

Institution: University of Birmingham

# Unit of Assessment: UoA 12, Engineering

# 1. Unit context and structure, research and impact strategy

#### 1.1. Overview:

Engineering at Birmingham comprises the Schools of Chemical Engineering (CE), Engineering (E), and Metallurgy and Materials (MM), forming three of the seven schools in the College of Engineering and Physical Sciences. They are led, respectively, by Prof. Mark Simmons (43.70 FTE), Prof. Clive Roberts (70.35 FTE) and Prof. Alison Davenport (29.39 FTE). The leadership work closely together, devising an interdisciplinary research strategy which provides strong cohesion between the different elements of Engineering at Birmingham.

Since REF2014, major restructuring has seen the creation of the School of Engineering, formed in 2016 via the merger of Civil, Mechanical, and Electronic, Electrical and Systems Engineering and over £65M of University investment in a new School building.

We have built on our REF2014 achievements by directing research into *nine thematic areas* which tackle research challenges identified nationally (UKRI, industrial strategy) and address UN sustainable development goals. Successes of our translational approach include healthier foods with up to 50% salt reduction and 40% fat reduction (Unilever, Pepsico, Nestle), improving the efficacy of washing detergents (Procter and Gamble), over 500,000 vehicles with next generation radar sensing (JLR) and the reduction of train delay minutes across the UK Network by 40% (Network Rail, Siemens Mobility). Significant successes over the REF period include:

- two **UK-RPIF funded innovation centres** (*Centre of Excellence in Digital Systems*; *High Temperature Research Centre*)
- the **Queen's Anniversary Prize** for the *Birmingham Centre for Railway Research and Education*
- more than **doubling our research income**, to >£186M (38% UKRI), plus £36.6M in-kind
- research awards worth >£248M
- increasing REF-eligible staff by 13% FTE
- >£260M investment in infrastructure and facilities
- a **diverse industry portfolio**, including over 80 international, 10 FTSE 100s and SMEs, 18% of our research income
- filing **86 patent families** (230 patents) and 25 licensing agreements (compared to 54 patent families and 13 licences in the previous REF period)
- £7.66M consultancy income
- **increasing the diversity of our staff** and leadership (e.g. 16% of professors are female, up from 2% in 2014)
- growing doctoral awards by 108% (to 916.62 FTE)

# 1.2. Research strategy:

As a UoA, our vision is to undertake transformative research with local, national, and global impact, reflecting institutional directives (REF5a-2.1.4) to foster a culture underpinned by industrial partnerships (REF5a-2.1.6) and to create "research that matters" (REF5a-2.1.1).

Over the REF period our vision has been built on five strategic aims:

# 1) Establish and sustain excellence in research that meets real-world challenges

Six research themes represent established strengths, while strategic investment in research aligned with Healthcare Technologies and Living with Environmental Change (EPSRC) led to the creation of three new themes.



Established themes:Advanced Manufacturing and Materials ProcessingGreen, Attallah, Pham (FREng), Dimov21 (E, MM)92.8524£41,436,1251Communications and Sensing Cherniakov, Cannon (FREng)16 (E) Cherniakov, Cannon (FREng)82.518£18,189,6743Formulation Engineering Challenging EnvironmentsFryer (FREng), Norton, Zhang (FREng), Stolkin20 (CE)129.3520£23,275,5302Materials for Challenging (FREng), Norton, Zhang (FREng), Stolkin12 (MM)96.229£26,805,1061Railway EngineeringBowen (FREng), Stolkin11 (E)40.2514£14,919,6951Energy Wilckens, XuDing (FREng), T solakis, Steinberger- Wilckens, Xu18 (CE, E, MM) (FREng), Shepherd6029£13,086,149InfrastructureMetje, Jefferson, Shepherd17 (E)100.0514£16,711,618	Theme	Leads	REF- eligible Staff (Schools)	Doctoral awards	Research Fellows	Research income	Impact Case Studies
Advanced Manufacturing and Materials Processing         Green, Attallah, Pham (FREng), Dimov         21 (E, MM)         92.85         24         £41,436,125         1           Communications and Sensing         Gardner, Lancaster, Cherniakov, Cannon (FREng)         16 (E)         82.5         18         £18,189,674         3           Formulation Engineering         Fryer (FREng)         20 (CE)         129.35         20         £23,275,530         2           Materials for Challenging Environments         Bowen (FREng), Norton, Zhang (FREng)         12 (MM)         96.2         29         £26,805,106         1           Railway Environments         Bowen, CrREng), Stolkin         11 (E)         40.25         14         £14,919,695         1           Energy         Ding (FREng), Stolkin, Steinberger- Wilckens, Xu         28 (CE, E, MM)         136.37         37         £23,018,324         1           New themes:         Healthcare Technologies         Grover, EI Haj (FREng), Shepherd         18 (CE, E, MM)         60         29         £13,086,149           Infrastructure         Metje, Jefferson,         17 (E)         100.05         14         £16,711,618	Established themes:						
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Materials for Walton, 7 (MM) 21.3 21 £8,870,673 Sustainability Kendrick (FRSC)	Materials for Sustainability	Walton, Kendrick (FRSC)	7 (MM)	21.3	21	£8,870,673	

Each theme is designed to constitute an area of excellence in the University's Strategic Framework for 2021-2026 (REF5a-2.4) through key initiatives, such as the recently funded UK Rail Research and Innovation Network *Centre of Excellence in Digital Systems* (£16.4M).



# 2) Enhance cross-theme capabilities

The University's Strategic Framework (REF5a-2.4) galvanises our ambitions to drive forward and strengthen our cross-cutting research capabilities in physical metallurgy, particle and fluid mechanics, electrochemistry, colloid science, complex fluids and rheology, materials science and robotics. As well as partnering the College of Life and Environmental Sciences on biopharmaceuticals and the College of Medical and Dental Sciences on healthcare technologies, we collaborate with the UK National Quantum Technology Hub in Sensing and Timing to drive innovation in quantum radar, in response to the Industrial Strategy Grand Challenge in AI and data (e.g. Metje's £8M for quantum sensing).

We link to multi-scale and reduced order modelling capability with the Turing Institute and develop next-generation measurement capabilities in fluid and particle mechanics with the School of Physics and Astronomy through EPSRC Programme Grants (~£7M). EPSRC and Innovate UK funding (>£5M) underpins strategic growth in autonomous vehicles. Collaborative work with the *Manufacturing Technology Centre* (MTC) at Ansty comprises cross-cutting research in recycling, automated disassembly and automated rail systems with international partners that feed directly into industry, e.g. via Siemens's Rail Accelerator and Innovations Solutions Hub for Enterprise.

Interactions through our industry steering groups have identified the need to grow new capability in **Data Science and AI** towards intelligent manufacturing and automation (including Industry 4.0). This will be underpinned by flagship activity at the fully digitised **High Temperature Research Centre** (HTRC), which we will develop as a Digital Lighthouse for Rolls-Royce manufacturing. We will consolidate strengths in haptics, micromanipulation, robot design and rehabilitation, through collaborations with the Turing Institute on intuitive human-robot interaction (Stolkin), energy storage (Ding) and with Computer Science via Cai's Turing Fellowship and the new **Birmingham Institute for Interdisciplinary Data Science and Artificial Intelligence**. This includes the £4M Baskerville computing facility (with Rosalind Franklin Institute, Alan Turing Institute and Diamond Light Source).

# 3) Deliver impacts through the translational pipeline

We shape the research landscape through embedding academics in industry, learned societies, funding bodies, government advisory groups and key policy-making bodies. Partnerships with over 200 companies, an Industrial Professorship (Withey), a RAEng Industrial Chair (Y Ding), a Royal Society Industry Fellow (Stolkin), five RAEng Industrial Fellows, a Royal Society Entrepreneur in Residence, Tech Entrepreneurship Seminar Series and regular industrial secondments allow us to take blue-skies research to high Technology and Manufacturing Capability Readiness levels (TRLs and MCRLs). The UoA exemplifies the University's translational research strategy (REF5a-2.1.6). 95% of REF-eligible staff work directly with industry, five ERDF-funded Business Support Programmes and four Policy Commissions drive innovation (section 4.1), while industrial-scale facilities at HTRC and MTC attract major collaborations. We have national and global strategic partnerships with Rolls-Royce, Jaguar Land Rover (JLR), Procter & Gamble (P&G), Siemens, Network Rail and Singapore Metro.

#### 4) Invest in world-class infrastructure and facilities

Strategic investment of >£260M has enhanced the vitality and quality of our research. The new 10,000 m<sup>2</sup> School of Engineering building is opening early in 2021 (REF5a-4.2.1), at a cost of £65M. A £37M refurbishment of the Metallurgy and Materials building in the previous REF period created space for the *Birmingham Centre for Energy Storage*, the *National Centre for Nuclear Robotics* (NCNR) and the *Quantum Technology Hub*, which were completed in 2018.

