

University of Oxford



Next Generation Lithium-ion Cathode Materials

The car industry wants better battery life, lower cost, greater energy storage to improve range and increased power available to the EV during acceleration. The greatest improvements in battery performance are likely to arise from refinements to the chemistry of the cathode, which is why the Faraday Institution is funding two projects in this area (CATMAT and FutureCat). Developing a new generation of lithium-ion cathodes that meet future performance requirements presents a major scientific and commercial challenge.

FutureCat

FutureCat brings together world-leading expertise in the UK battery field, with solid-state inorganic chemistry, polymer science, mechanical and thin-film engineering, computational analyses, chemical processing and state-of-the art characterisation to discover, develop and deploy next generation Li-ion cathodes. Layered nickel-manganese-cobalt (NMC) cathodes represent the current state-of-the-art, with the aim of moving to higher nickel-content to improve energy density and lower costs by reducing expensive cobalt dependency. Increasingly, cation-disordered rock salts are also emerging as high energy density cathodes. However, there remain persistent challenges in synthesis and scale-up, maintaining reversible capacities and optimising performance through fundamental understanding.

FutureCat will deliver significant energy density increases through high-capacity targeted-disorder and novel mixed-anion cathodes permitting multiple redox activity. Costs will be reduced by systematically reducing/ultimately eliminating cobalt-content. The consortium is also discovering new cathode chemistries and developing protective coatings/additives to extend lifetimes and reduce costs. The project's holistic approach combines complex atomic-level structure prediction, synthetic methodology development, full battery protocol and cell-testing development, novel computational/AI approaches and state-of-the-art structure and dynamics analyses to garner those critical insights that fast-track cathode optimisation and enable new discoveries.

Objectives

- Deliver new compliant electrode topologies highly resistant to fracture and extend battery life through novel approaches to morphologies and microstructures.
- Develop protective coatings and new electrolyte additives to increase power densities through faster interfacial ion transport and prevent active material erosion thus extending lifetime and reducing cost.
- Discover new cathode materials through a co-ordinated computational-experimental design approach, where cation and cation-plus-anion redox-activity and increased application of earth-abundant elements will increase energy densities and reduce costs.

Outcomes

FutureCat has established a dynamic consortium of world-leading academics and pioneering industry partners across the UK. Early-career researchers have synthesised a diverse library of cutting-edge cathode materials, drawing from cobalt-free, earth-abundant metals with traceable supply chains. Carefully selecting lithium-rich structures and active dopants, the project has developed computational methods for predicting optimised material compositions. The project's characterisation capabilities include established performance measurements as well as state-of-the-art techniques for probing disorder and dynamics in operando batteries. The team has realised new methods of data analysis to investigate the detailed structure and behaviour of active cathodes and identified key strategies for improving the performance of these materials.

1

RESEARCH STREAM 1

Lithium-ion

Project Duration

1 October 2019 – 30 September 2023

Principal Investigator

Professor Serena Corr
University of Sheffield

Project Leaders

Dr Alisyn Nedoma
University of Sheffield

Dr Sam Booth
University of Sheffield

University Partners

University of Sheffield (Lead)
University of Cambridge
University College London
Lancaster University
University of Oxford

Research Organisations, Facilities and Institutes

ISIS Neutron and Muon Source (STFC)

National Physical Laboratory (NPL)

+ 8 Industrial Partners

Project website

£9.9m investment

Lead Institution

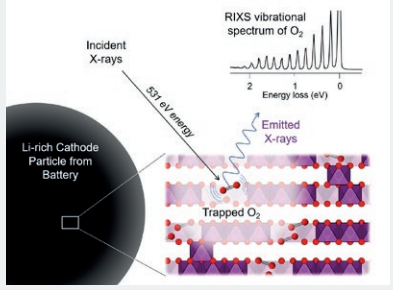
The University Of Sheffield.

CATMAT

The CATMAT project will offer benefits for car makers and their supply chain that are both large and near-term. It includes work to understand the origins of the current limitations of nickel-rich cathodes (with low or no cobalt) and to understand the fundamental electrochemistry of lithium-rich oxygen redox cathodes. The project is exploiting this new knowledge to inform the discovery of novel cathode materials with enhanced properties. The most promising materials will be identified, before scaling up their synthesis and integrating them in full battery cells to demonstrate performance. The project will support the accelerated development of new cathode materials towards practical commercial applications.

Objectives

- Discover and develop enhanced performance cathodes with high energy densities.
- Develop deeper understanding of the properties of nickel-rich and lithium-rich cathode materials.
- Use experiment, modelling, processing and cell performance evaluation to establish feedback between understanding of current systems and the properties of new materials.
- Exploit new knowledge to inform the discovery of novel oxide and mixed-anion cathode materials that would increase battery energy density (to increase EV range).
- Understand instability at the electrode/electrolyte interface and reduce performance losses using coatings or additives.
- Connect basic science to the manufacturing process, with the most promising cathodes taken forward to synthesise at scale and assimilation in battery cells, thereby demonstrating their performance in real devices for potential commercial applications.
- Build on partnerships with industry for pathways to technological impact.



First-cycle voltage hysteresis in Li-rich 3d cathodes associated with molecular O2 trapped in the bulk shown by RIXS spectroscopy [Published in Nature Energy, 2020].

Outcomes

The CATMAT programme has carried out detailed studies across its three interlinked work packages:

Understanding high energy density cathodes: The team's work to date is helping to build a detailed understanding of the microscopic processes that occur when cycling Li-rich cathode materials. By combining electrochemical, nuclear magnetic resonance (NMR) and resonant inelastic X-ray scattering (RIXS) analysis, the team has identified the formation of bulk molecular O2 during the cycling of Li-rich NMC cathodes and have explained how this contributes to voltage-hysteresis (published in Nature Energy, 2020). These findings suggest that strategies to reduce voltage-hysteresis should focus on finding structural modifications that suppress bulk O2 formation or that prevent O2 from escaping from cathode particles.

Materials discovery and synthesis: The project has explored mixed-anion materials, which present potential routes to new lithium-ion materials that go beyond conventional cation-substitution. The team has explored the synthesis of materials containing oxyanion dopants and successfully incorporated borate and sulfate ions into $LiNiO_2$ to form novel Li-rich materials. The team has also stabilised a novel sodium-based iron oxysulfide, which gives the project a platform for developing Li-ion materials based on this new cathode structure-type.

Coatings, scale-up and cell design: Initial work has examined scale-up and processing conditions for Ni-rich NMC cathodes. The team has developed a co-precipitation route using a continuously stirred reactor, which has successfully been used to manufacture NMC-811 and NMC-9½½. By using a combination of X-ray diffraction, scanning electron microscopy and X-ray tomography work is examining the change in particle morphology and effect upon battery cell performance.

1

RESEARCH STREAM 1

Lithium-ion

Project Duration

1 October 2019 - 30 September 2023

Principal Investigator

Professor Saiful Islam
University of Bath

Project Leader

Dr Benjamin Morgan
University of Bath

University Partners

University of Bath (Lead)
University of Birmingham
University of Cambridge
University of Liverpool
University of Oxford
University College London

Research Organisations, Facilities and Institutes

CPI

Diamond Light Source (STFC)

UK Battery Industrialisation Centre (UKBIC)

+ 15 Industrial Partners

Project website

£11m investment

Lead Institution

UNIVERSITY OF BATH

SOLBAT – Solid State Metal Anode Batteries

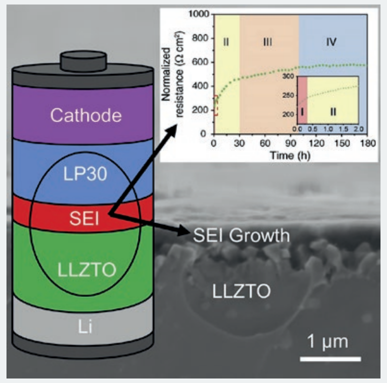
The solid-state battery (SSB) is one of the most important challenges in battery R&D. As well as increasing energy density, lifetime and transforming safety, SSBs would enable step changes in the safety, driving range and longevity of electric vehicles. In contrast to work on lithium-ion batteries, SSB research stands out as long-term and high-risk, but potentially high-gain. If SSBs could be realised and used in UK-manufactured EVs they would help secure the long-term growth of the UK's car industry, employment and economy. Ceramic solids are sufficiently conductive that electrolytes are no longer the biggest hurdle facing SSB development: the barriers are at the interfaces between the electrolyte and both electrodes, in the mechanics throughout the cell and in the manufacturing at scale.

Objectives

- Understand the fundamental challenges facing the construction of solid-state batteries.
- Use the new knowledge acquired to develop solutions to the problems, potentially including, but not limited to, new materials and new manufacturing approaches.
- Demonstrate, using technoeconomic modelling, that the solutions could scale to a commercially competitive product.

The following key metrics need to be demonstrated for solid-state batteries to be taken forward through development:

- Store at least 50% more energy as a conventional lithium-ion battery of the same volume (higher energy density).
- Non-flammable when subject to the nail penetration test and when operated at temperatures above 100°C (safer).
- Fully charged in less than 30 minutes (higher power); and
- Can be cycled 500 times with 80% capacity retention (cycle life).



SEI growth on LLZTO leads to increased interfacial resistance.

Outcomes

Significant progress has been made including: understanding the role of voiding at the Li/solid electrolyte (SE) interface on discharge; the mechanism of Li dendrite ingress and crack propagation/short circuit on charge; identifying new solid electrolytes (IP filed); development and implementation of a new probe structure method of SE materials discovery; understanding the effect of volume change in composite cathodes and highlighting the high impedance at the SE/liquid electrolyte interface in hybrid cells. (See Appendix: Scientific Publications).

The key to wider impact is solving the fundamental challenges in ways that can be applied credibly to commercial products. Discussions are under way between SOLBAT researchers, the Faraday Institution and industrial partners to establish a UK-based scale-up consortium that will provide facilities and the additional expertise to translate SOLBAT science into commercially valuable technology. The consortium is designed to take risk out of the translational stage by marrying academic and industrial expertise. The aim is to allow leading researchers to engage in translational work without sacrificing their scientific careers, bring in commercial experience and provide timely capital investments that are difficult to secure from the private sector at an early technology readiness level. In parallel to the effort of the consortium, the project will continue to maintain the option of taking the fundamental science advances to the next stage with one or more of SOLBAT's industrial partners, other companies or via spinouts.

2

RESEARCH STREAM 2

Beyond Lithium-ion

Project Duration

1 March 2018 - 30 June 2021

Principal Investigator

Professor Peter Bruce
University of Oxford

Project Leader

Professor Mauro Pasta
University of Oxford

University Partners

University of Oxford (Lead)
University of Cambridge
University College London
University of Liverpool
University of Sheffield
University of St Andrews

+3 Industrial Partners

Project website

£11m
investment

Lead Institution

UNIVERSITY OF OXFORD

NEXGENNA – Sodium-ion Batteries

Most current generation rechargeable batteries for transportation are based on the use of lithium. However, the relatively high cost, the somewhat limited global abundance of lithium, and environmental concerns around the sourcing of lithium mean that there is demand for a lower cost alternative that would increase the uptake of energy storage technologies in several sectors. Sodium-based batteries could be such an option, particularly for static storage, where cost is a more important factor than weight or performance.

This project will accelerate the development of sodium-ion battery technology by taking a multi-disciplinary approach incorporating fundamental chemistry right through to scale-up and cell manufacturing. Its aim is to put on the path to commercialisation a sodium-ion battery with high performance, low cost, that has a long cycle life and is safe.

Many models of future grid networks based on renewable energy incorporate storage on a local or domestic level for increased network resilience and to ensure efficiency of small-scale renewable sources. The widespread use of commercial Na-ion batteries that this project will facilitate would aid the realisation of these models and fulfil the need for low-cost electric transport options in the highly polluted and densely populated conurbations in developing economies.

Objectives

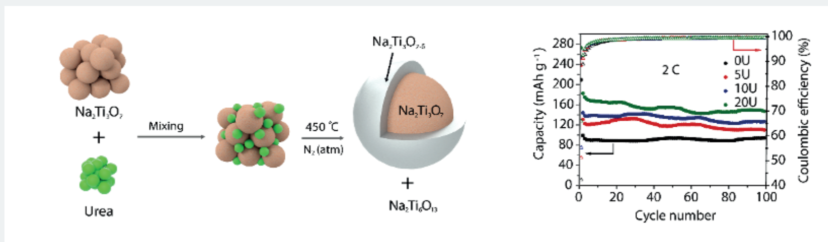
- Discover and develop innovative electrode materials for higher performance, lower cost Na-ion batteries.
- Discover and develop next-generation electrolyte materials, giving higher sodium mobility and therefore higher power.
- Refine the test and characterisation methods most applicable for materials for Na-ion batteries.

The project aims to develop a prototype of a next-generation sodium-ion battery with overwhelming competitive advantages. Key metrics, compared with existing technology is that the prototype needs to be able to displace lead-acid batteries from many current uses, be more cost-effective than Li-ion in some existing applications, and enable new markets to be electrified.

Outcomes

In its early stages the project team has tackled critical sodium-ion battery challenges, including investigations into organic and hard carbon anodes; vanadate and polyanionic cathodes; and novel electrolytes and their interfaces. The team has developed specialised sample environments for X-ray photoelectron spectroscopy, neutron scattering and nuclear magnetic resonance spectroscopy. Work on layered metal oxides has opened new avenues towards new long-life, capacious, fast charging cathode materials. Further the team's work on Na2Ti3O7 (NTO) has moved this safe anode material towards practical application by improving its capacity and rate performance.

The project's work on layered metal oxides and on NTO promises developments with a clear route to commercialisation. The commissioning of the University of St Andrews pilot facility (opening in 2021 / 2022) will allow the project to develop manufacturing know-how and knowledge exchange with commercial partners.



The reduction of NTO with urea results in the formation defects and the precipitation of the secondary phase Na2Ti6O13. The resulting material has an increased capacity when cycled at high rates (e.g. 2C).

2

RESEARCH STREAM 2

Beyond Lithium-ion

Project Duration

1 October 2019 – 30 September 2023

Principal Investigator

Professor John Irvine
University of St Andrews

Project Leaders

Dr Nuria Tapia Ruiz
Lancaster University

Dr Robert Armstrong
University of St Andrews

University Partners

University of St Andrews (Lead)
University of Cambridge
University College London
Lancaster University
University of Sheffield

Research Organisations, Facilities and Institutes

ISIS Neutron and Muon Source (STFC)

+ 3 Industrial Partners

£11.5m
investment

Lead Institution

University of St Andrews

LiSTAR – The Lithium-Sulfur Technology Accelerator

Next-generation battery chemistries are needed for energy storage for the electrification of sectors including transport, aerospace and grid-scale storage alongside a host of high-value niche markets. Li-S batteries are among the most mature of the post Li-ion technologies. They have unique attributes associated with their projected improved gravimetric energy density, operating temperature window, safety and reduced environmental impact and cost. However, commercial prospects depend on improving both the rate performance and longevity of cells. The academic and industrial partners of the LiSTAR project will tackle outstanding fundamental challenges in Li-S technology as a whole. It aims ultimately to demonstrate substantial performance increases in a technologically relevant format.