In addition to the world-leading *Birmingham Energy Institute* (BEI), *Centre for Formulation Engineering* and *Birmingham Centre for Railway Research and Education* (BCRRE), we created



four new strategically significant research centres: **HTRC** (UK-RPIF funded); the **Birmingham Centre for Strategic Elements and Critical Materials**; **NCNR**; and the **National Buried Infrastructure Facility** (investment totalling £90M). We won £22.6M investment for major new translational research facilities to drive developments at the 10-acre Tyseley Energy Park site (TEP, section 3.2).

# 5) Attract, support and grow world-class researchers

We have appointed staff from world-leading universities (including Harvard, Cambridge, Imperial College, McGill, ETH Zurich and Sydney), brought international-quality researchers back from industry (e.g. Profs Withey from Rolls-Royce, Green from Doncasters and Pelan from Unilever) and recruited leaders in translational research (e.g. Prof. El Haj) to create impact in a community that values equality, flexibility and openness. We empower new appointees to become leaders, e.g. Cox and Knowles's prestigious UKRI Future Leaders Fellowships cross themes (*Healthcare* and *Advanced Manufacturing and Materials Processing*) and embrace the translational pipeline. We support international collaboration (e.g. via £39.8M research income from EU and international sources) and promote successes widely, e.g. celebrating female role models through the global Birmingham Heroes campaign which showcases high-impact research (Goldberg-Oppenheimer, Cox and Metje).

By increasing our REF-eligible staff by 13% since 2014 we have enhanced research intensity, meeting our institutional objectives (REF5a-2.1.1). 206 research, industrial and knowledge exchange fellows are also fully integrated members of our academic community. Through our doctoral researchers we foster industry collaborations and train the engineers of the future. Doctoral awards more than doubled this REF cycle, compared to the previous, and three new EPSRC CDT/DTPs were established in Formulation Engineering, Hydrogen Fuel Cells and Structural Metallic Systems.

# 1.3. Unit structure and the achievement of our strategic aims:

Configuring research around nine themes enables us to focus on challenges and opportunities that emerged from our previous REF submissions (UoAs 12a, 12b, 13a, 13b and 14). **Due to the difference in submission approach, our achievements against the strategic objectives outlined in REF2014 are included in the relevant theme discussions**. Each theme has developed under the direction of senior academics, with Heads of School, College and Research, enabling us to set ambitious goals for 2026, described below, that ensure sustainability.

# Advanced Manufacturing and Materials Processing

Over £41M in research income has revolutionised our world-leading research capabilities to simulate and evaluate advanced manufacturing techniques. Work in *Advanced Materials Processing* is exemplified by our unique investment casting facility at HTRC (Green) which unites and fulfils the strategic aims of UoA12a and UoA13b (REF2014). HTRC delivered substantial improvements in Al-MMC alloys (Griffiths) and in Rolls-Royce aero-engine component production by preventing defects and reducing scrap in casting processes; the ongoing impact of this work is described in the Impact Case Study, 'Single Crystal Casting'.

The *Advanced Manufacturing Technology Centre* unites the strategic aims of UoA12a and UoA13b to **shape capability in High Value Manufacturing** (Dimov, £6.4M research income) through growth in advanced machining, industrial photonics and intelligent automation. In *Multifunctional Materials and Devices*, specialisms include additive manufacturing for new superalloys (BAE Systems, Honda) and space applications (European Space Agency), advanced functional materials, simulation, modelling, and Integrated Computational Materials Engineering (£9.8M research income). Cross-disciplinary research in biomaterials is **shaping capability in healthcare**, as outlined in UoA12a's REF2014 submission (Attallah and Cox).



**Over the next five years**, High Value Manufacturing will focus on **hybrid manufacturing** for high-value and sustainable production, **intelligent robotic technology** for remanufacturing; **3D printing** of functional materials, and manufacturing **smart structures and surfaces**. We will progress world-leading manufacturing solutions at HTRC (single-crystal turbine blades and blades for hybrid electric flight), a partnership of such strategic value to Rolls-Royce that budgets were protected throughout the COVID-19 crisis, and contributing to cross-cutting initiatives based on the post-COVID UK strategy, e.g. the proposed West Midlands £450M initiative 'Speed to Scale'.

# Communications and Sensing

Aligned with EPSRC growth areas in RF and microwave devices, our priorities emerged from the **strategic development of Microwave Devices and Systems research** outlined in UoA13a's REF2014 return. Income of over £18M supports research into *Microwave Integrated Systems*, *Emerging Devices Technology*, *Space Environment and Radio Engineering*, *Metamaterials Engineering* and *Antennas and Applied Electromagnetics*. Our portfolio focuses on new concepts and technologies (IoT, 5G communications and beyond) and we are the largest UK university radar research team, forming the national Electro Magnetic Systems Interest Group in 2017 to promote academic-industry collaborations. Research in automotive sensors and space weather is supported by significant partnerships (JLR, Met Office, DSTL) and new investment in staff (Cannon, Elvidge, Themens) involving over 50 patents and major UKRI funding (SWIMMR, £3.7M). We delivered on our 2014 growth strategy for THz electronics by establishing the nationally unique THz vector network analyser facility (£1.57M, EPSRC).

The strengths of this theme are highlighted in three **Impact Case Studies**. Cannon's RAEng report on the impacts of space weather led to policy changes to shape international preparedness for potentially catastrophic space weather events ('Space Weather Resilience'). Novel radar sensing technology in use by JLR has enhanced road and driver safety ('Advanced Driver Assistance Systems') and new multipurpose antennas for mobile devices have been commercialised via a spin-out company now valued at \$20M per year ('Antenna Technology'). £3.15M of EPSRC funding supports three new projects on **terahertz technology, video sensing** and **micromachined circuits** (Gashinova, Gardner, Lancaster) which are advancing the state of the art for antennas, propagation and microwave engineering for automotive sensing beyond the JLR impact case study.

**Over the next five years**, we will build on existing strengths to impact sustainable development goals in Industry, Innovation and Infrastructure, and Sustainable Cities and Communities. Key areas are **microwave, mm-wave and THz circuits and systems** and **radar, remote sensing and communications** for autonomous, integrated and sustainable transport, **space weather** (Met Office, Satellite Applications Catapult, DSTL), **active and passive antenna design**, and **micromanufacturing** for THz electronic systems (RAL, Fraunhofer, UK Compound Semiconductor Applications Catapult), for new applications in remote sensing, communications and healthcare.

# Formulation Engineering

Focusing on the manufacture of micro- to nano-scale structured products, this internationally leading Centre builds on the award of a Queen's Anniversary Prize in 2011. As pioneers of formulation engineering, we fulfilled our UoA12b strategic aim to **deliver impacts through strong industrial partnerships** with P&G and Rolls-Royce, and developed new relationships with Mondelez, PepsiCo and Diageo. **Excellence in doctoral research** is evidenced through the refreshed EPSRC CDT in Formulation Engineering (£5.2M), which embeds students in companies to deliver fully translational research.

In **Soft Materials, Interfaces and Complex Fluids (including food, health and nutrition)** we develop new energy-efficient processes employing emulsification and encapsulation technologies to create healthier foods and reduce waste (Norton, Zhang). Norton's work on salt,



fat and sugar reduction with globally leading companies forms the basis of our **Impact Case Study** in 'Microstructural Food Design'. £13M of awards fund next-generation positron imaging and multiphase processing for healthcare and FMCG (Barigou, Simmons). In **Resource Efficiency and the Environment**, we shape capability in high-added-value manufacturing e.g. in turbine blade casting with HTRC (Blackburn) and in detergent formulations with P&G (Fryer underpinning sales of ~\$12B p.a. ('Transforming Cleaning' **Impact Case Study**). In **Biomaterials and Nanotechnology**, UKRI and industry funding support interdisciplinary research in biopharmaceuticals and metal recovery from Li-ion batteries (Thomas, Overton).

**Over the next five years**, we will exploit cross-cutting capabilities in *Data Science and AI* to develop doctoral training and research opportunities in the digital manufacturing of formulated products via a new theme, *Manufacturing Industry 4.0*, learning from HTRC. We will work with SMEs to further our expertise in *imaging*, and apply this to the processing of novel complex products (e.g. next-generation batteries, with *Materials for Sustainability*). We will increase product **sustainability** through clean label approaches to design of foods and minimise waste through new manufacturing processes.

# Materials for Challenging Environments

Over £9M of capital awards have extended our experimental capabilities, supporting strengths in casting, electron microscopy, ceramics and nuclear robotics. Our flagship *Rolls-Royce Strategic Partnership*, University Technology Centre (UTC), delivered considerable impact in line with our UoA13b strategic aim. This includes ensuring safe operation of powder-disc alloys in jet engines for increased fuel efficiency and reduced emissions (Bowen), the subject of our 'Aero-engine Disc Alloy in Safety-Critical Components' Impact Case Study. The *Centre for Electron Microscopy* (Chiu) is critically important to the delivery of Rolls-Royce programmes (£20M funding). A new class of ultra-high-temperature *Ceramic Matrix Composites* for critical components in supersonic flights (Binner) won an MBDA Innovation award (2016). The *Extreme Robotics Laboratory* (Stolkin), which has its origins in nuclear decommissioning, now leads the *National Centre for Nuclear Research*, a major ISCF initiative. Significant achievements in nuclear research include the safe operation of nuclear reactors (Evans) and storage of nuclear waste (Davenport).