Objectives

- Enhance the sulfur loading and substantially increase the thickness of electrodes, making battery subcomponents that are significantly more representative of real-world requirements in a number of sectors.
- Improve safety via implementation of non-flammable electrolytes.
- Demonstrate new electrode and electrolyte approaches in a technologically relevant cell.
- Demonstrate a battery management system to maximise performance.
- Develop bespoke advanced cell monitoring and diagnostic techniques from the outset of the chemistry's commercialisation.

Metrics of success for the project include advancing all areas of Li-S technology to demonstrate cells which:

- Contain electrodes with more active material so they store enough energy to be commercially viable.
- Can be discharged fast enough to remove all energy in one hour, and therefore provide sufficient power for the intended aeronautic and heavy vehicle applications.
- Resist degradation when cycled.
- Have no other features that would plausibly prevent it being mass-manufactured at a cost competitive with that of existing Li-ion batteries.

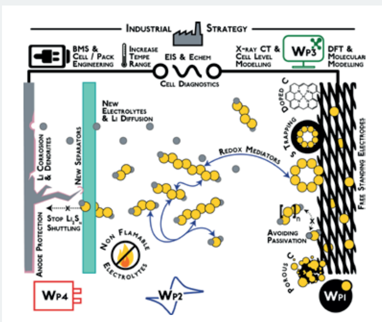
The LiSTAR consortium will also seek to make substantial contributions to the scientific literature and act as a catalyst in developing a cross-UK Li-S manufacturing industry by bringing together the leading interested academic and industrial partners.

Outcomes

Strong links to industrial partners have enabled LiSTAR to establish a world-class baseline of current, near market cell performance characteristics to build on with the project's breakthroughs.

The project has already made initial developments on the current state-of-the-art of Li-S batteries. The materials development team has begun evaluating the first phase of novel cathode architectures and electrocatalysts with impressive results – possibly doubling the energy capacity of the best lithium ion competitors. Modelling efforts have guided the design of electrocatalysts and begun to expand the limited existing knowledge base in this area, perhaps leading to valuable IP in the near future, particularly in the development of battery management techniques. On the anode side, the project has been expanded so that work has begun to protect the Lithium-metal films strengthening the anode team in the SOLBAT project to do so.

LiSTAR has identified routes to produce vital materials in substantially reduced times and identified a promising list of additives to improve the performance of Li-S cells – an important step towards increasing the future rate of development.



A schematic indicating the highly interconnected nature of the LiSTAR project.

2

RESEARCH STREAM 2

Beyond Lithium-ion

Project Duration
1 October 2019 – 30 September 2023

Principal Investigator
Professor Paul Shearing
University College London

Project Leader
Dr James Robinson
University College London

University Partners
University College London (Lead)
Imperial College London
University of Cambridge
University of Nottingham
University of Oxford
University of Southampton
University of Surrey

Research Organisations, Facilities and Institutes
National Physical Laboratory (NPL)

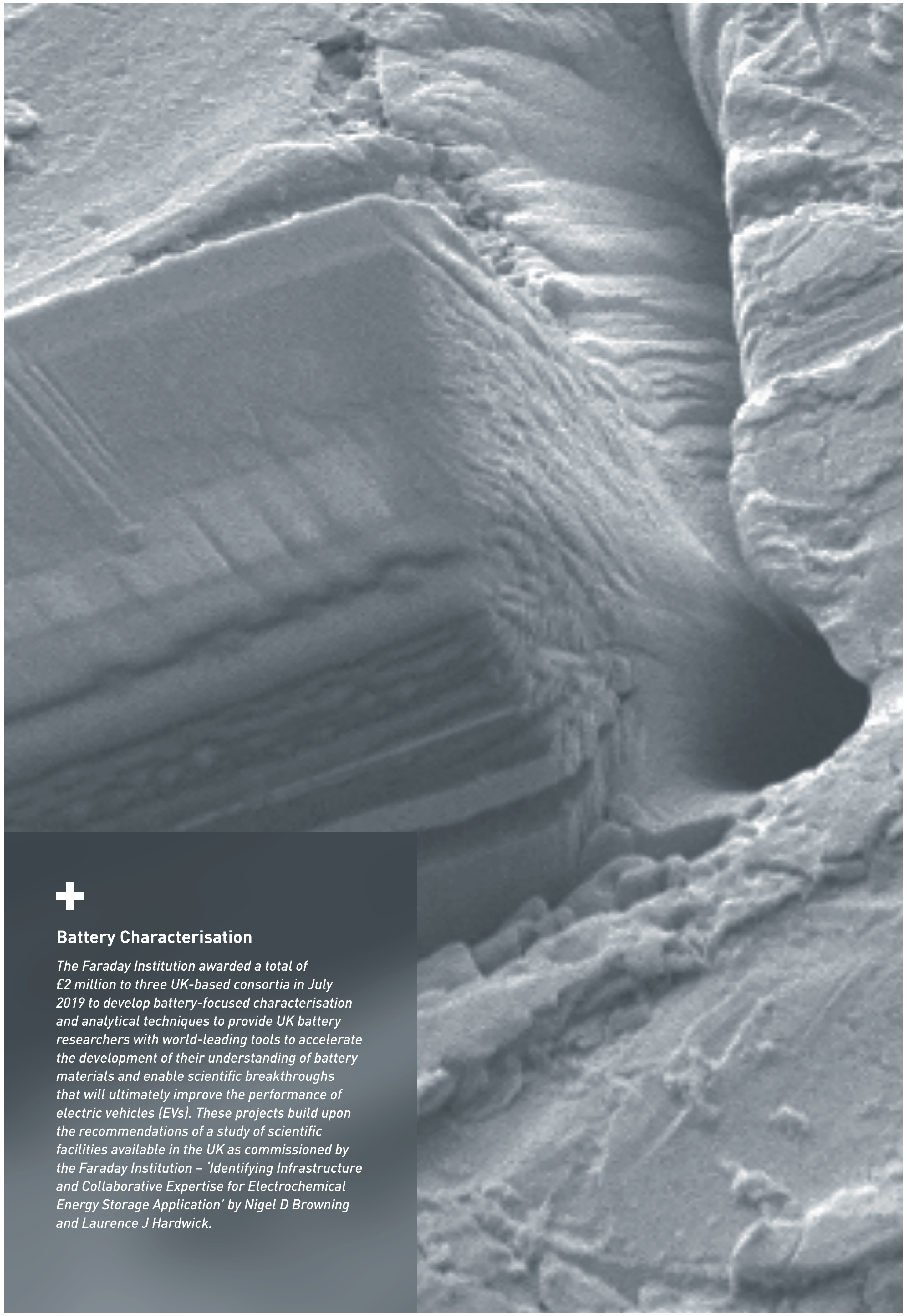
+ 4 Industrial Partners

Project website

£7.5m investment

Lead Institution

UCL



Battery Characterisation

The Faraday Institution awarded a total of £2 million to three UK-based consortia in July 2019 to develop battery-focused characterisation and analytical techniques to provide UK battery researchers with world-leading tools to accelerate the development of their understanding of battery materials and enable scientific breakthroughs that will ultimately improve the performance of electric vehicles (EVs). These projects build upon the recommendations of a study of scientific facilities available in the UK as commissioned by the Faraday Institution – 'Identifying Infrastructure and Collaborative Expertise for Electrochemical Energy Storage Application' by Nigel D Browning and Laurence J Hardwick.

Imaging Dynamic Electrochemical Interfaces

This project aims to make synergistic advances in operando characterisation methods needed to establish a robust, correlated multi-scale scientific framework for quantifying battery function. By emphasising calibration meta-data to accompany each individual method, artificial intelligence (AI) is being used to advance the achievable correlated temporal precision, chemical sensitivity and spatial resolution across the vital length/time scales for battery performance. By expanding the number of methods that provide key performance indicators, this project will increase characterisation options for businesses working on the battery supply chain, speeding up the establishment of new IP and the development of new products.

Objectives

The underlying project hypothesis is that fundamental transient effects at electrode/electrolyte interfaces control battery performance and lifetime. While experimental methods exist to measure these transients, no one method has the required spatial, temporal and chemical sensitivity to uniquely define the process. The advanced correlated methods being developed will be employed to identify and control:

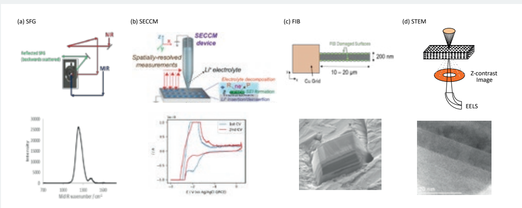
- The structural/chemical parameters determining the kinetics of ion transport across pristine electrode/electrolyte interfaces and leading to the formation of the solid electrolyte interface (SEI); and
- The structural/chemical parameters that suppress the evolution of dendrites and other degradation mechanisms under extended cycling.

Outcomes

The project team has established quantified methodologies for focused ion beam (FIB), scanning transmission electron microscopy (STEM), scanning electrochemical contrast microscopy (SECCM), sum frequency generation (SFG), X-ray tomography, scanning electron microscopy/helium ion microscopy (SEM/HIM), magnetic resonance imaging (MRI) and the use AI methods to coherently interpret the results for complex battery systems.

Even in the most standard of samples, results so far show fluctuations in the output of the most accurate characterisation tools. These are related simply to natural fluctuations in the atomic scale structure/chemistry at electrode/electrolyte interfaces or to systematic and unintentional changes induced by preparing the sample for evaluation. The project is working to identify control preparation methods to reduce these inaccuracies, eliminating false positive/negative evaluations of new battery systems. These results also highlight the need for operando methods that can avoid the artefacts of specimen preparation and identify the spatial/temporal location of specific reactions.

This project aims to advance the means by which the performance, lifetime, degradation and recycling processes for Li batteries can be characterised precisely and uniquely. Success will depend on demonstrating the feasibility of the methods, their accuracy and their unique benefits for widespread characterisation of battery systems. Commercial partners have been identified for battery systems. These methods also reach beyond battery science. Their applicability to energy conversion, personalised medicine, corrosion protection and colloidal materials synthesis is also being explored.



Through a combination of Sum Frequency Generation (SFG), Scanning Electrochemical Contrast Microscopy (SECCM) and Scanning Transmission Electron Microscopy (STEM) techniques, the project has been able to develop a comprehensive model of the link between electrode-electrolyte interface structure/chemistry and electrochemical performance.

3

RESEARCH STREAM 3

Battery Characterisation

Project Duration

1 July 2018 - 30 September 2021

Principal Investigator

Professor Nigel Browning
University of Liverpool

University Partners

University of Liverpool (Lead)
University of Bath
University of Birmingham
University of Manchester
University College London
University of Warwick

Research Organisations, Facilities and Institutes

Henry Royce Institute

+ 3 Industrial Partners

£1m investment

Lead Institution

University of Liverpool

The Development of High-Resolution Optical Microscopies

This characterisation project is exploring the use of high-resolution optical microscopies for studying battery systems. Building upon recent breakthroughs in characterisation methods developed for semiconducting materials, the project aims to provide a greater understanding of how electrode materials function at the single particle level and at shorter timescales than is currently available.

Understanding the mechanisms by which and the rates that lithium ions move in battery electrode materials is vital to developing high-rate battery materials with reduced capacity fade.

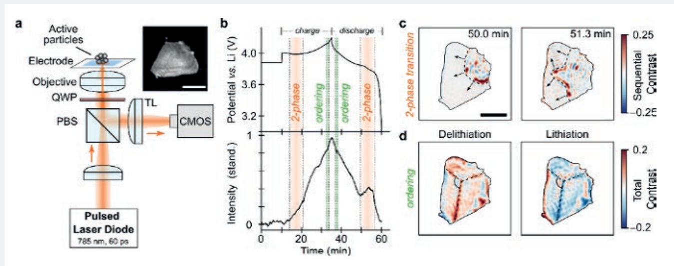
The team seeks to develop methods that can tackle crucial questions such as: how fast do the lithium-ions move, do electrodes transform via two or single-phase reactions, are electron and ion transport correlated, and what are the obstacles for transport caused by grain boundaries, defects, coatings? These world-leading methods will open a new window for the community to investigate these materials and provide the fundamental science underpinning the next generation of high-performance materials.

Objectives

- Develop a generic and easy to implement microelectrochemical cell platform that provides access for super-resolution optical and nitrogen vacancy (NV) centre probes, with quick deposition and easy integration.
- Develop and demonstrate high-speed hyper-spectral reflectance imaging to image lithiation of battery electrodes.
- Develop and demonstrate time-resolved super-resolution interferometric light scattering microscopy (TriSCAT) microscopy as a tool to track ion diffusion within single particles with sub-10nm spatial precision in real time.
- Demonstrate NVs as a local probe to track changes in magnetic properties within an electrode and develop tools to enable the use of NV centres in an operando optical cell.
- Promote, disseminate and collaborate these new techniques.

Outcomes

Preliminary measurements have been made on the three techniques being developed. The team has adapted its approach as more is learnt about the capabilities. iSCAT is the most developed and studies on LiCoO2 allow solid solution and biphasic reactions to be seen on a single particle level. Results on hyperspectral imaging and NV centres are less well developed and require further optimisation of the measurement and systems studied. Work is continuing on the microelectrochemical cell platform.



The project has demonstrated that it has been able to utilise an interferometric scattering (iSCAT) microscope to observe phase transitions at a single particle level and distinguish between different types of reaction.

3

RESEARCH STREAM 3

Battery Characterisation

Project Duration

1 July 2018 - 30 September 2021

Principal Investigator

Dr Siân Dutton
University of Cambridge

University Partners

University of Cambridge

£0.5m investment

Lead Institution

University of Cambridge

What Lies Beneath? Probing Buried Interfaces in Working Batteries

The interfaces between the different materials that make-up rechargeable batteries play a pivotal role in determining performance. This is where electrons and ions transfer between the electrodes and electrolyte during charging and discharging, as well as where many of the undesirable reactions that limit battery life take place. Understanding how the structure and chemistry of these interfaces changes during operation is critical to developing new higher capacity battery materials, fast charging protocols and models to predict when batteries need replacing. However, by their very nature, these interfaces are buried within the battery, making it extremely challenging to extract information without interference from the surrounding materials. This project looks at new approaches to investigate these interfaces.

Objectives

The principal goal is to develop new in-situ and operando cells for probing buried interfaces in working batteries. These platforms will be portable across many different characterisation instruments and applicable to a broad range of battery architectures/chemistries, including liquid- and solid-electrolytes. The major research objectives are:

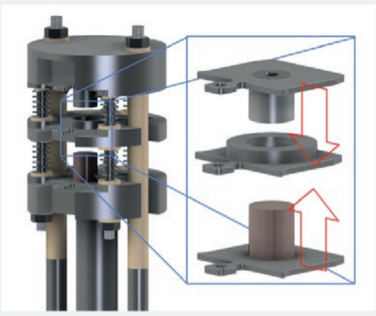
- Develop and demonstrate an in-situ cell where each battery component can be removed, measured and the battery subsequently reassembled.
- Develop and demonstrate an operando cell were the interfaces between components can be observed while the battery is charging/discharging.
- Confirm that the electrochemical performance of these cells is representative; and
- Demonstrate measurement across multiple characterisation tools (including hard X-ray photoelectron spectroscopy (HAXPES), secondary ion mass spectroscopy (SIMS), scanning electron microscopy (SEM), and X-ray diffraction (XRD).

Outcomes

Prototype versions of both the in situ and operando cells have been produced and undergone initial testing using solid electrolytes. These cells give good electrochemical performance while being compatible with the desired interface-sensitive methods.

Having tested protypes of the in situ and operando cells the team is now starting to perform targeted studies at national user facilities including Diamond Light Source and the Henry Royce Institute. The team is also extending the cell capabilities to operate with liquid electrolytes, which presents additional challenges when working in vacuum. Key battery materials problems have been identified for demonstrating the new capabilities offered and will be the focus of the next stage of the project.

In order to make the characterisation capabilities developed available to the wider research community in the near-term, the team is interacting closely with the degradation and solid-state battery projects in order to address questions relevant to these research programmes. Collaborations with industrial partners will help answer their materials problems. The potential for directly commercialising the in situ and operando approaches is also being explored with characterisation equipment manufacturers.



In Situ Battery Cell – anode, cathode and separator plates are combined in a vacuum chamber where liquid electrolyte can be injected, compression applied, and cycling performed. Each cell component can then be separately addressed for measurement.

3

RESEARCH STREAM 3

Battery Characterisation

Project Duration

1 July 2018 - 31 March 2021

Principal Investigator

Professor Robert Weatherup
University of Oxford

University Partners

University of Oxford (Lead)
University of Manchester

Research Organisations, Facilities and Institutes

Diamond Light Source (STFC)

+ 3 Industrial Partners

£0.5m
investment

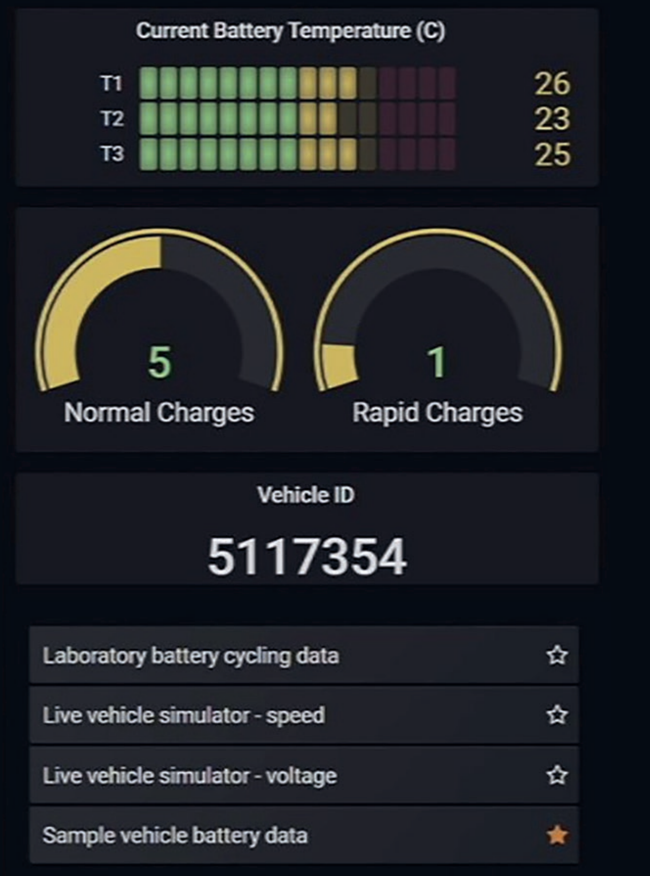
Lead Institution

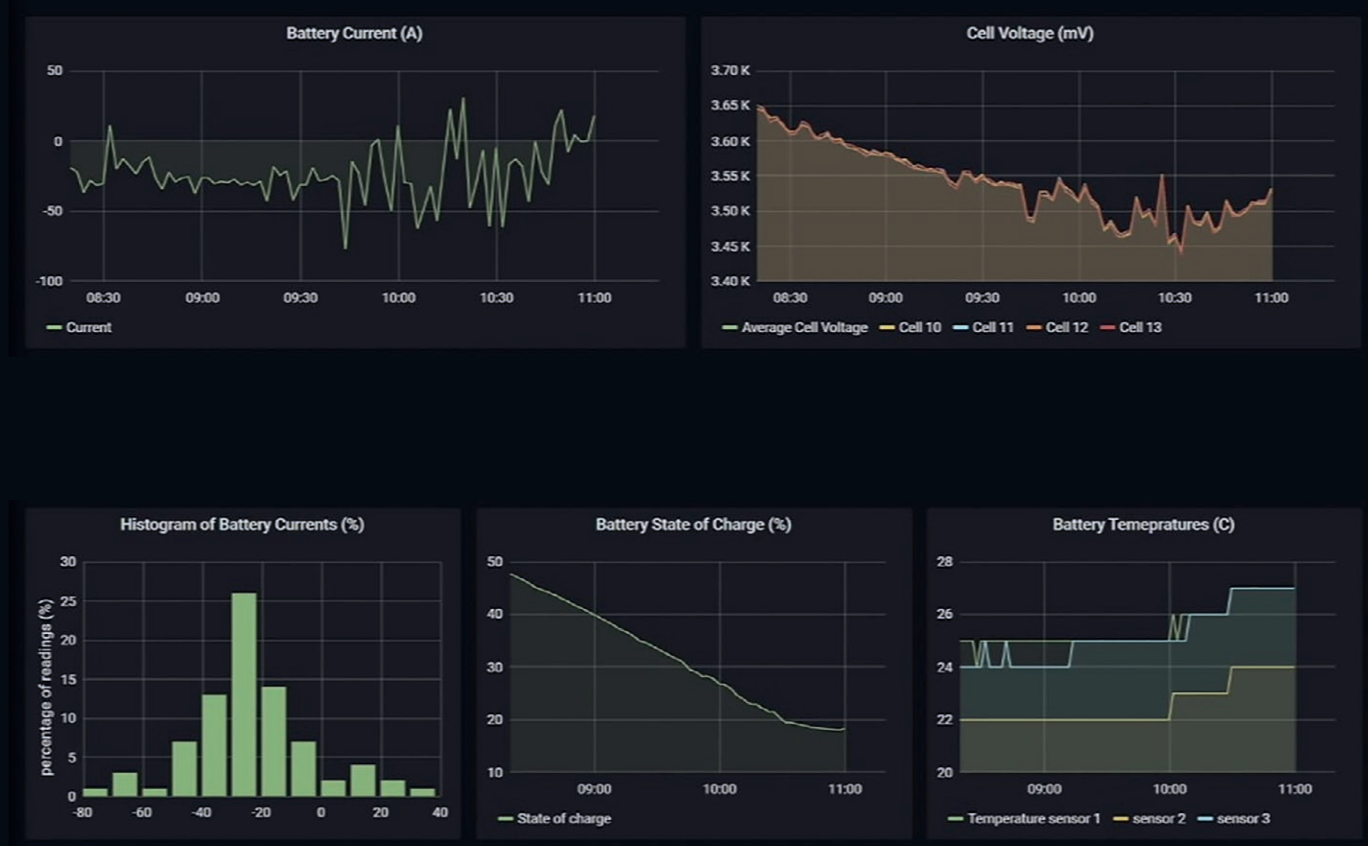
UNIVERSITY OF OXFORD

Case Study: Altelium – Diagnostic Models to Warranty Batteries

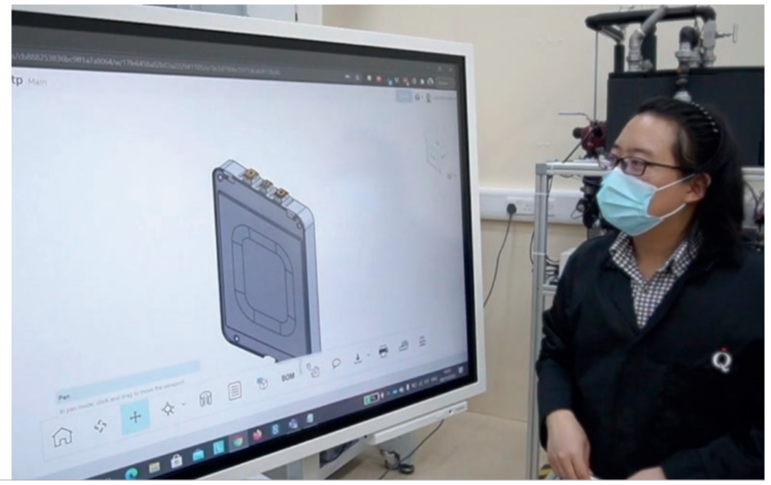
A team at Lancaster University led by Professor Harry Hoster, and brought together through the Multi-Scale Modelling project, recognised that data about battery history, state of health and future performance was crucial to the future economic viability of the EV battery market for both first and second life applications. After building diagnostic models on chemistry-related battery failure and securing interest from the insurance sector, they founded Altelium Limited, which today offers a non-intrusive diagnostic toolkit that enables the insurance industry to warranty batteries.

As of 2020, Altelium employs more than 20 people and has received follow-on funding from Innovate UK.





Accelerating Research to Commercial Outcomes



Accelerating Research to Commercial Outcomes

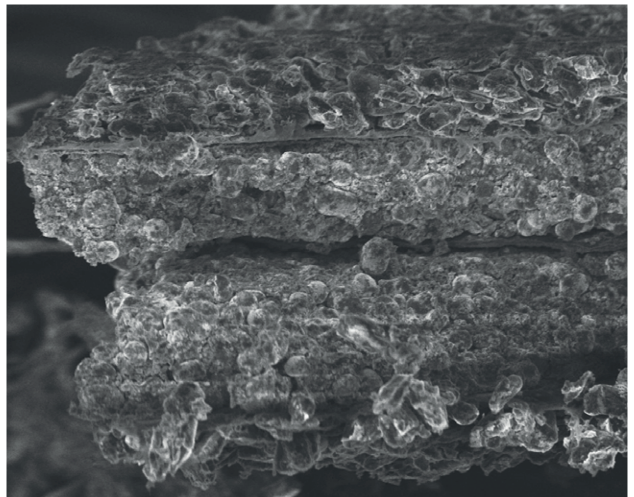
For energy storage to flourish, breakthroughs in the lab must be more readily translated into commercial products, services and solutions that improve performance and significantly reduce cost.

Following constructive and encouraging feedback from industry, the advice of its Board of Trustees and of EPSRC-UKRI, the Faraday Institution has been further strengthening its commercialisation capability. In 2020, it started to grow its commercialisation team in order to develop novel and specialised commercialisation evaluation processes to accelerate the commercialisation of the research outputs of the Faraday Institution's projects. The commercialisation team works closely with representatives from international industrial groups that are formally engaged with the Faraday Institution through its Board of Trustees, Advisory Committee and Expert Panel and directly with the research projects through various governance arrangements.

The team uses its expertise in technology R&D and commercialisation to analyse the research through a commercialisation lens, raise awareness of the competitive landscape, develop tailored commercialisation roadmaps and make introductions and recommendations for agile programme evolution. This is essential to ensure the research programmes remain on course to be commercially relevant and globally competitive.

The Faraday Institution has developed strong and significant collaborative links with a wide range of industrial partners. Today, more than 50 companies provide support and direction to the projects and this engagement continues to both grow and deepen. These partners take an active role in the selection and development of Faraday Institution research programmes to ensure that the outcomes are shaped to meet commercial needs.

To accelerate what is often the long journey from research breakthrough to commercial outcome, the Faraday Institution has introduced several innovation support programmes: Industrial Sprints, Entrepreneurial Fellowships and Industrial Fellowships.



UCL researchers working on the Faraday Institution's Degradation project have combined multiple techniques for industry partners to better understand why batteries fail. Pictured: collapsed electrodes following thermal abuse

Industrial Sprints

Sprints dedicate small multidisciplinary teams of researchers to solve a commercially relevant research opportunity identified from within the research programme and prioritised by an industrial partner. Over a period of 6 to 15 months, researchers work closely on the challenge, meeting frequently to review progress and hone plans. Sprints give early career researchers an opportunity to lead a focused team across multiple institutions, and to connect with leaders from industry and academia.

Cell Abuse, Off Gas Species and Related Behaviours

Timeframe
February 2020 - December 2020

Projects involved
Degradation

Industrial need
Industry partners have identified the need to find a better understanding of cell behaviour outside of their specification window. Potentially cells can give off gas and reach high temperatures under thermal, mechanical, or electrical abuse conditions. This needs to be understood to enable a robust design of pack structures especially in safety critical applications such as automotive and aerospace.

Work plan
This sprint combines multiple techniques to describe the mechanism of failure, gases released during an event, energy/mass released, and any geometric changes. Models generated will begin to be built from this effort that will enable faster, more efficient pack development processes.

Outcomes
This sprint has characterised cell failures under a range of conditions, determined the off gases, temperature changes, the energy contained in any ejecta as well as characterising the cycling behaviour of the cell in question. This testing will be continuing to the end of 2020, working in partnership with industry to determine the potential behaviour of any gases released. As a result of the success of this project, drawing interest from other large UK battery consumers, the Faraday Institution is developing a follow-on project studying the science of battery safety more widely.

TOPBAT – Optimising Pack Design for Thermal Management

Timeframe
July 2020 – January 2021

Projects involved
Multi-Scale Modelling

Industrial need
Imperial College London researchers, in collaboration with AMTE Power, identified the potential for improvements in battery pack and cell design to better control cooling at the cell, module and pack level.

Work plan
Optimise pack design for thermal management and demonstrate the current practice of optimising cell design primarily for energy density is suboptimal for pack energy density, cost and lifetime. This involves the manufacture, modelling and parameterisation of some custom designed cells. The team will validate a battery model that can be used to predict and optimise battery performance using alternative cooling strategies. This model will form part of a second phase working with the UK battery industry to produce optimised cell designs.

Potential outcomes
Improvements in useable energy at the pack level of 10-20% or more are expected, translating into either longer electric vehicle driving range or cheaper battery packs. Improvements in lifetime at the pack level of 100-200% are also expected, significantly reducing the cost of ownership and increasing opportunities for second life applications of batteries.

Cell Degradation

Timeframe
September 2019 - March 2021

Projects involved
Degradation, Multi-Scale Modelling

Industrial need
A major UK company identified an issue whereby some battery chemistries have been shown to suffer from increased capacity fade when stored at a specific state of charge.

Work plan
The aim of this work is to establish the mechanism of the capacity fade and indicate if the issue can be solved by modification to the cell chemistry, or whether battery management system strategies need to be employed to minimise residence time at these conditions.