**Over the next five years**, we will **develop our Rolls-Royce Strategic Partnership**, focusing on the new nickel disc alloy, RR1073, for next-generation gas turbine aero engines. UTC is uniquely placed to understand the processing-microstructure-property relationships required, and our extensive electron-optics facilities allow projects to proceed at an internationally leading pace. We will also focus on taking **ultra-high-temperature ceramic matrix composite technology** to TRL4. With the NCNR we will **grow robotics and AI**, scale up research at TEP, and diversify our portfolio in collaboration with the Culham Centre for Fusion Energy and Rolls-Royce. These initiatives will allow Robotics to emerge as a tenth independent research theme.

# Railway Engineering

The *Birmingham Centre for Railway Research and Education*, the largest of its kind in Europe, received a **Queen's Anniversary Prize** in 2017. Our strategy is to align with the themes of the UK Technical Leadership Group, of which Roberts is a member, investing strategically in key areas. This has enabled us to undertake research with **significant impact upon, and directed towards solving, key societal issues**, as set out in UoA14's REF2014 submission. In *Digital Systems – smart systems* we lead the £92M RPIF-funded UK Rail Research and Innovation Network (UKRRIN), which funds our *Centre of Excellence in Digital Systems* and facilitates translation via UK and international collaborations, including Network Rail.

We have expanded strategic partnerships in *Digital systems – simulation and modelling* with Network Rail, HS2, Siemens Mobility, Indian Railways, Brazilian Ministry of Infrastructure, Guangzhou Metro and Porterbrook. Our partnerships with industry have been nationally recognised: work with Siemens was awarded the 2020 PraxisAuril 'Knowledge Exchange



Partnership of the Year' and work with Porterbrook and its supply chain awarded The Guardian University Award for 'Business Collaboration of the Year' (2020). In 2017 our partnership with SMRT Corporation, Singapore's largest railway operator, fostered new research in network reliability.

*International Benchmarking, Infrastructure and Climate Effects* focuses on decarbonisation, renewable energy and the creation of the world's first operational hydrogen fuel cell train. This ground-breaking work led to international policy change (decarbonisation in the USA and Canada), energy savings in China, and reduced train delays in the UK, and is outlined in the **Impact Case Study** 'Transforming Policy and Practice'.

**Over the next five years**, we will continue to build on our position as world-leaders in railway research, **transforming the R&D landscape**, fostering new partnerships to increase UK rail innovation, including with HS2, and **supporting SMEs** to develop new technologies. Research into **digitalisation** will focus on digital twin development, data integration and cybersecurity, smart monitoring and autonomous systems.

# Energy

Meeting our UoA12b objectives, we have created **significant impact through strategic partnerships** supporting our internationally leading research in energy storage, bioenergy, vehicle technology, fuel cells and hydrogen. *Birmingham Centre for Energy Storage* (BCES) pioneered Liquid Air Energy Storage (LAES), commercialised by Highview Power with BEIS and Innovate UK funding as CRYOBattery<sup>™</sup> for use in two demonstrators (Y Ding). Construction of an additional 50MW cryogenic energy storage plant has begun following a £35M investment from Sumitomo. A world-first technology that converts curtailed wind power to heat entered commercial use in 2016 (Jinhe). Our *Vehicle and Engine Technology Centre*'s ambition to *develop alternative energy carriers for transportation* improved vehicle fuel economy and emissions through innovative catalytic technologies and hydrogen production (Tsolakis), and resulted in major advances in low and carbon-free fuels (Xu), outlined in the Impact Case Study 'Fuel, Propulsion and After-treatment Technologies'.

The *Birmingham Centre for Fuel Cell and Hydrogen Research* has over £2M of major EU funding and significant collaborations (e.g. with the Imperial College-led EPSRC Hydrogen and Fuel Cell Supergen Hub), to support sustainable solutions for cities, energy systems and transportation (Steinberger-Wilckens). In *Bioenergy, Recycling Catalysis and Reaction Engineering* our Birmingham-Fraunhofer UMSICHT joint platform supports Thermo-Catalytic Reforming (TCR®) for renewable energy technologies (A Hornung), winning £1.5M for two H2020 projects. Research in *Electrical Power and Control Systems* (XP Zhang) focuses on power grids, renewable energy systems integration and control in partnership with leading power companies (National Grid, E.ON, Network Rail, State Grid Corporation of China). XP Zhang provides national leadership in this area on the Expert Advisory Group of UK Government's Offshore Transmission Network Review.

**Over the next five years**, we aim to make BCES a globally leading centre for **thermal and chemical energy storage** research, policy influence and leadership of the EPSRC SuperGen Storage Plus Network. Using cross-cutting activities in **Data Science and AI** to tackle the climate emergency we will also focus on AI engine calibration, environmental catalysts and systems, carbon-free energy carriers and transportation, and creating an international presence at TEP (REF5a-4.2.2).

# Healthcare Technologies

We launched the *Healthcare Technologies Institute* (HTI) as a leading interdisciplinary national centre for translational research, meeting our UoA12a/b strategic aims. Research income of £13M has enabled us to **shape capability in healthcare** and **develop our real-world** 



**impact** in collaboration with clinicians at the Queen Elizabeth Hospital Birmingham (QEHB) in alignment with EPSRC Healthy Nation and Industrial Strategy Ageing Society outcomes.

Our strengths are in *early detection* of cancers, including bladder (Shepherd) and prostate (for which Mendes won the 2019 Women in Tech Academic Award), and brain injuries (Goldberg-Oppenheimer). We are *tackling antibiotic resistance* using additive manufacturing via an EPSRC Healthcare Impact Partnership, creating *bespoke prosthetics* (Cox) and pioneering research on nanoparticle-based *tissue regeneration* technologies (El Haj), scar reduction and prevention and bone formation and repair (Grover). Research into microbial keratitis led to an eye drop that is currently undergoing patient trials at QEHB (£4.1M from MRC and NIHR), with a spinout company planned to take the product to TRL 9.

Our vision **over the next five years** is to deliver across the full translational pathway while stimulating significant economic growth through the West Midlands Local Industrial Strategy. We will increase capacity via a £6M proposal by three Local Enterprise Partnerships and **grow into both medicine and pharmacology**, lead the development of the **Precision Healthcare Technology Accelerator** (£22M, Birmingham Life Science Park) to create 5km<sup>2</sup> of space for medical technologies development, and play a key role in the new *Birmingham Bladder Cancer Research Centre* (£11M UoB investment).

# Infrastructure Engineering

As a key partner in UKCRIC (the UK Collaboratorium for Research in Infrastructure & Cities), Rogers, Jefferson, Chapman, Metje and Soper won a £21.6M EPSRC bid to construct the *National Buried Infrastructure Facility* (NBIF), supplemented by an additional £7M investment from the University. Mejte leads the £8M Geophysics work package of the interdisciplinary Quantum Technology Hub, which is developing novel approaches to identify buried infrastructure, showcased in UoA9's 'Quantum Technology' **Impact Case Study**. Major EPSRCfunded collaborations include a £4M grant led by Leeds to understand the impact of infrastructure on natural systems and a £7.3M Sheffield-led project to develop pervasive sensing robots for water pipelines. ECR success informs new directions in AI (Faramazzi's EPSRC First Grant).

**Structural Engineering** has made significant advances in wind turbine engineering and alternative energy with £1M of EU investment (Baniotopoulos). *Fluid Mechanics* received over £4.5M for research in resilient transport, crop lodging and sustainable food production, while new Wind Engineering facilities support EPSRC-funded work in pedestrian and cyclist safety (Sterling). This is directly linked to our research in sustainable urban *Transport*, which also includes Soper's £1M involvement in TRAINrig. Rogers's collaboration in the £1M EPSRC CORONA project unites real-live observations (Birmingham UKCRIC Urban Observatory) with full-scale experiments in controlled conditions (NBIF). Burrow's work on rural roads informs international development (section 4.1).

**Over the next five years** we will develop collaborative projects with industry via UKRI and MTC initiatives through the Industry Strategy Challenge Fund Wave 3 on **Quantum Technology and Construction** and through our ERDF-funded project *Alternative Raw Materials with Low Impact*, which intersects with *Materials for Sustainability*. We will influence national and international codes and standards (Quinn), enhance our CPD portfolio in rural roads and exploit opportunities aligned with government infrastructure strategy (UKCRIC and NBIF). Apriority is **interdisciplinary sensor technology and AI** for the development of **SMART infrastructure**. This is our overall direction of travel and builds on **UKCRIC** initiatives such as the £1M EPSRC PLEXUS project and NBIF work in sensors for performance monitoring and mapping.

# Materials for Sustainability

We identified critical materials research as a **priority growth area** in REF2014 (UoA13b) and activities have expanded greatly with the formation of the *Birmingham Centre for Strategic* 



*Elements and Critical Materials*. Successes include the UKRI-funded Critical Elements and Materials Network (CrEAM) and related Policy Commission. Strengths lie in *Rare earth magnets*, especially the development of new processes to sense, sort, extract and reprocess from end-of-life products (Walton, EU, Innovate UK) and *Batteries*, with major awards totalling £11.5M on safety and the economic and legal aspects of recycling (Kendrick, Faraday Institute, EU) in collaboration with *Energy*. In *Hydrogen Materials*, where we led the £1.7M interdisciplinary 'Science City: Hydrogen Energy Project', work on hydrogen storage (Book) led to a metal hydride compressor prototype for energy applications and the manufacture of sustainable polymers.