Progress to date
Researchers have been analysing commercial cells after prolonged periods of temperature-controlled storage. Currently the researchers are performing electrochemical testing and electrochemical impedance spectroscopy at Warwick Manufacturing Group. When travel and lab access eases, test work will take place at Cambridge and UCL, including CT scanning. Work is also planned using ISIS Neutron and Muon Source and Diamond Light Source beamlines.

Materials for Thermal Transfer

Timeframe
February 2020 - December 2020

Projects involved
Multi-Scale Modelling

Industrial need
A leading engineering company is seeking better thermal control of its battery pack as it is vitally important to performance and longevity. Higher performance thermal materials could usefully improve both, by transferring heat efficiently from the cells to the cooling system, and by isolating cells from their neighbours in cases where an individual cell is going into thermal runaway. Materials with high heat transfer rates, low density and good thermal stability could significantly improve cell performance and life.

Work plan
This sprint aims to develop nanomaterials composites, phase change materials and functional scaffold materials with class leading performance to meet these aims, then both model and experimentally validate them.

Progress to date
The lab scale process optimisation has proven successful and is now being scaled up to produce larger quantities. This process is likely to result in intellectual property, which will be protected. Later in the project, modelling and larger scale physical testing will take place to validate performance.

Entrepreneurial Fellowships and Spin-Outs

The Faraday Institution's Entrepreneurial Fellowship programme supports researchers across the UK looking to create new businesses and commercialise battery technologies. These fellowships have been set up to facilitate the creation of new business opportunities that have emerged from Faraday Institution research programmes and elsewhere from the broader UK battery research community. The programme provides seed funding, business support and mentoring to maximise the potential of success and accelerate the spin-out process.

Solveteq

Timeframe
July 2019 - December 2020

Overview
Led by CEO and Co-founder, Dr Ola Hekselman of Imperial College London, Solveteq is developing sustainable technology for recycling of lead-acid batteries, whilst significantly reducing the environmental impact of lead. Despite the rise of Li-ion batteries, lead-acid batteries are expected to remain a viable technology in the energy storage sector in the foreseeable future particularly in emerging markets. Solveteq's solution replaces the most polluting and energy-intensive steps in the lead acid battery recycling process with a low-temperature, solvent-based technology. The IP-protected technology produces lead and lead oxides, commodities that can be directly used in the production of new batteries. This research originates from RELAB, an EPSRC-UKRI-funded research project.

Outcomes
The 2019 Entrepreneurial Fellowship allowed Solveteq to scale up a successful lab-scale process into an intermediate-scale continuous-operation prototype, designed to recycle 1kg/h of lead paste from used batteries into lead and lead oxides.

The fellowship additionally enabled Solveteq to establish strategic relationships with international industrial partners and future customers. More recently, Solveteq's technology received further validation of its potential by securing funding from Innovate UK, which puts this company on a more secure path to commercialisation.

Enabling the Fast-Charging of Automotive Batteries

Timeframe
May 2020 - March 2021

Overview
Dr Tom Heenan, UCL, along with co-inventors Dr Chun Tan, Professor Paul Shearing and Professor Dan Brett have patented a charging-enhancement technology that uses a dynamic magnetic field to accelerate the fast charging of lithium-ion batteries, which has already demonstrated charge time reductions of over 60% in commercial cells. The Fellowship aimed to propel the technology into commercial battery applications, from cordless power tools to electric vehicles.

Outcomes
After testing at UCL demonstrated repeated success in reducing charging times in commercially available cells, the Faraday Institution funded the further development and commercialisation of this technology. During the course of this several key factors have been uncovered that, with further optimisation, will improve the charging times of commercial cells. These findings allow a higher average electrical current to be used during charging, which reduces the overall charging time whilst maintaining the cell's energy and power density (and hence EV range and acceleration) and battery lifetime.

The technology is now ready for real-world proof-of-concept projects for automotive applications but also for portable electronics and hand-held power tools. Early stage discussions have begun with commercial entities from various sectors including a major consumer power tool company. This will be carried out in parallel with continued fundamental research that is required to achieve true optimisation of the device.

Qdot

Timeframe
September 2019 - September 2020

Overview
This University of Oxford spin-out is developing cutting-edge heat transfer technology to solve some of the world's most challenging thermal engineering problems. The three co-founders – Dr Jack Nicholas, Dr Holt Wong and Professor Peter Ireland – are aiming to apply the company's patented heat transfer technology to achieve a step change in the recharge rate of Li-ion batteries. For electric vehicles (EVs), Qdot aims to increase the recharge rate from 6 miles/min to over 15 miles/min. Qdot's heat transfer technology was originally developed for applications in a nuclear fusion tokamak, where heat loads can be in excess of 10 MW per square metre and the temperatures are over 100 million Kelvin.

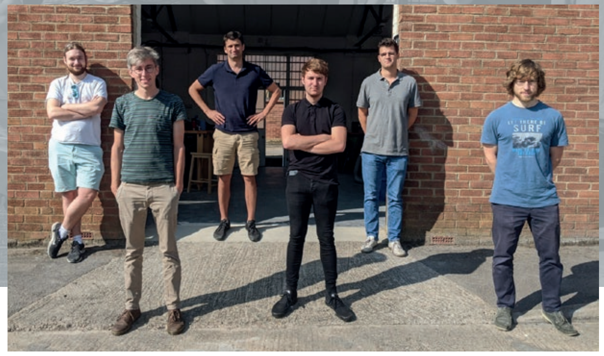
Outcomes
The Faraday Institution Entrepreneurial Fellowship provided Qdot the resources to develop and validate a prototype thermal management system to achieve extremely fast charging at the battery cell level.

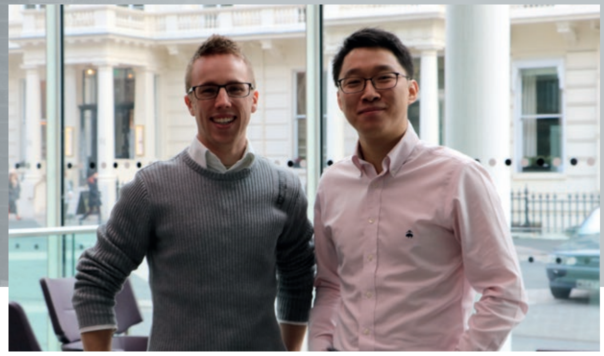
Follow-on technology development funding has been successfully secured through the Harwell Cross-Cluster Proof-of-Concept Fund, the UK Innovation & Science Seed Fund and Innovate UK Accelerator Programme, and the Innovate UK and Office for Low Emission Vehicles Catalysing Green Innovation – Securing the Future of ZEV funding competition.

Future research will expand the technology to a battery module, and then pack, level. Qdot will initially look to market its technology in the EV sector, particularly in applications that demand high availability, or performance, such as motorsport and HGVs.

'Complex technical challenges, long development cycles and expensive equipment can be significant hurdles for even the most determined innovators to overcome. Our goal is to give some of the brightest entrepreneurs in the battery space the best chance of success.'

Ian Ellerington, Head of Technology Transfer





Cognition Energy

Timeframe
November 2019 - November 2020

Overview
Cognition Energy was founded by Tom Cleaver and Imperial College London's Dr Yatish Patel, Dr Greg Offer and Prof Peter Cawley. The group is taking a physics-based approach to developing high performance batteries with a particular focus on thermal management to extend life and reduce ownership cost. Their concept solution includes an innovative thermal management system, a custom battery management system, improved safety and a design that is both easy to manufacture and recycle. Target markets include commercial robotics with a longer-term aim to expand to the vehicle and grid sectors.

Outcomes
Following an award of a Faraday Institution Entrepreneurial Fellowship in 2019 to help fund development of a thermally managed 5kWh battery prototype, Cognition Energy took on its first full-time staff member. Today it has 6 full-time and two part-time employees, not counting its Imperial founders. It has taken on customers to adapt the 5kWh prototype design for a robotics application and to develop a prototype battery charge station. In 2020, the company won an Innovate UK grant with Imperial College London to develop a cell rapid characterisation toolset: Advanced Cell Test (ACT) Feasibility Study. It has established a dedicated headquarters in Oxfordshire, moving out of university labs which had been closed during the Covid-19 lockdown. It plans to commercialise its 5kWh prototype over the coming year and explore other commercialisable technology in development.

In July 2020, Cognition Energy successfully completed a funding round valued at £200k.

Breathe Battery Technologies

Timeframe
July 2019 - June 2021

Overview
Breathe is an independent start-up founded by Drs Yan Zhao and Ian Campbell of Imperial College London. Breathe is targeting a step reduction in the charging time of batteries by replacing widely used static charging algorithms used in existing battery management systems. By adapting the charging process to the unique, evolving health of every battery, the researchers believe they can unlock substantial latent performance. Health-adaptive charging could also potentially increase battery lifetime and decrease battery cost. The start-up has received backing from Climate-KIC and the Imperial Enterprise Lab, where the duo were recently winners of the Energy & Environment category of the Venture Catalyst Challenge.

Outcomes
Following the company's incorporation and award of a Faraday Institution Entrepreneurial Fellowship in 2019, Breathe has achieved important technical and commercial milestones as it asserts itself in a growing market for intelligent battery management software.

In 2020 the company filed a patent application to secure intellectual property that has been demonstrated to enhance battery lifetime and manage vehicle fast charging. On the back of these technical demonstrations the team has gained new commercial traction. Breathe is now engaged in battery charge management trials with a global consumer electronics OEM, setting in motion activities that support their roadmap to mainstream deployment in electric vehicles. Breathe has additionally expanded its focus to include the grid battery storage market and is now developing solutions with the support of Innovate UK and project partners.

In the last 12 months the company has also garnered support from the European Regional Development Fund and CTO Dr Yan Zhao was awarded a Royal Academy of Engineering Enterprise Fellowship. Attracting key talent has been instrumental in the company's progress and, in addition to attracting a full-time member of staff from Porsche, this summer Breathe hosted one undergraduate intern from the Faraday Institution FUSE programme as well as another intern and graduate of the 2019 FUSE cohort. With a pre-seed investment round completed, the company is entering 2021 with the aim of expanding its partnerships in the automotive market.

Case Study: Qdot

Faraday Institution-funded spin-out Qdot is applying fusion energy technology to make possible extremely fast charging – adding 200 miles of range in just 10 minutes for ground vehicles. This makes mid-journey charging stops quick and convenient, increasing the effective range of a vehicle using a smaller battery pack. Since the batteries make up the lion's share of the cost of an electric vehicle, this also brings down the cost to OEMs and consumers.

Qdot Co-founder Dr Holt Wong

Industrial Fellowships

The Faraday Institution awarded its first Industrial Fellowships in 2020, a new programme to strengthen ties between battery researchers working in industry and academia. Each fellowship enables academics and industrialists to undertake a mutually beneficial, electrochemical energy storage research project that aims to solve a critical industrial problem and that has the potential for near- and longer-term benefit to the wider UK battery industry.

Coventry University with CB2Tech

A spin-out from Prof Clare Grey's group at the University of Cambridge – to demonstrate the high-power potential of niobium tungsten oxides in prototype lithium-ion battery cells of standard commercial sizes. These new anode materials show potential in improving fast charging capabilities without reducing battery lifetime.

Imperial College London with Ilika Technologies

To deploy its physics-based battery modelling expertise, including that developed within the Faraday Institution's Multi-Scale Modelling project, to help Ilika's cell developers optimise and develop larger format solid-state batteries.

Cranfield University with Delta Motorsport

To explore potential applications of artificial intelligence to develop novel temperature prediction techniques that improve the performance of battery thermal management systems, bringing possible benefits to battery performance and lifespan.

The University of Sheffield with PV3 Technologies

To develop processes to control particle morphology and size for next-generation high-nickel cathode materials in a continuous manufacturing process, as part of a long-term aim of maximising battery performance and reducing manufacturing costs.

The University of Sussex with CDO2

A business incubator and centre for research commercialisation, to characterise and understand the capability of a newly developed device based on quantum magnetometer technology that could potentially be used to improve the prediction of state-of-health and state-of-charge on-board electric vehicles.

The University of Strathclyde with CDO2

To design a micro-electrochemical system (MEMS) fabrication process for a new type of magnetometer to enable its miniaturisation and potential use as a low-cost sensor in battery management systems, helping to estimate state-of-charge and -health and to detect faults early.

Inspiring and Training the Next Generation

Educational programmes and skills development initiatives lie at the heart of the work of the Faraday Institution to meet future industry R&D staffing needs and to strengthen university research groups in energy storage.

The Growing Impact of Faraday Institution Educational Programmes

The Faraday Institution has built a comprehensive outreach and education programme – with a strong focus on equality, diversity and inclusion – that extends across STEM outreach, undergraduate attraction, PhD researcher training and early career professional development to create a steady stream of trained battery scientists and engineers for the UK for years to come.

44
PhD Researchers
from 16 universities trained through our doctoral programme

100+
undergraduate interns
(50 in 2020)

10
undergraduate Faraday Scholars
supported to diversify researcher pipeline

7,500+
young people
engaged through the Fully Charged Battery Box programme, spanning all parts of the UK

19
Faraday Masterclasses
and 6 Faraday TECH workshops, providing early career researchers collectively with over 2,800 hours of specialist training in 2020

Undergraduate Attraction

Each summer, the Faraday Institution funds up to 50 undergraduate internships in partner universities. These 8-week, competitive internships give students access to leading scientists, unique facilities, hands-on research experience and inspires them about future STEM careers. A number of graduates from this programme have since gone on to pursue PhDs in energy storage related disciplines, further internships, work in battery development for UK industry and to join a Faraday Institution spin out.

Faraday Undergraduate Summer Experience (FUSE)

A success story from 2020 was the adaption of the Faraday Undergraduate Summer Experience (FUSE) programme to create bespoke virtual internships for the online environment this summer. Successfully widening reach and participation, the scheme was highly competitive with over 900 applications. A dynamic and diverse pool of talent was drawn from over 17 universities and including some students who had previously attended two SEO London undergraduate attraction events.

Supplementing the work experience, the Faraday Institution hosted a programme of career shaping events to give interns greater insight into the field and potential opportunities. They were also joined by 10 undergraduates from the Faraday Institution Scholars Programme, which seeks to diversify science and engineering talent attending universities. Guest speakers presented on a day in the life of a battery researcher, what PhD research entails, and a glimpse into launching an entrepreneurial spin-out. Rounding out the career development aspects of the programme, interns presented research posters at the Faraday Institution Annual Conference. Results from this programme were highlighted by the Royal Society of Chemistry: *Remote Teaching and Learning During a Pandemic*.

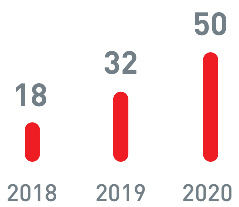
'I honestly feel as though I have experienced the highs and lows of innovative research and how exciting it is.'

Ellie Bibby, FUSE Intern
Read about University of Sheffield student Ellie Bibby's internship journey.

'The guidance given for future careers was invaluable to the experience and makes this internship stand out.'

Matthew Quarrell, FUSE intern, University of Liverpool

Number of FUSE interns



Gender

58% male / **42%** female

Degree Course

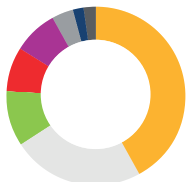
- 26% Chemistry
- 22% Chemical Engineering
- 16% Physics
- 12% Natural Science
- 12% Electrical Engineering
- 6% Mechanical Engineering
- 4% Other Engineering
- 2% Economics
- 2% Law

Education

60% State school education from age 11
18% Received free school meals
34% First generation to attend university

32% None of the above, 2% Prefer not to say

Ethnicity



- 42% White – British
- 24% White – European
- 10% Asian – Chinese
- 8% Black – African
- 8% Other
- 4% White – Irish
- 2% Mixed – White & Asian
- 2% Asian – Pakistani

These programmes were delivered virtually in 2020 due to the coronavirus and were nonetheless high in quality and impactful.

Before FUSE 26% of students would consider a PhD

After FUSE 84% of students would consider a PhD
93% of students would consider a career in battery technology

Doctoral Training

Now in its third year, the Faraday Institution offers a comprehensive PhD training programme, supporting 44 PhD researchers from 16 UK universities. Faraday Institution PhD cohorts have access to networking opportunities, industry visits, mentorship, internships, as well as other quality experiences that will further develop knowledge, skills, and aspirations.

The training programme aims to equip students with the in-depth knowledge and skills needed to support their research projects with modules such as the battery safety courses from Newcastle University, WMG Battery School, an energy-storage themed mini-MBA programme from Imperial College London and other providers. In addition, the Faraday Institution brings in external expert trainers to prepare PhD researchers with skills that will transfer to future industrial and academic roles in areas ranging from presentation training, project management, negotiations, and thesis and grant writing. These programmes were delivered virtually in 2020 due to the coronavirus and were nonetheless high in quality and impactful.

'The Faraday Institution is instrumental for building confidence in my skills and my network for my future career in the chemistry energy industry.'

Cameron Bathgate, University of St Andrews

'I am truly so grateful for the Faraday PhD programme. Each training session has given me so much to take away, whether it be a wider understanding of issues faced by lithium-ion battery researchers or presentation techniques and skills that will help me to develop professionally.'

Beatrice Browning, University of Birmingham

'Perhaps the aspect of the PhD I cherish the most is the collaborative side of it. I found the collaboration and discussion with colleagues within my own lab, the Faraday Institution consortium or industry partners extremely valuable and stimulating. It really made me understand that science is made through good collaboration. Overall, I feel engaged, challenged and supported throughout my PhD journey.'

Alexander Dimitrijevic, UCL

'I have had unique opportunities to gain a genuine insight into the forefront of human knowledge on energy storage, observe how research is progressed through collaboration, and understand how industrial partners are adapting to a changing world. The programme provides PhD researchers with the best opportunity to have a successful career in energy storage technology following their studies.'

Jacob M. Dean, University of Bath

'The programme truly does well in achieving its ambition of educating well-rounded battery experts with an insightful balance of theoretical and practical elements as well as breadth and depth of topics.'

Axel Forssberg, University of Oxford

'Being part of the Faraday Institution opens so many doors and provides so many more opportunities/ experiences than a normal PhD. I feel so lucky to be a part of it.'

Rosie Madge, University of Birmingham

'The most rewarding aspect of being part of the Faraday PhD programme is being a member of the PhD cohort. It's been a great way to learn about different aspects of battery research and get to know researchers at other universities.'

John-Joseph Marie, University of Oxford

Increasing gender diversity

The Faraday Institution's commitment to diversifying and widening the pool of talent and continuing work with university partners has seen greater gender diversity over three years, achieving a 50/50 female to male ratio in its third PhD cohort.

PhD cohort 1

15% female

85% male

PhD cohort 2

24% female

76% male

PhD cohort 3

50% female

50% male

Faraday Institution PhD Course Guide

The Faraday Institution programme of battery-related courses, delivered by experts in the field from university and industrial partners, ensures students are equipped with the in-depth knowledge and skills needed to maximise the potential of their research projects.

Download guide

Early Career Development

Over 200 Post-Doctoral Research Assistants (PDRAs) in the Faraday Institution community are supported through annual career development reviews with supervisors, a training budget, access to a training champion and multiple professional learning opportunities.

Professional Development

The Faraday Institution is committed to the continuing professional development of UK-based battery researchers. It has selected a range of CPD, residential and short courses from its partner university and other reputable providers for members of the UK research community, other academics and industrial partners to further develop and enhance their abilities. The majority of these are offered as online courses.

Faraday Masterclass Series

Amid the coronavirus pandemic, the Faraday Institution– working with leaders from our research community – launched a virtual masterclass series to keep engagement up and to offer valuable insights to early career researchers. Masterclasses were weekly, one-hour interactive discussions around science, state-of-the-art techniques, and professional development. The result tallied 19 recorded masterclasses throughout 2020, totalling over 2,800 hours of training collectively for early career researchers.

Faraday Masterclass series
Correlative Imaging for Energy Materials Paul Shearing, University College London
Data-driven Materials Optimisation and Discovery Aron Walsh, Imperial College London
Advanced High Resolution and In-situ STEM Imaging of Battery Materials and Systems Nigel Browning, University of Liverpool
Faraday's Fast Software for Simulating Battery Operation in your Research Robert Timms, University of Oxford, and Jamie Foster, University of Portsmouth
Intellectual Property – A Spotter's Guide Anna Gregson, Mathys and Squire
Size Matters – Atomic-Scale Insights into Battery Materials Saiful Islam, University of Bath
Writing for Impact Karl Ziemelis, Nature
Use of In-situ NMR: What Can We Learn? Clare Grey, University of Cambridge
Building out the Li-ion Supply Chain Andy Leyland, Benchmark Mineral Intelligence
Designing Batteries for Recycling Andy Abbott, University of Leicester
Battery Entrepreneur Insights Yan Zhao, Breathe Technology; Carolyn Hicks, Brill Power; and Ola Hekselman, Solveteq
NMR Crystallography in Energy Materials Research John Griffin, Lancaster University
Restarting Faraday Research Labs: Lessons from UCL and Imperial Greg Offer, Imperial College London; Paul Shearing, University College London
Equality, Diversity and Inclusion in Research Kevin Coutinho, University College London
Synthesis Methodologies and Operando Characterisation of Battery Materials Serena Corr, University of Sheffield
Revealing Interfacial Processes with X-ray Spectroscopies Rob Weatherup, University of Oxford
Cell prototyping – the First Step between Lab Discovery and Cell Manufacture Alex Roberts, Coventry University
Introduction to Impedance Spectroscopy for Electrochemical Power Sources Dan Brett, University College London
Battery Materials Research at Johnson Matthey: An Industrial Perspective James Cookson, Johnson Matthey

Faraday TECH Workshops

To provide more in-depth training on equipment, techniques and facilities, Faraday TECH workshops were launched covering topics such as nuclear magnetic resonance (NMR), X-ray photoelectron spectroscopy (XPS), intellectual property, advanced scanning transmission electron microscopy (STEM), mathematical modelling, and equality, diversity and inclusion (EDI) in conjunction with partners such as the Henry Royce Institute. In addition, training and coaching on scientific writing and publishing was led by *Nature* for members of the Faraday Institution research community.

Early Career Researcher Day

The Faraday Institution Annual Conference includes an Early Career Researcher Day, which this year provided a supportive environment in which 7 PhD Researchers and 9 Faraday Institution Research Fellows shared their results and identified opportunities for future collaboration. 12 PhD Researchers and 28 Research Fellows also presented scientific posters in on-line poster sessions. Contributions were selected on merit from a pool of over 100 submissions.

STEM Outreach

STEM AMBASSADORS

The Faraday Institution is actively committed to STEM outreach through training and equipping STEM Ambassadors to inspire future generations about careers in energy storage and battery technology.

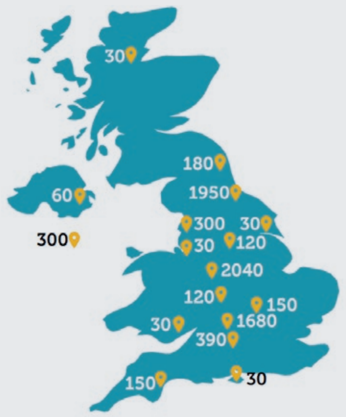
STEM Ambassador training is at the heart of the PhD training programme, with 30 researchers trained to date on how to present their research in creative, age-appropriate ways to pupils.

The Fully Charged Battery Box

To inspire young people across the UK about STEM careers, the Faraday Institution, in collaboration with the Curiosity Box, launched its bespoke, curriculum-linked Fully Charged Battery Box to foster curiosity amongst pupils aged 7-11+ about battery technology and STEM careers.

The resource provides teachers, researchers and STEM Ambassadors with everything they need to deliver high quality key stage 2 sessions that build science capital through exploring batteries and electricity, stimulating discussion about challenges and opportunities of the UK's electric future.

To date, over 7,500 young people have been engaged with hundreds of boxes being deployed across the UK. In 2020, a pilot project with 22 Faraday Fully Charged Battery Boxes is being tested by Primary Science Teaching Trust Fellows in classrooms up and down the country.



The number of children who have engaged with the Fully Charged Box across the UK and Ireland

Informing Policy and Engaging the Public

Informing Policy

National Skills Framework for the Electrification of the Auto Sector

As a member of the Automotive Council Skills Working Group, the Faraday Institution is preparing the sector to anticipate and deliver the skills needed to fully electrify auto production and serves as a model for other sectors, such as aero and grid. To gain an appreciation of the scale of the skills requirements for electrification of the volume automotive sector alone, which directly employs over 180,000 people, estimates of the skills shortage stand at 10,000 employees in need of reskilling to manufacture electric vehicles immediately, which rise to 50,000 by 2025 and around 100,000 by 2035/40. In addition, the sector predicts that over 80% of job roles related to the vehicle's powertrain will be impacted over the next decade by the electrification agenda.

In 2020, the Faraday Institution, working with the Auto Council, commissioned WMG and the High Value Manufacturing Catapult to develop a National Skills Framework for electrification of the auto sector. The first phase of this effort, which identifies the competencies required to produce electric vehicles across job types and levels in engineering and manufacturing roles, has been completed. By the end of 2020, a gap analysis of skill requirements will be complete, mapping current provision of courses to need and identifying curricula that will need to be created. Future phases extend through 2021.

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, industrial and financial communities. The Faraday Institution's Chief Economist, Stephen Gifford, regularly presents to departments and this year provided key economic intelligence and analysis on the EV market to the Department for Business, Energy & Industrial Strategy (BEIS) as input into their development of policy and a briefing for the disposal and recycling of EV batteries for a House of Commons debate. He also presented at various events throughout the year such as the All Party Parliamentary Group for Energy Storage, Bernstein 'Hour of Power' Annual Conference on Battery Economics, Benchmark Mineral Intelligence Electric Vehicles Festival and the Minex Conference on Battery Metals.

Policy consultations

The Faraday Institution responded to several policy consultations this year including:

- The Department of Transport consultation on bringing forward the end to the sale of new petrol and diesel cars to 2030
- The 6th Carbon Budget of the Committee on Climate Change
- The Zero Carbon Commission examining the role of carbon pricing and which led to its report: *How Carbon Pricing Can Help Britain Achieve Net Zero by 2050*.

Faraday Insights

The Faraday Institution has continued to publish Faraday Insights, evidence-based assessments of the market, economics, technology and capabilities for energy storage technologies and the transition to a fully electric UK. The insights are concise briefings that aim to help bridge knowledge gaps across industry, academia and government.

Solid-State Batteries: The Technology of the 2030s but the Research Challenge of the 2020s

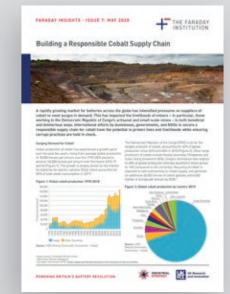
The development of solid-state batteries that can be manufactured at a large scale is one of the most important challenges in the battery industry today. The ambition is to develop solid-state batteries, suitable for use in electric vehicles, which substantially surpass the performance, safety, and processing limitations of lithium-ion batteries. In contrast to research into lithium-ion batteries, which will provide incremental gains in performance toward theoretical limits, research into solid-state batteries is long-term and high-risk but also has the potential to be high-reward.

Download issue 5

Lithium, Cobalt and Nickel: The Gold Rush of the 21st Century

Ending UK sales of new diesel and petrol cars and vans by 2030 will massively increase the demand for lithium, cobalt and nickel used to manufacture electric vehicle batteries. Many countries around the world are embarking on a similar path to electrification. Even so, global markets for raw materials should be able to deliver the demand in the UK and elsewhere. But action is needed now to iron out likely bottlenecks in supply chains. This Insight was updated in December to reflect the new 2030 end date, which is ten years earlier than planned.

Download issue 6 (updated December 2020)



Building a Responsible Cobalt Supply Chain

A rapidly growing market for batteries across the globe has intensified pressures on suppliers of cobalt to meet surges in demand. This has impacted the livelihoods of miners – in particular, those working in the Democratic Republic of Congo's artisanal and small-scale mines – in both beneficial and deleterious ways. International efforts by businesses, governments, and NGOs to secure a responsible supply chain for cobalt have the potential to protect lives and livelihoods while ensuring corrupt practices are held in check.

Download issue 7

Lithium-Sulfur Batteries: Lightweight Technology for Multiple Sectors

Lithium-sulfur technology has the potential to offer cheaper, lighter-weight batteries that also offer safety advantages. After initially finding use in niche markets such as satellites, drones and military vehicles, the technology has the potential to transform aviation in the long-term. Electric aircraft offering short-range flights or vertical take-off and landing (including personalised aviation and flying taxis in cities) are distinct possibilities by 2050. The UK, which is already home to established lithium-sulfur battery manufacturers and to leading academics in the field, has a great opportunity to be the global leader in this ground-breaking technology.

Download issue 8

The Importance of Coherent Regulatory and Policy Strategies for the Recycling of EV Batteries

The move to EVs has the potential to reduce carbon emissions and air pollution. However, the transition also brings associated environmental challenges with the need for efficient recycling systems to tackle the large numbers of EV lithium-ion batteries reaching end-of-life. Unless this waste flow is managed, some of the gains of the transition to EVs will be lost. Effective waste management infrastructure and a supportive regulatory framework will be necessary to realise the full benefits of a decarbonised transport sector.

Download issue 9

Report: UK Electric Vehicle and Battery Production Potential to 2040

On March 12, 2020 the Faraday Institution published an update to its study *UK Electric Vehicle and Battery Production Potential to 2040*, first published in 2019. The study finds that while there will be demand for seven UK-based gigafactories (large, high volume battery manufacturing facilities) by 2040, each producing 20 GWh per year of batteries, the UK is at risk of falling further behind Europe for battery manufacturing. The Faraday Institution study forecasts that the overall industry workforce in the automotive and EV battery ecosystem could grow by 50,000 employees by 2040.