**Over the next five years** we will develop full-scale **rare earth magnet recycling** facilities at Tyseley Energy Park (ISCF, Driving the Electric Revolution) and **robotic disassembly** pilot lines for recycling batteries, automotive components and electronics to extract critical materials. The **circular economy** underpins University investment in a £390k Battery Testing facility and a £1.2M Dry Room, enabling research on battery safety and battery architectures for safer recycling, longer-life, lower-cost batteries with substitution of critical materials and lower-energy manufacturing with green solvents, which have won recent awards totalling over £4M. We will continue to build on our parliamentary advisory work (centred on the Policy Commission) to influence UK critical materials policy alongside partners within CrEAM specialising in legal and economic aspects of our technologies.

# 1.4. Strategy for enabling and sustaining impact:

Our impact strategy develops key aspects of our research strategy (point 3, section 1.2) and feeds directly into our staffing strategy (point 4, section 2.1). We design our research with in-built pathways to impact via horizon scanning for partners and commercialisation routes, and identify opportunities for policy engagement, supported by University initiatives (REF5a-2.1.3). This is achieved by:

# 1) Targeted support to grow pathways to impact

We identify and support research with environmental, economic, social and political significance in numerous ways. Theme leads, academics and professional colleagues engage in constant discussion with industrial collaborators to embed impact-generation into grant applications. Metje co-ordinates and supports this activity, which includes working closely with the Public Affairs team to identify opportunities to inform parliamentary debate, e.g. by advising the Department for Transport, the Science & Technology Select Committee and Parliamentary Office of Science & Technology on the circular economy (*Materials for Sustainability*). We work with the University's Business Engagement team (REF5a-4.1) to foster and benefit from strategic partnerships with industry. A measure of our success is the award of four out of 19 RAEng Industry Fellowships to Birmingham in the last round (with Recycling Technologies, P&G, TÜV Rheinland Risktec Solutions, Hitachi Rail).

Our Advisory Boards engage key stakeholders (industry, clinicians) to provide strategic support for our CDTs, Research Centres/Institutes and Industry Strategic Partnerships. We draw on the expertise of UoB Enterprise (the University's technology transfer company, REF5a-4.1) to develop spin-outs, eight of which were formed in the REF period (section 4.1). We promote commercialisation and exploitation of our research through patents, licensing agreements and spinouts. 230 patent applications were filed and 25 IP agreements entered into.

This process of uniting academics with industry partners and end-users **led to the identification of nine key areas that form the basis of our Impact Case Studies**, each showcasing how we directed research towards a particular challenge, outlined in the relevant themes above (section 1.3).



# 2) Strategic use of impact funds

We make full use of the institutional EPSRC Impact Acceleration Account. 20 academics received IAA funding and three benefitted from the EPSRC Accelerating Major Strategic Projects fund. This funding supported numerous impacts including an MoU with the Anglo-Indian company Intellex to develop commercial software for rail maintenance (Burrow). EPSRC Policy Impact Programme funding supported Walton's work to minimise waste in magnet materials production which resulted in the National Centre for Critical Materials collaborating with over 50 companies on recycling projects. A report to government (2019) and Policy Commission (2021, section 4.1) embed critical materials in UKRI and BEIS strategy, shaping the direction of UK research and waste strategy. To facilitate this impact, we used the Royal Society Science in Parliament scheme to shadow MPs (Liz Saville Roberts, Hywel Williams and Ben Lake). This led to ongoing policy engagement, informing parliamentary debate, and presenting policy recommendations to funding councils. Goldberg-Oppenheimer and Alberini won Innovate UK ICURe funding to exploit the commercial potential of their research. Through the same scheme Robinson (with Preece, Chemistry) formed ChromaTwist, winner of the Nature Merck Spinoff Prize 2020.

**Over the next five years**, we will increase the impact of our research by supporting secondments, helping ECRs win funding, and integrating training as part of PDRA positions. We will continue to support staff to communicate their research beyond academia, which Stamboulis currently leads through membership of the University's Public Engagement with Research Committee. We will expand activity at off-campus centres (HTRC and MTC) and use the expertise of our industrial professors and Strategic Advisory Boards to unite academics with the end-users of our research.

# 1.5. Approach to supporting interdisciplinary research:

Our approach is to enable research that transcends traditional discipline boundaries through our thematic structure and our inter/multidisciplinary centres (BEI, HTI, Critical Materials). Successes include activities with Physics and Astronomy via the Quantum Technology Hub (Infrastructure, Communications and Sensing, Rail) and the Positron Imaging Centre via a joint EPSRC Programme Grant (Formulation Engineering). We run wind engineering projects with Sport and Exercise Sciences, work on industrial control systems with Computer Science and on the *Faraday Institute* battery challenge ReLiB and NEXTRODE projects with Chemistry (Materials for Sustainability). Major collaborations with BEI unite us with Birmingham Law School and Birmingham Business School. These drive energy policy decisions in government (*Energy*) and collaboration in the local area, e.g. through the Urban Living Birmingham Consortium ('From Citizen to Co-innovator, from City Council to Facilitator' project, Infrastructure). The HTI facilitates collaboration with clinicians and colleagues in Medicine on anti-scarring and bone reformation (Healthcare). We have also been involved in collaborative AHRC, ESRC, BBSRC, and NERC-funded projects on remote sensing for archaeology, urban shrinkage, biofilm catalysts and flood prevention. Section 4.1 further details our interdisciplinary work locally and globally.

#### 1.6. Progress towards an open research environment:

We have a strong commitment to Open Research to facilitate collaboration, remove barriers to knowledge and enable impact through online access to open publications, data and advocacy. We are guided in our UoA-level activities by the University's Open Research Board (REF5a-2.2) whose commitment to DORA and Plan-S is implemented in our approach to fair and responsible metrics in research and staff assessment (e.g. probation and promotion) and in our active promotion of open publication.

5,803 articles were deposited in the University's e-repository over the REF period, 57% of which (3,334) are open access. 113 papers were published as Gold Open Access via Internal OA Funds. 36 working papers, 25 data sets and all theses (unless sensitive) are publicly available.



We advocate open access via leadership on the editorial boards of the Open Journal of Fluid Dynamics and the IEEE Open Access Journal of Power and Energy, amongst others, write for non-academic audiences (offering commentary on current affairs via 12 articles in The Conversation), run blogs (BCRRE, BEI), and contribute to podcasts (Aerospace Engineering, Ideas Lab Predictor Podcast, Our Conversation).

We support the Concordat on Open Research Data through our Research Data Management Policy; this sets out a conscious decision-making process (data management plan) for each project to release open data through the University's e-repository, whilst protecting confidential data and IP in line with legislation. For example, Morris shares 100,000s of model crystal structures of battery materials as part of the Optimade consortium enabling re-analysis of data via online workbooks, Easton developed the National Railway Research Data Platform and Cassidy supports the Data & Analytics Facility for National Infrastructure (DAFNI).

# 1.7. Support for a culture of research integrity:

Staff adhere to the University's Code of Practice for Research and Code of Practice for Ethics (REF5a-2.2), complete Research Integrity Training, GDPR and ethical self-assessment in line with the Universities UK Concordat to Support Research Integrity. Fraga sits on the STEM Ethical Review Committee and advises on best practice. We fulfil our ethical responsibility to PGRs through a CDT-run programme accessible to all that provides training in responsible research methods, responsible innovation, EDI, and science communication.

# 2. People

# 2.1. Staffing strategy and staff development:

Our staffing strategy is to attract and retain current and future generations of academic leaders. Through four strategic objectives, we have created a vibrant and inclusive research environment:

# 1) Develop a pipeline of leadership in innovative and impactful research by recruiting academic staff from leading universities and global industry

We have appointed or promoted 39 lecturers, 12 senior lecturers, 7 readers and 24 professors on the basis of their innovative and impactful research. Through the University's highly competitive flagship recruitment programmes we appointed a Professorial Fellow (Davies), an Interdisciplinary Professorial Fellow (El Haj), and six Birmingham Fellows (Goldberg-Oppenheimer, Collins, Morris, Laver, Hanham and Chen; REF5a-3.4.1). Each appointment is through open competition, advertised using gender-neutral language. We seek advice to widen applicant pools, aim for inclusive shortlists and endeavour to appoint staff to stable long-term positions: out of 150 REF-eligible Category A staff, 141 are on open-ended contracts.

We have actively appointed leaders from global industry to professorships, e.g. Green (Doncasters), Metcalfe (F-star Biotechnology), Withey (Rolls-Royce), Jack (Rail Safety and Standards Board) and Pelan (Unilever Vlaardingen), and world experts in translational research, e.g. Kendrick, El Haj, Metcalfe, Dixon and Cassidy. We have appointed staff from leading universities (section 1.2) and will continue to prioritise recruitment to our nine themes; whilst remaining open to the creative potential of individuals, we will build expertise in AI, digital and automation. This ensures vitality and sustainability in **current and future research leadership**.

Key appointments in *Advanced Manufacturing and Materials Processing* include Green as Director of HTRC and Withey as Professor of Casting, alongside three additional academic appointments. Attallah, Basoalto and Dearn were promoted to professor to lead the Advanced Materials and Processing Lab, PRISM<sup>2</sup> and tribology research, respectively. In *Communications and Sensing*, Baker was appointed Professor of Intelligent Sensor Systems, along with a Senior Birmingham Fellow, three lecturers, and two senior lecturers. Prof. Cannon was appointed to create a new group in space weather, with two new lecturers and RAEng Chair



(Angling). In addition, Gardner, Constantinou (College Director of Research) and Gashinova were promoted to professorships to lead microwave, electrodynamics and radar research.

In *Formulation Engineering* Profs Pelan and Wolf were appointed to lead microstructure engineering with Prof Seville as Director of the Collaborative Teaching Laboratory, supported by four new lecturers. New appointments in *Materials for Challenging Environments* include Binner as Professor of Ceramic Science and Engineering and two lecturers. Prof. Davenport became the first female Head of the School of Metallurgy and Materials, following Bowen's promotion to Deputy Pro-Vice Chancellor for Industrial Partners and Stolkin was promoted to professor to lead NCNR. Prominent appointments in *Materials for Sustainability* are Kendrick as Professor to lead critical materials, a Birmingham Fellow and two lecturers. Walton was promoted to professor to lead critical materials research. Two new professors, Dixon in Control Systems Engineering and Jack in International Railway Benchmarking, take leading roles in *Railway Engineering*, alongside a senior lecturer and three lecturers.

Prof. El Haj, a leading figure in regenerative medicine, and Prof. Metcalfe, an expert in wound healing, were appointed alongside a Birmingham Fellow and seven lecturers to substantially strengthen *Healthcare Technologies*. Shepherd's promotion to professor cements bio-medical engineering leadership. Prof. Leeke was appointed to lead *Energy* research in the circular economy and Prof. A Hornung to develop the UK-Fraunhofer platform at Tyseley Energy Park. Tsolakis was promoted to professor to lead low- and carbon-free energy research. Two readers, a senior lecturer and four lecturers were also appointed. In *Infrastructure* six new lecturers joined Profs Davies, Cassidy and Kopp, who now lead Water Technology, Geotechnical Infrastructure Engineering and Wind Engineering, appointed in conjunction with Jefferson (Deputy Head of College), Chapman and Metje's promotions to professor. Visiting roles are detailed in section 4.1.

# 2) Tailored training and leadership programmes for all staff reflecting their individual needs

We support staff throughout their careers to embrace a culture of intellectual stimulation, creative diversity and high achievement. Individual training needs are identified through annual **Personal Development Reviews** to ensure staff are equipped with skills in leadership, people and resource management, planning and pedagogy as well as the technical skills to carry out their research. Milestones are discussed towards promotion, which can be awarded for research, impact, teaching and academic citizenship.

Training is organised at University level by the People and Organisational Development unit, who through the Leadership Academy run programmes specific to emerging, team, research and senior academic leaders (including Aurora, which supports women to achieve positions of seniority, REF5a-3.4.4). 45 staff at all career levels have completed these programmes during the REF period. Promotion workshops aimed at female colleagues, whom we identified as holding back from applying, and courses to improve management culture were introduced in 2014.

Those in leadership roles are supported by appropriate workload balancing and we run a comprehensive series of College support activities (e.g. grant writing workshops with individualised support) to assist colleagues returning from career breaks (e.g. maternity) or who need to otherwise rebuild their research. All new lecturers receive tailored support to write their first major grant applications. A workshop series to support grant writing initiated in 2019 prioritised 30 early career researchers. Mentoring is available for all staff, who are supported to disseminate ideas and foster research excellence.

# 3) Create an environment in which Early Career Researchers can thrive

We take a similar individual approach for ECRs, reflecting the diversity of our academic cohort. A senior academic mentor works with each ECR to define individual career direction, research objectives and training needs. Birmingham Fellows receive five years' protected research time



and all ECRs benefit from two years' reduced teaching post appointment. Birmingham Fellows run a staff network and the Postdoctoral and Early Researcher Career Development and Training network supports the PDRA community. Eleven of our PDRAs were awarded lectureships at Birmingham and others have gone on to permanent positions at institutions including Imperial College. Stafford and Thomas-Seale are EPSRC Early Career Forum in Engineering members (as was Metje).

Guided by the principles of the Concordat to Support the Career Development of Researchers and best practice in support of the Vitae Researcher Development Framework, ECRs receive 12 days per year for professional development, undergo structured probation and are allocated a funded PhD student to gain supervision experience. Attendance is expected at seminars and away days to provide opportunities for collaboration and to contribute to the UoA's direction and strategy. These continue to be held virtually in the wake of COVID-19. Financial support is available for staff to attend external research events with priority for ECRs and those with EDIrelated needs. Industry interactions are promoted through support for fellowships and secondments.

CV and interview training are provided for PDRAs nearing the end of their contracts to help them find employment externally or through redeployment. Three-month extensions for fixed-term PDRAs are available to staff from under-represented backgrounds through the EPSRC-funded Inclusion Matters project 'Challenging Different Forms of Bias in Physical Sciences and Engineering Research' (REF5a-3.4.5). Three were awarded to UoA12 women in 2019. The results of this novel study of bias in peer evaluation will inform changes at UoA and University levels.

# 4) Support academics to achieve impact

A key strength is our focus on embedding staff in industry to **support and enable them to achieve impact from their research; individual recognition of excellence in research impact** is given through schemes such as the University Impact Awards.

We support **exchanges with business** for staff at all career stages, for example Thomas-Seale's secondment at MTC and Davenport's 20% secondment at Harwell Imaging Partnership. Staff were awarded RAEng Industrial Fellowships with Johnson Matthey, TÜV Rheinland Risktec Solutions, Recycling Technologies and P&G. A Royal Society Industry Fellowship enables Stolkin to spend 50% of his time working with the National Nuclear Laboratory on technical transfer. In addition, seven IAA Knowledge Transfer Secondments, nine Strategic Business Collaboration Fund grants, a Strategic Award, and two Strategic Placement Fund grants were awarded. Staff benefit from the University's Medici Enterprise Training programme (Stamboulis, Robinson).

*Hosting visitors* is a key component of our strategy (section 4.1). A series of publications on nuclear decommissioning resulted from the hosting of Jeff Kuo, a National Nuclear Laboratory Fellow at the Extreme Robotics Lab. We hosted an RAEng Industrial Fellow from Hitachi Rail and one of our two Royal Academy of Engineering Visiting Professors chairs our Civil Engineering Industrial Advisory Board.

**Consultancy**, valued at £7.66M, includes Norton's work with Bakkovor and Diageo, Herreros's with REPSOL that contributed to the future automotive fuels **Impact Case Study**, and Attallah's with Rolls-Royce and the European Space Agency. Consultancy arises both from the support given by UoB Enterprise and Business Engagement to pair staff with industry partners, and through secondments, exchanges and collaborations. Policy work is supported by the Public Affairs Team.

# 2.2. Research Students:

We have invested strategically to *grow the number of doctoral students* (>108%). A 15% increase in UKRI studentships (to 336), including 53 iCASE awards, reflects our ambition to attract students of the highest quality. Other major funding sources include UK industry (e.g. Unilever, Rolls-Royce, Cargill, Johnson Matthey, Imerys, P&G and numerous SMEs), the EC and British Council. Recruitment data is monitored by our EDI committees and 27.6% of PGRs in our 2018/19 cohort identified as female.

We lead the following EPSRC Centres for Doctoral Training and Doctoral Training Partnership:

Name	Lead	Current students	Degrees awarded	Duration
Formulation Engineering: Sustainable Structured Products (CDT)	Fryer	39	66	2014-2028
Hydrogen Fuel Cells and their Applications (CDT)	Steinberger- Wilckens	19	28	2014-2022
Doctoral Training Partnership in Structural Metallic Systems for Gas Turbine Applications	Bowen	9	16	2009-2020

 Table 2: CDT enrolments and awards (31 July 2020)

Our translational research strategy is realised by embedding students directly in sponsoring companies through the CDT in Formulation Engineering. Staff are co-directors of the following CDTs led by other institutions (section 4.2): Innovative Metal Processing; Midlands Integrative Biosciences; Carbon Capture and Storage and Cleaner Fossil Energy; Sustainable Hydrogen; and Engineered Tissues for Discovery, Industry and Medicine. We collaborate in the UoA9-led CDT in Topological Design. All industry-funded students receive training aligned with relevant CDT cohorts.