Download report

Public Engagement

The Faraday Institution has a responsibility to ensure that the public has access to evidence-based information as the UK transitions to a fully electrified economy. It regularly engages with top tier media outlets in the UK and internationally and has established itself as a reputable source of information regarding energy storage research and technology and EVs, including on topics ranging from battery safety, recycling, the need for a sustainable supply chain, and the potential role for battery manufacturing in the UK. This has led to substantial top tier media coverage – and consequently hundreds of thousands of views by the public – in outlets that include the BBC, *The Telegraph, Bloomberg, The Guardian, Reuters, Financial Times, Wired and The Times*.

BBC *Ian Ellerington on BBC Countryfile*

Royal Institution Battery Engagement Programme

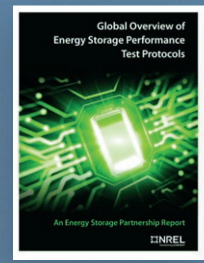
This year, the coronavirus lockdowns and social distance requirements have paused many opportunities for public outreach and engagement. Despite this, the Faraday Institution has been able to continue its public engagement work with the Royal Institution.

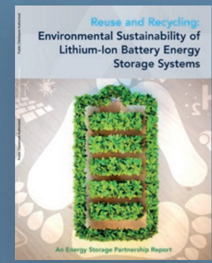
Professor Serena Corr, University of Sheffield and Principal Investigator of the FutureCat project, presented a LiveStream event on the *Hunt for Future Batteries*. Prof Corr provided a look at the science behind batteries, discussed why researchers are hunting for new batteries and outlined what tools scientists use to pave this pathway to discovery.

Now in its second year, this battery engagement programme with the Royal Institution has led to over 200,000 views online and continues to grow.

Ri The Royal Institution
Science Lives Here

Energy Access and Sustainable Development





The Faraday Institution's international work in sustainable development, supported through UK Aid and the Foreign, Commonwealth and Development Office, seeks to effect global change and allow communities without connectivity to have reliable access to sustainable energy sources.

Additionally, this work contributes to raising the profile of the Faraday Institution and the UK in an area of global importance. It enables the UK to build and leverage potentially valuable relationships with international energy storage organisations and supply chains and understand international market requirements that influence its research and commercialisation efforts.

World Economic Forum Global Battery Alliance

The Global Battery Alliance (GBA) is a collection of 70 public and private sector organisations founded in 2017. It has become the global platform to help establish and collaborate on a sustainable battery value chain. The Faraday Institution with the other GBA partners in the World Economic Forum, helped launch a 2019 report entitled *A Vision for a Sustainable Battery Value Chain in 2030*. Building on this work, GBA Energy Access Initiative was formed, which supports investigation into systemic interventions required to enable energy access potential.

In 2020, the Faraday Institution joined a GBA initiated collaboration to deliver an analytical study and recommendations to address barriers for broader battery recycling and reuse in Africa. The lead partners are the World Bank Group, World Economic Forum, Ministry of Foreign Affairs of Denmark and the Faraday Institution.

Access to electricity

Over 800 million people worldwide do not have access to electricity and, of those that do, many suffer from an unreliable supply. Diesel and petrol generators commonly used in developing countries bring problems of noise, air quality and climate impacts. Energy storage technologies including batteries have the potential to displace generators and provide cheap, clean and reliable electricity to millions of people.

World Bank Energy Storage Programme

The World Bank's $1B Energy Storage Programme, which is targeting the financing of 17.5 GWh of energy storage projects in developing countries by 2025, brings together 28 international partners through seven technical working groups focused on providing guidance to people making energy storage focussed investment decisions. The Faraday Institution continues to support two of these working groups. It is a lead partner with the National Renewable Energy Laboratory in the US on developing test, demonstration and performance protocols for energy storage in microgrids.

In 2020, this effort led to the publication of *Global Overview of Energy Storage Performance Test Protocols* that provides support and knowledge to stakeholders across the developing world on emerging opportunities and technologies for energy storage in the electric sector. Another result of this partnership, which leveraged the unique knowledge of the Faraday Institution's ReLiB programme, is the 2020 publication of the *Reuse and Recycling: Environmental Sustainability of Lithium-Ion Battery Energy Storage Systems* that provides an overview of the situation with regards to reuse and recycling of lithium-ion batteries, in order to assess if and to what extent developing countries can and should play a larger role in this burgeoning area.

Transforming Energy Access (TEA) and the Shell Foundation

The Faraday Institution is working with the University of Oxford to advise a Shell Foundation-funded project that is monitoring the design, procurement, installation, commissioning and performance of 4 next generation, novel battery based microgrid trials in Nigeria.

This international work is funded through £3m of UK aid funding and the Foreign, Commonwealth and Development Office Transforming Energy Access (TEA) Programme, administered by the Carbon Trust. The outputs of the TEA programme are being used to inform the UK's £1bn Ayrton Fund Programme that will be launched in April 2021.

Appendices

Board of Trustees

Peter B. Littlewood, Chair

Peter B. Littlewood is Professor of Physics at the University of Chicago. He served as the 13th Director of the US Department of Energy's Argonne National Laboratory, after having served as the associate laboratory director of its Physical Sciences and Engineering directorate. He spent the previous 14 years at the University of Cambridge, where he last served as the head of the Cavendish Laboratory and the Department of Physics. Littlewood is internationally recognised for his research in a number of areas, including superconductivity, semiconductor optics, and magnetic materials. Littlewood holds a bachelor's degree in natural sciences (physics) and a doctorate in physics, both from the University of Cambridge.

Stephen Heidari-Robinson, Vice-Chair

Stephen Heidari-Robinson is co-founder and Managing Director of Quartz Associates. He served as former UK Prime Minister David Cameron's energy and environment adviser and was one of the architects of the UK's generation strategy and decarbonisation plan. Heidari-Robinson spent nine years as a leader in McKinsey and Company's energy practice and was a vice president of Schlumberger. Heidari-Robinson read history at the University of Oxford, holds an MA in architectural history from the Courtauld Institute, University of London, and studied Farsi at the School of Oriental and African Studies.

Jeff Chamberlain

Dr Jeff Chamberlain is CEO of Volta Energy Technologies, a company that identifies and invests in battery and energy storage technology after performing deep diligence with the support of unparalleled global research institutions. In service both to its strategic corporate investors and to entrepreneurs, Volta identifies and invests in the most promising energy-storage innovations. Chamberlain holds a PhD in physical chemistry from the Georgia Institute of Technology and a BS in Chemistry from Wake Forest University.

Andreas Docter

Dr Andreas Docter is the Director of Electric Powertrain at Jaguar Land Rover (JLR). He leads a team of specialist engineers, senior managers and chief engineers in the field of batteries, power electronics, electric drive units, transmissions and fuel cell development - responsible for the research, design and development of next generation of hybrid and electric vehicle powertrain systems and components for JLR. He studied Mechanical Engineering at Northwestern University in Chicago and at Bochum University in Germany, where he completed his PhD in Thermodynamics.

Board of Trustees

Kristina Edström

Professor Edström leads the Ångström Advanced Battery Centre (ÅABC) and she is a professor of Inorganic Chemistry at Uppsala University, Sweden. Her main research interests are lithium-ion batteries for all applications including electric vehicles, 3D microbatteries but beyond lithium batteries (sodium-ion, organic batteries, lithium-sulfur, lithium/sodium-oxygen batteries and solid-state batteries). She also develops photon science and neutron scattering in operando methods for studying dynamic processes in materials and batteries, in addition to having a great interest in teaching and guiding young researchers. She is a member of the Royal Academy of Engineering Sciences.

Johney Green

Dr Johney Green Jr. serves as the Associate Laboratory Director for the Mechanical and Thermal Engineering Sciences directorate at the US Department of Energy's National Renewable Energy Laboratory (NREL). Green oversees early-stage and applied research and development in NREL's advanced manufacturing, buildings efficiency, concentrating solar power, geothermal energy, sustainable transportation, water power, and wind energy programs. Green holds a bachelor's degree in mechanical engineering from the University of Memphis and a master's and doctorate in mechanical engineering from the Georgia Institute of Technology.

Julie Maxton

Dr Julie Maxton CBE is the Executive Director of the Royal Society, the first woman in 350 years to hold the post. Before taking up her position at the Royal Society in 2011 Maxton was Registrar at the University of Oxford, the first woman in 550 years in the role. Maxton combined a career as a practising lawyer with that of an academic, holding a number of senior academic positions, including those of Deputy Vice Chancellor, Professor and Dean of the Faculty of Law at the University of Auckland, New Zealand.

Jorge Pikunic

Dr Jorge Pikunic is Managing Director of Centrica's global Distributed Energy & Power business, established to deliver distributed energy solutions for large energy users as part of a more flexible energy landscape. Born in Venezuela, Pikunic is an engineer and holds a MSc and PhD in Chemical Engineering. He was a research fellow at the University of Oxford before joining McKinsey & Company, where he advised a number of institutions in energy and other sectors.

Mark Spearing

Professor Mark Spearing is the Vice-President, Research and Enterprise at the University of Southampton. Previously he was the Pro Vice-Chancellor (International) and Head of the School of Engineering Sciences, having been appointed as the Professor of Engineering Materials in 2004. He was a faculty member at the Massachusetts Institute of Technology from 1994-2004. His personal research focuses on structural and functional materials. He holds a BA and PhD in Engineering from the University of Cambridge.

Maurits van Tol

Maurits van Tol is Chief Technology Officer at Johnson Matthey. Before joining Johnson Matthey, Maurits was Senior Vice President Innovation and Technology at Borealis, where he was responsible for shaping the circular economy business as well as being part of the company's management board responsible for their plastics business. He has a PhD in Catalysis and an MSc in Physical Chemistry and Catalysis, both from Leiden University, The Netherlands. Parts of his studies were also performed at the University of East Anglia, and UC Berkeley.

Sir Oliver Letwin,
Senior Advisor to the Board of Trustees

Sir Oliver served as the Member of Parliament for West Dorset from 1997 to 2019. From 2010, he was the Minister for Government Policy in David Cameron's coalition government and coordinated the push to make the UK a world leader in electric vehicles. He continued to serve as Chancellor of the Duchy of Lancaster, Cabinet Minister in overall charge of the Cabinet Office until July 2016. He was educated at the University of Cambridge, Princeton University, and London Business School. In a varied career, Sir Oliver has been a research fellow at the University of Cambridge, a civil servant, and a bank director.

Faraday Institution Team

Pam Thomas, Chief Executive Officer

Professor Pam Thomas was appointed to the role of Chief Executive Officer of the Faraday Institution in September 2020. From 2016 she served as the Pro Vice Chancellor for Research at the University of Warwick with responsibility for academic leadership of the research portfolio and strategy across the whole of the institution.

In her personal research, she leads the Ferroelectric Crystallography group at the University of Warwick, which is part of the Condensed Matter and Materials activity in the Department of Physics. She has published more than 160 peer-reviewed journal articles and two patents, one of which became the basis of a spin-out company, Pro KTP, to exploit the invention of a new low-conductivity variant of the nonlinear optical material potassium titanyl phosphate (KTP).

She was educated at the University of Oxford, where she took a BA (Hons) in Physics and a DPhil on the subject of Optical Activity in Crystals in the Physical Crystallography Group of the Clarendon Laboratory.

Susan Robertson, Chief Financial Officer

Prior to joining the Faraday Institution, Susan Robertson was Chief Financial Officer of Velocys, the AIM-listed renewable fuels company, a position she held for 10 years through the company's transformational years from early stage start-up to the point of having a commercial plant in operation. Prior to this, she was at the BOC Group (now Linde Group) where she held various senior-level financial management and business development positions in the UK and in Japan. Susan helped to set up and then, from 2003 to 2006, served as Vice President and CFO of Japan Air Gases (JAG), a joint venture between The BOC Group and Air Liquide.

Susan has an honours degree in economics from the University of Cambridge and is a chartered accountant (FCA) having originally trained with Arthur Andersen in London.

Peter G Bruce, Chief Scientist

Professor Peter G Bruce is a founder and Chief Scientist of the Faraday Institution. He is also leading the research project on solid state batteries. He is the Wolfson Professor of Materials at the University of Oxford.

Peter's research interests embrace materials chemistry and electrochemistry, especially lithium and sodium batteries. Recent efforts have focused on the synthesis and understanding of new materials for lithium-ion batteries, on understanding anomalous oxygen redox processes in high capacity Li-ion cathodes, the challenges of the lithium-air battery and the influence of order on the ionic conductivity of polymer electrolytes.

His research has been recognised by a number of awards and fellowships, including from the Royal Society, the Royal Society of Chemistry, the German Chemical Society and The Electrochemical Society. He was elected to the Royal Society (UK Academy of Sciences) in 2007 and the Royal Society of Edinburgh (Scottish Academy of Sciences) in 1994. He has appeared on the Thomson Reuters list of highly cited researchers since 2015.

Craig Chapling, Project Manager

Prior to joining the Faraday Institution as Project Manager, Craig Chapling was responsible for the delivery of components and systems into many vehicle lines at a UK-based OEM, including upgrades to high capacity battery packs. He was also part of the team developing a hybridised dual clutch transmission through an APC funded start-up. Responsible for large engineering investment budgets, and annual bill of material spends measured in the hundreds of millions, his ability to effectively plan and deliver was essential in the automotive industry.

As a student, Craig helped to develop a hybrid vehicle during an exchange at Penn State University in the USA, through the Challenge X programme sponsored by GM, the US Department of Energy and managed by Argonne National Laboratory. He holds a first class Master's degree in Automotive Engineering from the University of Leeds.

Ian Ellerington, Head of Technology Transfer

Ian Ellerington joined the Faraday Institution in 2018 after six years in central government where he worked on designing and implementing innovation programmes in the energy sector. He was responsible for the government's energy innovation programme in the Department of Energy and Climate Change and continued in the Department of Business, Energy and Industrial Strategy as Head of Disruptive Energy Technologies and Green Finance Innovation.

Ian is an engineer who graduated from the University of Cambridge with an M.Eng. in manufacturing engineering in 1993 and is now an experienced technical manager who has worked with small, medium and large corporates, academia and government. His early career was spent working on gas turbine engines with the Ministry of Defence before moving to project management at QinetiQ where he was responsible for research programme management and delivery of large test programmes. He left QinetiQ to join Meggitt Defence Systems that developed and operated new technical products. As UK General Manager Ian set up and ran a new R&D and manufacturing facility.

Stephen Gifford, Chief Economist

Stephen Gifford has over 25 years of economics experience, including as the Chief Economist at Grant Thornton, the Director of Economics at the CBI and as a senior economist at KPMG, Oxford Economics and the Prime Minister's Strategy Unit. Prior to joining the Faraday Institution, Stephen was Head of Economic Regulation at the Civil Aviation Authority, where he focused on the regulation of Heathrow and Gatwick airports, and the development of the new runway at Heathrow. Stephen is currently a Commissioner in the National Infrastructure Commission for Wales.