#### PGR support and progress monitoring

PGRs are integrated via a comprehensive induction to their group and School and are trained in ethics, health and safety, and research data management. They are introduced to central services, including Registry, the Careers Network and Graduate School (REF5a-3.2). All have a primary expert supervisor and a mentor, complete an annual Development Needs Analysis and attend monthly progression meetings (pro rata for part-time). CDT training modules are offered to all, regardless of funding status, to ensure key experimental and analytical skills (e.g. Design of Experiments, Numerical Analysis) and the latest industry and research trends (e.g. Industry 4.0 and Big Data) are embedded.

PGR wellbeing is supported in each School by a Wellbeing Officer. Reasonable adjustments are made for those with protected characteristics and international students can be matched with a mentor. Students are empowered through PGR reps attending Staff-Student Fora, monitored at College level. The Postgraduate and Mature Student Association supports and promotes the work of part-time PGRs.

# Skills development

PGRs are integral to the research life of the UoA. They are required to engage in seminars, away days and team building activities and encouraged to suggest activities which meet their needs. Students can become demonstrators or supervise UG/PGT projects to enhance their skills and employability.

Students gain experience organising events (e.g. the School of Engineering Annual Symposium) and have taken part in public engagement activities including the Pint of Science festival, Three Minute Thesis, Famelab, PubhD, Pecha Kucha, TEDxBirmingham, Café Scientifique, Skeptics in the Pub, and events organised by the British Science Association and #BrumSciComm. The University's Alice Roberts Award for Public Engagement was won three out of four years by PGRs from UoA12.

Our graduates go on to rewarding careers, e.g. 90% from the Formulation Engineering CDT gained jobs in the sector. Graduates are PDRAs at University of Technology Gothenburg, Stanford, Faraday Institute, Fraunhofer Institute UMSICHT and Helmholtz Institute Erlangen-Nürnberg for Renewable Energy, and lecturers at Liverpool, Lancaster, Heriot Watt, Coventry and Michigan State, for example. Positions with companies include Intelligent Energy, the Carbon Trust, Axion Recycling, Deutsche Bank, Mondelez, Nestlé, AstraZeneca, Johnson Matthey, Morgan Advanced Materials and Rolls-Royce.

#### 2.3. Equality, Diversity and Inclusion:

EDI is integral to our research environment. All staff complete compulsory diversity training and those involved in recruitment or internal REF assessment undertake unconscious bias training. We aim for a culture of inclusivity through 'open doors' policies. Key events and committees are held at family-friendly times and minutes shared for transparency. We hosted two RAEng Visiting Professors to inform EDI practice and, in 2019, appointed Prof. Averil MacDonald OBE FRSA as EDI advisor.

In **the construction of our REF submission** we ensured that Output reviews were undertaken by a broad cross-section of staff. In accordance with UoB's REF Code of Practice, and to ensure equity, equality and transparency, members took compulsory EDI training and compared the pool of available outputs with the outputs selected for submission to confirm consistency and fair representation. The Output Selection Panel (15 senior staff, including three female and two BAME) monitored internal scoring for potential biases and to ensure that particular output types or research areas were not privileged over others.

#### Career development

We are committed to eliminating barriers to success and supporting researchers at all stages of their careers. Our research and teaching staff originate from 44 countries, 42% identify as black, Asian or minority ethnic, 2% have a known disability and 23% are female. Women occupy prominent leadership roles (Davenport, first female Head of MM; Mendes, Deputy Head of CE; Metje, Head of Enterprise, Engagement and Impact) and research (El Haj in *Healthcare*, Kendrick in *Materials for Sustainability*, Metje in *Infrastructure* and Wolf in *Formulation*).

16% of professors and 33% of readers are female (up from 2% and 12.5% in REF2014). Interview panels are as diverse as possible, we require staff to shortlist qualified female candidates and an EDI statement accompanies recruitment campaigns to encourage applications from those with protected characteristics. In 2019, 27% of academic appointments were women (from the 25% shortlisted and 18% that applied). 85% of women who applied for promotions over the REF period were successful, compared to 81% of men. ECR mentoring has been extended to all staff until they achieve promotion to senior lecturer, and addressing discrepancies in the promotion of BAME staff (61% success rate) compared to white applicants (90% success rate), is key to our EDI strategy over the next five years.

# Support for staff with protected characteristics

University EDI strategy is supported and implemented by School leads who provide visible leadership and who are empowered to challenge biases in the promotion and reward of staff. Each School has an EDI committee and there is an open invitation for all staff to attend these meetings. Our commitment to gender equality can be seen in active Athena SWAN working groups: Chemical Engineering was awarded Athena SWAN Bronze in 2018 and will submit its application for Silver in 2023 (date extended due to the impact of COVID-19); Engineering received its Bronze award in 2020; and Metallurgy and Materials prepared and submitted its Bronze application in 2020.

A review by the EDI Projects Officer and senior academics of the support available for staff with protected characteristics identified the need for greater support for funding applications, monitoring of the academic pipeline and EDI training for technicians and Heads of Operations. These are priorities going forward. A family leave support group has already been established which will create guidelines for managers and establish a support network. Staff who return from parental leave or who have disabilities work in teams to manage workloads. Reverse mentoring, pioneered in Engineering and now incorporated at University level, pairs senior staff with those from underrepresented groups to provide learning opportunities and to raise awareness of challenges.

Exemplar EDI activities include Stamboulis' work on the University's Equality and Diversity Advisory Panel, as an invited speaker at the International Women in Engineering Day (London, 2017) and the E&D assessment panel for REF. We hosted several events including the first 'Equal in STEM' conference (2020) with WISE (Women in Science and Engineering), oSTEM (out in STEM), and BEaMS (Black Ethnic and Minority Scientists), 'Women in Engineering' seminar (Kendrick), International Women's day events, and the 2020 LGBT+ STEMinar. Binner is a member of the EPSRC Equality, Diversity and Inclusion Strategic Advisory Group and Mottura of The Inclusion Group for Equity in Research in STEMM (TIGERS). Since 2019, 'Academic Women in EPS' shares best practice on issues affecting female, BAME, LGBTQ+ and non-binary staff.

# Flexible working, leave and wellbeing

We advocate flexible working to enable staff to balance their work and home lives and support those with family or caring responsibilities. 20% of staff (including PDRAs) work less than 1 FTE and their career progression is actively supported via PDRs and training. New management skills developed as a result of the COVID-19 lockdown will inform future flexible working arrangements, guided by the Equality and Human Rights Commission guidance on COVID-19-related reasonable adjustments. Study leave is available in line with University policy (REF5a-3.4.3), with 15% of REF-eligible staff holding secondments in industry.

Parental, adoption and care leave arrangements are made through HR in consultation with managers. Keep-in-touch days help the transition back to work and central funding buys out teaching for the term following leave. Returning staff are assisted with research funding opportunities and supported with funded PhDs to accelerate research (Ghag, Thomas-Seale). All staff who took maternity leave returned to their existing roles.

All staff can access Workplace Wellbeing and Occupational Health. The Staff-Student working group, led by Sheridan, ensures wellbeing support for staff, students and under-represented groups, facilitates training on sexual harassment and bullying, and organises 'School life' events (socials and sporting activities). A support network facilitates international and BAME student integration and empowers BAME students to take up opportunities like demonstrating.

# 3. Income, infrastructure and facilities

# 3.1. Income strategy:

Enhancing our impact through translation can only be achieved through major investment in fundamental research supported by an increased income portfolio. This is supported by a strategy to 1) shape funding calls and target major funding opportunities, 2) diversify our funding sources, and 3) increase industry funding. This is supported by three Research Facilitators, Business Engagement and the EU and International Funding team. The success of this strategy is demonstrated by **more than doubling our research income since the last REF period**.

Source	REF 2014	REF 2021
Research Councils	£31,651,669.00	£70,331,251.00
Research Councils income-in-kind	£1,129,518.00	£36,658,809.32
UK government	£22,051,574.00	£41,216,316.00
UK-based charities	£754,993.00	£2,557,057.00
UK industry and other	£15,193,282.00	£33,099,820.00
EU government	£10,422,852.00	£29,190,381.00
EU industry and other	£2,529,299.00	£4,191,024.00
All other sources	£2,201,709.00	£5,727,043.00
Totals	£85,934,896	£222,971,701.32

Table 3. Income by funding source

Across our nine themes, research income shows a significant overall upward trajectory:





# 1) Shaping funding calls and targeting major funding opportunities

Our research leadership is instrumental in shaping **UK and EU strategic themes** (e.g. energy and health, section 4.2) and we have secured major funding from both these sources. We have substantially grown UKRI funding (38% of total income), in particular by prioritising applications for major multi-partner grants to create networks. Awards include three EPSRC Programme Grants: 'Probing Multiscale Complex Multiphase Flows with Positrons for Engineering and Biomedical Applications' (Barigou, with Physics and Astronomy, KCL and Edinburgh, £4.33M to UoB); 'PREdictive Modelling with Quantification of UncERtainty for Multiphase Systems' (Simmons, with UCL, and Cambridge, led by Imperial College London, £1.6M to UoB, £6.3M overall); and 'Structural Metallic Systems for Advanced Gas Turbine Applications' (Bowen, £2.7M, led by Cambridge).

Our strategic emphasis on translational research secured EPSRC funding through the Centre for Innovative Manufacturing in Food (with Nottingham and Loughborough, total £4.5M) and Sustainable Energy use in Food Chains (with Brunel and Manchester, total £5.7M) led to a further £1.3M for new manufacturing technologies. We are partners in a major project on pervasive sensing robots for water pipelines with Sheffield (£7.2M, £1.4M to UoB) and led work on terahertz communications (Lancaster and Gardner, £2.2M), glycoprotein recognition (Mendes, £1.15M), remote sensing (Stolkin, £1.4M), computational modelling of twin-screw extruders (Adams, £725k), after-treatment systems for clean and road vehicles (Tsolakis, £900k) and mixing phenomena in complex fluids (Fryer, £1.3M). Bowen received £1.14M from Innovate UK for the 'ATI Project 'Dual Wall Turbine Technology Development', while work to produce onvehicle hydrogen by recovering waste exhaust gas and heat funded by Innovate UK (£8M) and EPSRC (£1.8M) sparked global interest.

EPSRC awards include three projects worth  $\pounds$ 5.26M in robotics in nuclear environments (Stolkin, Pham), part of the  $\pounds$ 42M consortium of eight institutions led by UoB that form NCNR. Aligned with our focus on industrial exchange, Withey secured an EPSRC Manufacturing Fellowship ( $\pounds$ 900k). Grover leads two Healthcare Impact Partnerships, interdisciplinary research on additive manufacturing led to  $\pounds$ 1.07M (Grover, Shepherd), and we were awarded four New Investigator awards (totalling  $\pounds$ 1.4M).

Increased interdisciplinary research allows us to address global challenges, steer funding priorities and diversify our research portfolio. In particular, we won large-scale investment into clean energy, evidenced by the £7.5M Faraday Challenge ReLiB grant (Industrial Strategy Challenge Fund). Related cross-disciplinary and collaborative grants on batteries include Faraday's CATMAT (£11.2M), NEXTRODE (£12M), MSM (£10M), and five Innovate UK projects (Kendrick).

We successfully targeted EU calls to win 90 FP7/H2020 awards. These include funding to sort nuclear waste (Stolkin, £1.3M), to develop biofuels (Ouadi, £850K), novel fibre-based materials (Dong, £800K) and diagnostic technology for inflammation (Mendes, GLYCOSURF, £1.5M), and to develop innovative railway switches (Roberts and Dixon, S-CODE, £1.5M). Two projects on rare earth production and recycling (REProMag and NEOHIRE, Walton, £1.46M) created technologies central to the 20-partner SUSMAGPRO project (£12.2M), now licensed to Hypromag facilitating Innovate-UK funding to scale-up magnet recycling with 12 partners (£2M). EI Haj's EU Advanced Grant explores mechano-nano-therapeutics (DYNACEUTICS £1.95M).

A series of major ERDF awards secured development in the local region, with UoB matched funding. These are the Advanced Materials Characterisation and Simulation Hub (Chiu, £6M total); Digital Rail Demonstrator (Roberts, £5.4M total); Alternative Raw Materials with Low Impact (Jefferson, £5.2M total); Data-Enabled Medical technologies ANd Devices Hub (Grover, £6M total); and is part of the Smart Factory Hub (Dimov, £11.M total, Advanced Manufacturing Technologies to Create, Activate & Automate project). All are detailed in section 4.1. Similarly, we are partners in the €6.33M Interreg North-West Europe H2SHIPS project on the commercial potential of hydrogen bunkering and propulsion for shipping.

# 2) Diversify our funding sources

Funding from charities and international sources has increased as a result of horizon scanning activities and tailored assistance from the Research Support Office. *Healthcare* exemplifies this diversification, reflecting our work at the engineering-clinical boundaries. It includes £2.8M for technologies designed to reduce the impact of scarring (Wellcome Trust, £1.6M and ScarFree Foundation, £1.2M), MRC funding for bone regeneration and for preventing scarring on the cornea (Developmental Pathway Funding Scheme, £2.8M) and NIHR i4i funding for novel eyedrops (Grover with Logan (Institute of Inflammation and Ageing), £1.3M). Mendes won funding from Prostate Cancer UK, Grover from the ORUK and DEBRA UK. We also diversified UKRI funding (NERC, MRC, BBSRC) and won Leverhulme Trust grants (Rees, Alberini, Alexiadis).

The UKRI Strategic Priorities Fund supports two projects in space weather (NERC, Elvidge and Cannon, £3.7M total) and the flagship Industry Strategy Challenge Fund Gravity Pioneer project (>£8M) is developing the first commercial gravity gradiometer sensor surpassing the performance of traditional gravity sensors. We have also seen new growth in charity and internationally funded PhD studentships and post-doctoral fellowships (e.g. NC3Rs, Wellcome Trust, RAEng, ERC). We have also diversified our industry funding, outlined below.

# 3) Increase our industry funding

Our active pursuit of national and international partnerships, aligned with UoB strategy (REF5a-2.1.3) has resulted in a **funding increase of 118%**. A key driver of this success has been our strategy to conduct innovative research at higher TRL/MRL levels to promote translation to industry and other stakeholders. Highlights include the Rolls-Royce strategic partnership with projects led by Bowen (totalling £1.9M), the cross-disciplinary SAMULET programme in strategic manufacturing technology (~£7M), novel fast-make technology (Blackburn, £1.4M, Rolls-Royce, Innovate UK), and the establishment of the HTRC (£3M per annum). A major £2M Network Rail strategic partnership has established a framework in digital rail technologies.

Direct support includes China's Baowu Steel Group which invested £2.95M in the University Research and Technology Centre, spanning *Advanced Manufacturing and Materials Processing* and *Materials for Challenging Environments* (Bowen). Business Engagement is key to disseminating and developing new opportunities, e.g. securing £4M industry investment in *Infrastructure*'s Innovate UK projects. Our CDTs/DTP also brought in ~£1.45M direct industrial funding to support PGRs' research (2014-19).

# 3.2. Infrastructure and facilities:

A strategy of sustained and sustainable investment in equipment, infrastructure and facilities to secure the long-term sustainability of our research has amounted to over £260M since 2014. We house numerous world-class facilities, all monitored to ensure fair access on EDI grounds.

# Organisational infrastructure

Since 2014, major investment in the following has been crucial to **strengthening our research and enhancing our impact**:

**The Engineering Building** will open in 2021 as part of the University's Accelerated Capital programme. This fully accessible and sustainable state-of-the-art facility (£65M) co-locates *Communications and Sensing, Railway Engineering* and *Infrastructure Engineering*. New laboratory facilities include an anechoic chamber and the **THz Measurement Facility** (£1.57M EPSRC strategic equipment funding). The Chemical Engineering Building also received £500k University investment into improved office space.



**The High Temperature Research Centre** (HTRC, £60M) opened in 2015. It employs over 100 people specialising in key design and manufacturing aspects of a strategic technology, single crystal investment casting for aero-engines, with Rolls-Royce. HTRC was highlighted by Research England in 2018 as an exemplar of successful UKRPIF Funding. Co-located facilities (at Edgbaston and Ansty) support corporate organisations and businesses whilst protecting Rolls-Royce's 'crown jewel' IP. HTRC has a processing capability exceeding any individual Rolls-Royce plant worldwide and its priority is rapid translation of research into industrial applications to ensure commercial competitiveness through comprehensive collaborative and simultaneous engineering approaches.

**The Manufacturing Technology Centre** has grown beyond all expectations since 2014 to become the most ambitious and wide-reaching HVM Catapult Centre (worth £100M p.a.). With over 1,000 employees, 300+ industrial partners and unique processing and manufacturing capabilities, it has developed secure facilities for research on some of the most sensitive technologies in the UK national interest. Its training portfolio includes three centres for apprentices while proximity to HTRC enables secondments.

**Tyseley Energy Park** (TEP) has received £30M of investment from government and the University (Energy Research Accelerator, ERA, LEP funding). A new building provides over 600m<sup>2</sup> of state-of-the-art lab facilities and equipment for the **Birmingham Centre for Energy Storage**, an **Innovation Hub** housing the **UK Fraunhofer Centre**, opening 2021, and a technology transfer centre in partnership with Jiangsu Industrial Technology Research Institute (China). The first phase of the building opened in 2020 with research facilities for thermal energy storage (Y Ding), strategic elements and critical materials (Walton, ReLiB Faraday Project), hydrogen and fuel cells (Steinberger-Wilckens), Thermo-Catalytic Reforming (Hornung), and Lion battery production and magnet processing (Kendrick).

**The National Buried Infrastructure Facility** is a unique facility for research in buried infrastructure-ground interaction, geophysical sensing, soil stabilisation and pipeline detection, funded via a £21.6M investment through the £138M UK Collaboratorium for Research in Infrastructure & Cities (UKCRIC) award. Completed in 2020, it hosts laboratories for *Infrastructure Engineering* and facilities to simulate subsurface ground displacements, material storage and test assembly areas, pipeline and small-structure testing rigs, material characterisation facilities and a visualisation suite.