Stephen brings particular skills and expertise in economic policy, transport economics, infrastructure, market assessment and the role of the public sector. He has a first-class degree in economics from the University of Liverpool and a MSc in econometrics and mathematical economics from the London School of Economics.

Louise Gould, Communications Lead

Louise Gould is a marketing and communications professional who has centred her career around technology-based organisations. She joined the Faraday Institution after five years as Marketing Communications Manager at the renewable fuels company Velocys. There she was responsible for all marketing, communications and brand activities for this pre-profit, publicly-listed company as it endeavoured to commercialise its proprietary technology by developing biorefineries in the UK and US. Her role included formulation of communications strategy with C-suite executives, as well as the operational delivery of projects across messaging development, stakeholder management, PR, annual reporting, events, naming and branding, social media strategy and website development.

Prior to joining Velocys she served as Marketing Manager for an equipment manufacturer serving the print industry. She was also Product Manager for one of Oxford Instruments' range of low temperature sample environments used for spectroscopic techniques. She started her career as a scientific consultant and project manager at AEA Technology.

Louise graduated from the University of Cambridge with a BA in Natural Sciences (Chemistry) and holds an MSc in the Chemistry of Advanced Materials from the University of Manchester Institute of Science and Technology (UMIST).

Alison Green, Financial Analyst

Alison Green joined the Faraday Institution from Navitas, a leading global education provider where she helped to set up the European shared services centre and ran the general ledger team. Prior to that she held finance roles in an international paints and coatings company.

Alison has a BA (Hons) in accounting and finance from Leeds Metropolitan University and is currently in the process of completing her accountancy qualification with the Chartered Institute of Management Accountants (CIMA).

Faraday Institution Team

Vicki Harper, Executive Assistant

Vicki Harper has over 25 years' experience working in the administrative, HR and office management fields. Most recently Vicki held the position of Office Manager at Oxford Biotrans, a University of Oxford spin-out company developing and commercialising enzymatic process technologies that yield high-value chemical compounds. Prior to that she was at Velocys plc, an AIM-listed renewable fuels company for 11 years, where she was the Office & HR Manager. Vicki holds an advanced diploma in business studies and also a certificate in Human Resource Management. She is an associate member of the Chartered Institute of Personnel and Development (CIPD).

Gareth Hartley, Business Intelligence Manager

Gareth Hartley joined the Faraday Institution in June 2020 as the Business Intelligence Manager. He is interested in UK decarbonisation policy and is passionate about facilitating the commercialisation of sustainable technologies.

Prior to joining the team, he undertook a DPhil in Materials at the University of Oxford under the supervision of Prof Peter Bruce, where his research was primarily focused on solid-state batteries. He previously worked with Prof. Mike Bowker at the UK catalysis hub and with Prof. Thomas Maschmeyer at the University of Sydney on solar technologies and hydrogen production. Gareth has managed several multi-million-pound projects and has experience working within a financial institution.

In 2015, Gareth attained a 1st Class MChem from the University of Sheffield. His Master's project focussed on modelling the properties of semiconductors for solar applications.

Matthew Howard, Head of Engagement and Education

Matt Howard joined the Faraday Institution in March of 2018. Prior to this, he served as Chief Communications Officer and as director of the communications and public affairs division for the US Department of Energy's Argonne National Laboratory. In this capacity, he was responsible for communications strategy, brand and visual identity, media relations, crisis communications, internal communications, educational programmes and community engagement.

Before joining Argonne in 2007, Matt served as the director of the media initiatives group at the University of Chicago. In the past, Matt has worked as a higher education adviser, as an editorial lead for multiple start-up companies, and as an editor for an academic publisher.

Matt holds an MBA from the University of Chicago Booth School of Business, a master's degree from Miami University, and a bachelor's degree from the University of Rochester.

Fran Long, Education and Training Lead

Fran Long develops and implements the Faraday Institution's educational and training programmes to include undergraduate attraction initiatives, PhD cohort events, and PDRA professional career development.

Prior to her work at the Faraday Institution, Fran served as a STEM engagement specialist and award-winning primary science teacher who is passionate about promoting science and engineering. In 2017, Fran was honoured to receive a Primary Science Teacher Award (PSTA), endorsed by the Institute of Physics, and is now a Fellow of the Primary Science Teaching Trust (PSTT).

Fran was the creator of a pioneering STEM assembly series that brought STEM professionals (scientists and engineers) into school to share about a day of their working life over a 16-month period. Research to evaluate the impact of the programme on STEM career aspirations showed a statistically significant increase in the number of pupils who would consider scientific and engineering career paths.

As part of a Post Graduate Certificate for Professional Recognition in Engineering STEM Learning, Fran interviewed 35 engineers in the work place, gaining insight into 'Engineering Habits of Mind' (EHOM) as described by Bill Lucas in 'Thinking Like An Engineer'. She ascertained the inspiration behind STEM career choices and presented findings to industry experts and colleagues.

Stephen Parry, Technical Specialist

Stephen Parry is technical specialist for the Faraday Institution on secondment from Diamond Light Source. He has a track record of applied research and is particularly interested in the application of advanced characterisation techniques to accelerate scientific discovery, solve commercial R&D challenges, and underpin commercialisation.

Stephen has over 20 years' experience of chemistry research and instrument development in collaboration with international laboratories including Lawrence Berkeley National Laboratory and Argonne National Laboratory. He has a background in the civil nuclear sector, first working as a Postdoctoral Fellow at the University of Manchester with his own research programme characterising nuclear wastes; later joining UKAEA Ltd as a lead consultant working on several multi-million-pound decommissioning projects.

Stephen holds a PhD in Earth Sciences from the University of Manchester and an Industrial Chemistry degree from the University of Liverpool. Stephen is a member of the Royal Society of Chemistry and is Treasurer of the Mineralogical Society of Great Britain and Ireland. He is a member of several independent scientific committees funding academic research and steering UK science strategy.

Nick Smailes, Commercialisation Programme Manger

Nick joined the Faraday Institution in April 2020 to help develop and grow its commercialisation capability and also lead its FCDO UK Aid funded work.

In 2015 Nick set up the Energy Systems Catapult on behalf of UK Government. He was an Executive Director there for 5 years, helping to build it into a £20m, 200 staff organisation. His achievements included enabling the Catapult to leverage and acquire the Energy Technologies Institute's 10 year legacy including its Strategic Analysis capabilities and the Smart Systems and Heat Programme and also supporting the origination of the Industrial Strategy PFER programme.

In 2008 Nick co-founded and was MD of PowerOasis Ltd, a spin-out from Motorola. PowerOasis developed energy solutions for telecoms networks in parts of the works where the electricity grid is unreliable or unavailable. Nick build the company into a micro multinational with business in Asia, Africa, Europe and the US before exiting after securing a large round of venture capital investment to further grow the company.

In 2002 Nick co-founded and was MD of SETsquared, the leading global technology accelerator that works with the Universities of Bath, Bristol, Cardiff, Exeter, Southampton and Surrey. SETsquared has supported over 4,000 entrepreneurs and helped raise over £1.8bn of venture investment.

Principal Investigators

Paul Anderson, ReLiB

Dr Paul Anderson is a Reader in Inorganic and Materials Chemistry in the School of Chemistry at the University of Birmingham and co-founder of the Birmingham Centre for Strategic Elements and Critical Materials.

The synthesis and development of improved materials for energy applications has been a major theme of his research for over two decades, with particular interests in ion mobility in hydrogen storage materials and related Li+ and H+ electrolyte systems, and the efficient husbandry of the earth's elemental resources.

Peter G Bruce, SOLBAT

See executive team

Serena Corr, FutureCat

Prof Serena Corr is Chair of Functional Nanomaterials and Director of Research at the Department of Chemical & Biological Engineering at the University of Sheffield and leads the Energy Storage Research Centre. She obtained her BA (2002) and PhD (2007) in Chemistry from Trinity College Dublin. She completed her PhD work on New Magnetic Nanostructured Materials with Professor Yurii Gun'ko, where she developed new magnetic materials for biomedical applications. After a lectureship at the University of Kent, Serena joined the School of Chemistry at the University of Glasgow as a lecturer in Physical Chemistry in 2013, was promoted to Reader in 2016 and made Professor and Chair of Energy Materials in 2018.

Her research addresses the rational design and morphology control of energy storage materials, particularly their structure-performance interplay (including high Ni-content cathodes and high capacity electrodes). She is an international leader in the battery community, directing several multi-institutional research programmes, serving on international advisory boards, publishing in high-impact journals and proactively engaging public interest in next-generation batteries.

Patrick Grant, Nextrode

Patrick Grant FREng is the Vesuvius Professor of Materials and Pro-Vice-Chancellor for Research at the University of Oxford. His research takes place at the interface between advanced materials and manufacturing. Particular applications include electrodes for energy storage and advanced metallics for power generation. Many of his research projects are concerned with solidification behaviour in complex alloys, and/or the use of liquid metal, ceramic or polymer droplet and powder sprays to create unusual materials. All the research work involves close collaboration with industry.

Clare P Grey, Degradation Project

Clare P Grey, FRS is a Royal Society Research Professor, Geoffrey Moorhouse-Gibson Professor of Chemistry at the University of Cambridge and a Fellow of Pembroke College Cambridge. She received a BA and D. Phil. (1991) in Chemistry from the University of Oxford. Her current research interests include the use of solid-state NMR and diffraction-based methods to determine structure-function relationships in materials for energy storage (batteries and supercapacitors), conversion (fuel cells) and carbon capture.

Recent honours and awards include Honorary PhD Degrees from the Universities of Orleans (2012) and Lancaster (2013), the Research Award from the International Battery Association (2013), the Royal Society Davy Award (2014), the Arfvedson-Schlenk-Preis from the German Chemical Society (2015), the Société Chimique de France, French-British Prize (2017), the Solid State Ionics Galvani-Nernst-Wagner Mid-Career Award (2017), the Eastern Analytical Symposium Award for Outstanding Achievements in Magnetic Resonance (2018), the Sacconi Medal from the Italian Chemical Society (2018), the Charles Hatchett Award, Institute of Materials, Minerals and Mining (2019), and the RSC John Goodenough Award (2019). She is a foreign member of the American Academy of Arts and Sciences, and a Fellow of the Electrochemical Society and the International Society of Magnetic Resonance.

John Irvine, NEXGENNA

John Irvine FRSE, FRSC is Professor in the School of Chemistry at the University of St Andrews. He has made a unique and world-leading contribution to the science of energy materials, especially fuel cell and energy conversion technologies. This research has ranged from detailed fundamental to strategic and applied science and has had major impact across academia, industry and government. Prof Irvine's science is highly interdisciplinary extending from chemistry and materials through physics, bioenergy, geoscience, engineering, economics and policy.

The quality and impact of Prof Irvine's research has been recognised by a number of national and international awards, including the Lord Kelvin Medal from the Royal Society of Edinburgh in 2018, the Schönbeim gold medal from the European Fuel Cell Forum in 2016, the RSC Sustainable Energy Award in 2015, with earlier RSC recognition via Materials Chemistry, Bacon and Beilby awards/medals. Irvine has almost 500 publications and has an WoS h-index of 64. He has strong international standing having held senior visiting appointments in the US, Australia and China and has strong links with a number of leading laboratories across the Chinese Academy of Science including being Thousand Talents professor at Fujian Institute of Research on the Structure of Matter.

Saiful Islam, CATMAT

Saiful Islam is Professor of Materials Chemistry at the University of Bath. He grew up in London and obtained his Chemistry degree and PhD from University College London (with Richard Catlow FRS), followed by a Postdoctoral Fellowship at the Eastman Kodak Labs in New York. He returned to the UK to the University of Surrey before joining the University of Bath in 2006. His research interests include structural, transport and computational studies of new materials for lithium-ion batteries and perovskite solar cells. He has presented more than 80 invited conference talks and has over 215 publications. He is the recipient of several awards including the 2020 ACS Award in Energy Chemistry, 2017 RSC Peter Day Award for Materials Chemistry and 2013 Royal Society Wolfson Research Merit award.

Prof Islam presented the 2016 Royal Institution Christmas Lectures for BBC TV, entitled 'Supercharged: Fuelling the Future.'

Gregory Offer, Multi-Scale Modelling

Dr Gregory Offer is a Reader at Imperial College London and leads the Electrochemical Science & Engineering Group in Mechanical Engineering. Since starting his group in 2010 it has worked with multiple industry partners on projects worth over £32.5 million. Dr Offer has also worked as a management consultant and a government advisor.

Dr Offer's research is at the interface between the science and engineering of electrochemical devices. Having trained as an electrochemist before moving to engineering, his research portfolio focuses on understanding the limits of operation, degradation mechanisms and failure modes of batteries, supercapacitors and fuel cells in real world applications, and the impacts and consequences on system design, integration and control. He has published multiple peer reviewed journal papers, patents, technical reports and books. Dr Offer is also a co-founder of two battery related start-ups, Cognition Energy Ltd and Breathe Battery Technologies Ltd.

Paul Shearing, LiSTAR

Paul Shearing is a Professor of Chemical Engineering at UCL, where he holds the RAEng Chair in Emerging Battery Technologies, which recognises 'global research visionaries'. He is co-director (alongside Dan Brett) of the Electrochemical Innovation Lab (EIL), the UK's largest electrochemical engineering laboratory. He was 2014 Young Chemical Engineer of the Year and the 2016 RAEng Young Engineer of the Year. His work focuses on the development of next generation battery materials (the subject of his RAEng Chair) with work on Li-S batteries including the first application of 4D-imaging tools and the first use of image-based modelling to describe electrode behaviour. He has worked extensively with industry to translate this understanding of Li-S electrodes to commercial environments. He is a Fellow of the IChemE, leads the UK's STFC Batteries Network, and chairs the Faraday Institution's Training & Diversity Panel.

Expert Panel

The Expert Panel, led by the Faraday Institution Chief Scientist, Peter Bruce, and joined by the Faraday Institution Principal Investigators, brings the UK's best battery experts together across academia and industry in one organisation. The Expert Panel is the engine of the Faraday Institution, acting formally in an advisory role to the Faraday Institution Chair and Board.

Jerry Barker

Jerry Barker is Chief Technology Officer of Faradion. He is a world-renowned battery scientist, having set up and managed battery research facilities in the US and the UK. Over the course of his career, he has gained a wealth of knowledge and experience in the field of battery technology, from the active materials to their scale up and integration into battery systems. Former chief scientist at Valence Technology Inc., Dr Barker is an inventor on over 90 issued and ~ 50 pending US battery patents. Some noteworthy examples of his inventions include the well-known Li-ion materials LiVPO4F, Li3V2(PO4)3, LiMSO4F, Li2MP2O7, LiFe(Mg)PO4 along with the carbothermal reduction (CTR) manufacturing method. As a result of Dr Barker's impressive track record in this field, he was presented with the International Battery Materials Association Technology Award 2012, for his contributions to identifying new secondary battery cathode materials and related materials.

Nigel Brandon

Professor Nigel Brandon OBE is Dean of Engineering at Imperial College London, Director of the UK Hydrogen and Fuel Cell SUPERGEN Hub, Co-Director of the UK SUPERGEN Energy Storage Hub, and Chair of Imperials' Sustainable Gas Institute. His research is focused on electrochemical devices for energy applications, with a particular focus on fuel cells, flow cells, electrolysers, and batteries. He was the founding Director of the Energy Futures Lab at Imperial College, a founder of Ceres Power, an AIM listed fuel cell company spun out from Imperial College in 2000, and a founder of RFC Power, a flow battery company spun out from Imperial College in 2018. He was awarded the Royal Academy of Engineering Silver Medal in 2007, the Institution of Civil Engineers Baker Medal in 2011, and the ASME Francis Bacon Medal in 2014. He is a Fellow of the Royal Academy of Engineering, the Institute of Materials, Minerals and Mining, and the Energy Institute.

Dan Brett

Dan Brett is Professor of Electrochemical Engineering at UCL, where he is a director of the Electrochemical Innovation Lab (EIL) and Advanced Propulsion Lab (APL). He received his PhD in Physical Chemistry from Imperial College London in 2000. Prof Brett's research encompasses a broad range of electrochemical technology, with a particular focus on fuel cells, batteries, supercapacitors, electrolysers, and redox flow batteries. His research has been recognised through the 2009 De Nora Prize for Applied Electrochemistry (International Society of Electrochemistry), the Baker Medal in 2011 (Inst. Civil Engineers), and The Engineer Collaborate to Innovate Award for lithium-ion battery safety research in 2017. His research has been commercialised through the spin-out companies Amalyst (advanced electrochemical materials) and Bramble Energy (fuel cell stacks and systems), where he is the Director of Innovation.

Anthony K Burrell

Anthony K Burrell is chief technologist for energy storage at the US Department of Energy's National Renewal Energy Laboratory (NREL). He has been working in the areas of energy science and technology since the early 1990s with a specific focus on energy storage. Recently, he was the department head for electrochemical energy storage at Argonne National Laboratory. He holds a PhD in chemistry from the University of Auckland, New Zealand.

Nick Butler

Nick Butler is visiting professor and chair of the Kings Policy Institute at Kings College London. Nick Butler chairs Promus Associates and Ridgeway Information Ltd. He is also a Senior Adviser to Coller Capital and Linton Capital and a member of the Strategic Advisory Council of Equinor (formerly Statoil). From 2009 to 2010 he worked for former Prime Minister Gordon Brown as Senior Policy Adviser. From 2007 to 2009 he was Chairman of the Cambridge Centre for Energy Studies. Prior to this he was Group Vice-President for Strategy and Policy Development at BP from 2002 to 2006 and previously BP's Group Policy Adviser, having joined the company in 1977. Nick is an Energy Policy Adviser at the Cavendish Laboratory in Cambridge, a Non-Executive Director of Cambridge Econometrics. He is a Trustee of Asia House, a Vice-President of the Hay-on-Wye literary festival, and a regular contributor to the Financial Times. Nick's particular interests are international energy policy, including energy security, industrial policy, the future of higher education, and European issues.

David Greenwood

David Greenwood is the CEO of the WMG centre High Value Manufacturing (HVM) Catapult at the University of Warwick, where he is also Professor of Advanced Propulsion Systems. His research spans batteries, electric motors, power electronics, and the integration and control of these for propulsion and energy applications. He joined WMG in 2014 from engineering consultancy Ricardo UK Ltd where he was Head of Hybrid and Electric Systems leading advanced technology projects for OEM and Tier 1 customers in passenger cars, defence, motorsport and the clean energy markets. Professor Greenwood holds advisory and board positions for the Advanced Propulsion Centre, and Innovate UK (Faraday Challenge and IDP), EPSRC (Energy). He is head of the Advanced Propulsion Centre's Electrical Energy Storage Spoke.

A Robert Hillman

Robert Hillman was educated at Imperial College London (BSc, 1976) and the University of Oxford (DPhil, 1979). After postdoctoral research at Imperial College, he was appointed to a Lectureship at the University of Bristol (1983), to the Chair of Physical Chemistry at the University of Leicester (1992), and as Dean of the Faculty of Science (2003-2009). He was Scientific Editor of Faraday Transactions and Faraday Discussions (1994-1997) and has been Editor in Chief of Electrochimica Acta since 2014. Prof Hillman has served the International Society of Electrochemistry as UK National Secretary (1994-1998), Secretary General (1999-2005), Chair of the Scientific Meetings Committee (2006-07) and President (2009-2010), and the Electrochemical Society through its Sensor Division and Education Committees. He is an elected Fellow of the International Society of Electrochemistry and of the Electrochemical Society.

His research interests in electrochemistry have involved surface modification, electrodeposition, interfacial characterisation, materials science and interfacial analysis and imaging. He has pioneered the development of a number of acoustic wave, optical, spectroscopic, neutron reflectivity and surface analytical techniques for in situ interfacial characterisation. These works are represented in over 230 publications.

Robert Millar

Rob Millar is the Head of Electrical for Williams Advanced Engineering, the technology and engineering services business of the Williams Group.

He has been involved with vehicle electrification since 2004 when he founded his own company developing electronic systems for Modec, Tata, JLR and Daimler vehicles amongst others. Having first worked with Williams in 2010, when he was part of the team who delivered the Jaguar C-X75 programme, he joined the company as a full-time employee in 2016 to head up the company's battery and electronics programmes.

John Owen

John Owen is an Emeritus Professor in the Southampton Electrochemistry Group. After his early studies on lithium anodes, polymer electrolytes and composite electrodes at Imperial College, London in 1979 he began an academic career at Salford in 1984 then Southampton since 1991, training students and postdoctoral researchers in batteries, supercapacitors and simple models of their energy and power limitations. His research has mainly comprised the characterisation of electrochemical materials, e.g. ceramic, glass, polymer, gel and liquid nonaqueous electrolytes, electron conducting polymers, nanocomposites, redox mediators and their applications in batteries, particularly lithium-ion, lithium-air and lithium sulfur.

Andrea Russell

Andrea Russell is Professor of Physical Electrochemistry at the University of Southampton. Her research interests are mainly in the application of spectroscopic methods to study the electrode/electrolyte interface, with particular emphasis on electrocatalysts and electrode materials for batteries including metal-air systems, fuel cells and electrolysers as well as gas sensors. Prof Russell received her PhD from the University of Utah and then proceeded to hold an NRC Postdoctoral Research Fellowship at the US Naval Research Laboratory. She came to the UK in 1991, first holding lectureships at the Universities of Liverpool, Newcastle and the University of Southampton before being appointed to her current position in 2007. She is the author or co-author of more than 70 refereed papers and is Chair of the Physical Electrochemistry Division of the International Society of Electrochemistry.

Julia Rowe

Julia Rowe is Sustainability Manager for Johnson Matthey (JM), a position she has he held for over a decade. In this role, she ensures the corporate sustainability strategy is incorporated into all aspects of its business, from the way decisions are made on R&D projects & capital investments to the way manufacturing plants are run globally. Her current focus is developing JM's corporate Net Zero strategy, enhancing its global responsible sourcing strategy and building up its product life cycle assessment capability. Over the last few years, she has been working with JM's Battery Materials business to ensure sustainability is integral to the design of its first cathode manufacturing plant, currently under construction in Poland, and all its supply chains. In prior positions over her 25-year career at JM, she has managed technical projects in the area of hydrogen generation and hydrogen PEM fuel cell technology and as served as Technology Commercialisation Manager for JM's first membrane electrode assembly plant. Julia has an MA (Oxon) in chemistry and a PhD in catalysis with surface science.

Nigel Taylor

Nigel Taylor is Senior Manager Concept Batteries at Jaguar Land Rover. Nigel has worked at Jaguar Land Rover for 30 years in a number of areas including as a technical specialist in acoustics, winning an award for time domain route tracking. The move to hybrid and electric vehicles came about in 2008 with Limo Green, a range extended electric Jaguar XJ. From here Nigel moved to technical lead for Jaguar Land Rover, WMG and TMETC on the HVM Catapult Energy Storage project; this team based on the Warwick University campus developed a number of the fundamental measurement techniques and knowledge around cell to pack design of a battery. Nigel is the senior manager for the concept battery team who are responsible for everything from fundamental battery research to concept pack design.

Scientific Publications

Research from the Faraday Institution's programme is already having an impact. Scientific discoveries have led to highly cited publications, a suite of patents, and commercial spin outs – growing evidence that the research programme is hitting its mark.

In its two and a half years conducting energy storage research, the Faraday Institution has contributed over 150 publications to the scientific literature. Half of the published research coming out of the Faraday Institution has international collaboration and an additional 38% has intra-UK collaboration, spanning 122 institutions and five continents. Key countries that collaborate most frequently with the Faraday Institution include the USA, France, Germany, China and Sweden, in that order.

While it is early for the Faraday Institution to be able to definitively measure the impact of its outputs, these publications appear to be of a high quality. 91% of Faraday Institution publications appear in Q1 journals (as measured by CiteScore percentile), and 66% in the top 10% journals. 44% of the papers are in the top 10% most cited papers worldwide (between 2017 and 2020). In 2019 (the last full year of record), the Faraday Institution paper-set had a Field Weighted Citation Index (FWCI) of 2.50, which compares well with UK-wide research at 1.52. Data from the SciVal® database, Elsevier B.V., www.scival.com (downloaded on 10 December 2020)

As of November 2020, papers published by Faraday Institution researchers are as follows.

Lithium Ion

Battery Degradation

In-Situ Electrochemical SHINERS Investigation of SEI Composition on Carbon-Coated Zn0.9Fe0.1O Anode for Lithium-Ion Batteries
Cabo-Fernandez, L., Batteries & Supercaps (Sep 2018) DOI:10.1002/batt.201800063
https://onlinelibrary.wiley.com/doi/abs/10.1002/batt.201800063

Evolution of Electrochemical Cell Designs for In-Situ and Operando 3D Characterization
Shearing, P., Materials (Nov 2018) DOI:10.3390/ma11112157
https://www.ncbi.nlm.nih.gov/pubmed/30388856

4D Visualisation of In-situ Nano-compression of Li-ion Cathode Materials to Mimic Early Stage Calendering
Shearing, P., Daemi, S.R., Materials Horizons (Dec 2018) DOI:10.1039/C8MH01533C
https://pubs.rsc.org/en/content/articlelanding/2019/mh/c8mh01533c#!divAbstract

Evolution of Structure and Lithium Dynamics in LiNi0.8Mn0.1Co0.1O2(NMC811) Cathodes during Electrochemical Cycling
Märker, K., Chemistry of Materials (Mar 2019) DOI:10.1021/acs.chemmater.9b00140
https://pubs.acs.org/doi/10.1021/acs.chemmater.9b00140

Modelling and experiments to identify high-risk failure scenarios for testing the safety of lithium-ion cells
Finegan, D. P., Journal of Power Sources (Mar 2019) DOI:10.1016/j.jpowsour.2019.01.077
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Temperature Considerations for Li-ion Batteries Comparing Inductive Charging with Mains Device Charging Modes for Portable Electronic Devices
Loveridge, M., ACS Energy Letters (Apr 2019) DOI:10.1021/acsenergylett.9b00663
https://www.researchgate.net/publication/332475349_Temperature_Considerations_for_Charging_Li-Ion_Batteries_Inductive_versus_Mains_Charging_Modes_for_Portable_Electronic_Devices

Spatially Resolving Lithiation in Silicon–Graphite Composite Electrodes via in Situ High-Energy X-ray Diffraction Computed Tomography
Finegan, D. P., Nano Letters (May 2019) DOI:10.1021/acs.nanolett.9b00955
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Porous Metal-Organic Frameworks for Enhanced Performance Silicon Anodes in Lithium-ion Batteries
Loveridge, M., Chemistry of Materials (May 2019) DOI:10.1021/acs.chemmater.9b00933
https://pubs.acs.org/doi/10.1021/acs.chemmater.9b00933

Concentrated Electrolytes for Enhanced Stability of Al-Alloy Negative Electrodes in Li-Ion Batteries
Chan, A. K., J. Electrochem. Soc. (Jun 2019) DOI:10.1149/2.0581910jes
https://iopscience.iop.org/article/10.1149/2.0581910jes/meta

Electron Paramagnetic Resonance as a Structural Tool to Study Graphene Oxide: Potential Dependence of the EPR Response
Wang, B., J. of Physical Chemistry C (Aug 2019) DOI:10.1021/acs.jpcc.9b04292
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Virtual unrolling of spirally-wound lithium-ion cells for correlative degradation studies and predictive fault detection
Kok, M. D. R., Sustainable Energy and Fuels (Aug 2019) DOI:10.1039/C9SE00500E
https://pubs.rsc.org/en/content/articlehtml/2019/se/c9se00500e

Kerr gated Raman spectroscopy of LiPF6 salt and LiPF6-based organic carbonate electrolyte for Li-ion batteries
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https://pubs.rsc.org/en/content/articlelanding/2019/cp/c9cp02430a#!divAbstract

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https://www.sciencedirect.com/science/article/pii/S0013468619321565

In situ Electron paramagnetic resonance spectroelectrochemical study of graphene-based supercapacitors: Comparison between chemically reduced graphene oxide and nitrogen-doped reduced graphene oxide
Wang, B., Carbon (Dec 2019) DOI:10.1016/j.carbon.2019.12.045
https://www.sciencedirect.com/science/article/abs/pii/S0008622319312801

Spatial quantification of dynamic inter and intra particle crystallographic heterogeneities within lithium-ion electrodes
Finegan, D. P., Nature Comms (Jan 2020) DOI:10.1038/s41467-020-14467-x
https://www.nature.com/articles/s41467-020-14467-x#Ack1

Theoretical transmissions for X-ray computed tomography studies of lithium-ion battery cathodes
Heenan, T. M. M., Materials & Design (Feb 2020) DOI:10.1016/j.matdes.2020.108585
https://www.sciencedirect.com/science/article/pii/S0264127520301192#s0120

Thermal Runaway of a Li-Ion Battery Studied by Combined ARC and Multi-Length Scale X-ray CT
Patel, D., J.Electrochem. Soc (Apr 2020) DOI:10.1149/1945-7111/ab7fb6
https://iopscience.iop.org/article/10.1149/1945-7111/ab7fb6/meta

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Zhang, Y., Nature Comms (Apr 2020) DOI:10.1038/s41467-020-15235-7
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Rapid Preparation of Geometrically Optimal Battery Electrode Samples for Nano Scale X-ray Characterisation
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Lu, X., Nature Comms (Apr 2020) DOI:10.1038/s41467-020-15811-x
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Usseglio-Viretta, F., Journal of The Electrochemical Society (Jun 2020) DOI:10.1149/1945-7111/ab913b
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Multi-Scale Modelling

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Hoster, H.E., Nature Catalysis (Apr 2018) DOI:10.1038/s41929-018-0060-2
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Oxidation states and ionicity, Walsh, A., Nature Materials
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