**The National Centre for Nuclear Robotics**, opened 2018, is a £42M eight University EPSRC Birmingham-led consortium with more than 30 nuclear industry partners (part funded by the Industrial Strategy Challenge Fund). It received £2.5M capital funding and hosts the Extreme Robotics Lab which is already a market leader. It has state-of-the-art facilities for navigation of remote robot vehicles and real-time 3-D characterisation. This facility is driving impact in robotic manipulation for nuclear sorting and segregation (£1.9M, H2020) to deliver a TRL6 demonstration in an industrial plant-representative environment at the National Nuclear Lab Workington test facility.

**The Centre of Excellence in Digital Systems** (£16.4M) was created as part of the Birmingham-led *UK Railway Research and Innovation Network* (a £92M consortium), funded by Research England's UK Research Partnership Investment Fund. £64M of funding from industry supports research projects over 10 years, while £28M from Research England has created facilities and multi-disciplinary project labs to develop systems (in virtual and real environments) and provide verification and validation and process-based 'Route to market' activity.

*The Healthcare Technologies Institute* was established in 2018 via a £3.5M ERDF investment (UoB match funded) to create the *Medical Devices Testing and Evaluation Centre*, a joint venture with local industry to mature early-stage technologies and test medical devices within simulated clinical environments. 1200m<sup>2</sup> of lab space was created in the *Institute of Translational Medicine*, which enables direct collaboration with NHS staff at QEHB. The £4.5M



**Centre for Conflict Wound Research** cements our position as the national leader in the translation of anti-scarring technologies.

**The Birmingham Centre for Strategic Elements and Critical Materials**, the first of its kind in the UK, was launched in 2017 via £2.5M of UoB internal 'Dynamic Investment *Funding*' to develop solutions to the critical materials challenge. The centre focuses on substitution, recycling and efficient use of materials and the examination of trade and regulation for infrastructure and equipment.

*The Centre for Electron Microscopy* won £2.8M of ERDF investment in new microscopes to underpin exemplar research in metallurgy and materials, e.g. a Talos STEM, Helios PFIB and Tecnai F30 STEM. 1.97M in EPSRC funding (plus 500k of UoB investment) for a unique Tri Beam instrument at the Centre (Chiu).

**TRAINrig** (Transient Aerodynamics Investigation Rig), a state-of-the art facility in Derby, was extended and refurbished (£1.5M) as part of the UKCRIC investment to support our research into infrastructure and aerodynamics in railway engineering and to maintain our commercial competitiveness. Access to TRAINrig led to collaborations with West Coast Mainline, HS2 (via Arup) and the Railway Safety and Standards Board.

**Shared facilities and consortia** include a partnership with Diamond Light Source associated with the development of the DIAD beamline (Davenport), which has given access for proof-ofconcept experiments on other Diamond beamlines. This is in addition to access to central facilities, e.g. ISIS Neutron and Muon Source, and Parabolic Flight. We are partners in the DISTINCTIVE nuclear consortium and collaborate with the National Formulation Centre at the Centre for Process Innovation. BEIS funded a consortium on Liquefied Air Energy storage Technologies (Industrial Energy Efficiency Accelerator programme, PRISMA project). As members of the M9 consortium, we ensure that new facilities do not duplicate existing provision at other Midlands universities.

Our *Science City* partnership (with Warwick) is one of Europe's leading research facilities in Advanced Materials. The *Birmingham Centre for Energy Storage* underpins international impact in Liquid Air Energy Storage (with CRRC) and facilities for research in Fuel Cells (including a new £390k Plasma Furnace Hydrogen Reactor), Microencapsulation, Micro-NanoPhotonics, Physical Properties, Bio-Medical and Micro Engineering, Vehicle Technology, and Micro Machining attract global partnerships.

Major cash and **benefits-in kind** include student placements with industry, including £8.5M committed to the refreshed CDT in Formulation Engineering (2020, up from £920K in the period 2014-19), £3M for the Gas Turbine DTP and >£2M for the Fuel Cells CDT across the whole consortium (£388k to UoB).

*Future strategic plans* focus on the continued expansion of our infrastructure and facilities to inform our strategy of translating fundamental research through the TRL pipeline, notably at TEP, to scale up technology from lab to market. The next development phase at TEP is the completion of 2000m<sup>2</sup> of business incubation space, including a skills academy and community hub. This will foster strong industrial partnerships and promote further interdisciplinary research across *Energy*, *Materials for Challenging Environments* and *Materials for Sustainability*.

#### **Operational infrastructure**

59 technicians enable our growing research portfolio and are supported in their development by the **Technical Academy** (REF5a-4.4) to attain professional recognition and take part in crossinstitutional networking. Technicians provide vital support and are managed by five Technical Managers who oversee health and safety. Seville provides leadership in this area as a member of the Board of Governance of the National Technician Development Centre, while our



involvement in the Midlands Innovation TALENT project (UKRI) provides a regional focus for our Technician Commitment activities.

The College **Research Support Office** assists with all aspects of grant proposals. Assistance is given to prepare complex projects and bids to corporate business (e.g. costings, interview training with consultants). Every effort is made to assemble diverse internal selection panels and equal support is given regardless of career status, FTE or protected characteristics. Additional assistance is provided to applicants for whom English is not their first language. The Grant Setup team facilitates timely starts to projects and Research Support Administrators provide postaward support.

Support for social and economic impacts is provided by Business Engagement and UoB Enterprise. Educational Enterprise assists in developing CPD courses (currently 26, including food safety, geotechnical engineering, rail systems and industrial project management, and a new level 7 degree apprenticeship with GSK, launching 2021) and MOOCs (e.g. Electrical Engineering: Sensing, powering and controlling). Impact is further supported by Research Planning, International Relations, the Byrne Outreach Officer, the Henry Royce National Outreach Officer for Materials Science, the Public Engagement with Research team and Impact Development Officer.

# 4. Collaboration and contribution to the research base, economy and society

# 4.1. Research collaborations:

Collaborations with academics, industry, governments and NGOs are vital to the innovative work that delivers our world-leading research and sustains our influence as a civic University at the heart of the local community. Through our research, we contribute to the University's **Institute of Global Innovation**'s challenge-led themes in Resilient Cities, Water Challenges, Ageing, Frailty and Resilience, Clean Air, and Environmental Pollution Solutions (REF5a-2.3.3).

#### National networks

In addition to the networks outlined in section 3.2, we **contribute to the sustainability of the discipline** through leadership of major partnerships such as the UK Rail Research and Innovation Network which created three Centres of Excellence, including ours in *Digital Systems*. The Critical Materials and Elements Network (CrEAM) unites academic and industry leaders across law, economics, chemistry and the life sciences, while UNIFY and UNIFY Plus (with Loughborough) support clinical partnerships (EPSRC Network Grants). We lead the NewJet Network+, which is working to decarbonise the UK aviation industry (EPSRC), and SWIMMR, a major STFC-NERC consortium drawing together experts in upper atmosphere modelling.

As partners in *Med-Tech CONNECT West Midlands*, we work with seven industrial sponsors and MTC to support regional economic growth. Further large-scale academic-industrial collaboration includes the EPSRC UK Collaboratorium for Research on Infrastructure and Cities (UKCRIC) and the Supergen Storage Network Plus which unites 57 energy organisations. Roles within UKRI networks (e.g. 'TERANET', 'Bioprocessing', 'Metals in Biology', 'UK Car-Parinello High-End Computing Consortium') further utilise our expertise.

#### International collaborations

We actively seek overseas collaborations to maintain our profile and address global challenges. Key partnerships via UoB's **China Institute** (Z Zhang, Co-Director, REF5a-2.1.8) enable exchanges including Zhang's Newton Advanced Fellowship (Sichuan University). A joint research centre with the Chinese Academy of Sciences sends nine doctoral students on China Scholarship Council-funded exchange programmes annually. This facilitated projects on next-generation thermal energy storage technologies (£1.7M) and two CRRC projects (Y Ding). In



2013 we established the Anhui-Birmingham International Research Institute in Rail Transportation (Roberts), facilitating six additional CRRC projects and five with Guangzhou Metro.

Partnerships initiated through UoB's **India institute** (REF5a-2.1.8) also achieved significant impact. The EU project 'India H2O' (Davies) works with local communities to solve critical water shortages and Indian Railways is using our simulation capability to make investment decisions on future signalling (Roberts). BEI's strategic partnership with the State Government of Haryana will develop a Centre of Excellence for Post-Harvest management and Clean Cold-chains (Peters, Y Ding, Al-Dadah), and with Shakti Sustainable Energy Foundation, the National Centre for Cold-chain Development and Indian counterparts we are creating integrated Community Cooling Hubs to reduce food waste.

European partnerships include Innovative Training Networks on skin tissue (STINTS), magnet recycling (EREAN), biofilm management (BIOCLEAN) and recycling critical materials from hybrid and electric vehicles (DEMETER) totalling over €15.4M, a Marie Curie Initial Training Network with S14 Implants (France) and multiple H2020 collaborations (e.g. Partial-PGMs, €5M and Knocky, €900K). A joint industrial Energy Storage lab with the Global Energy Interconnection Research Institute (Berlin) was founded in 2016.

# Responses to national and international priorities and initiatives

Our work both sets and responds to the international research agenda. **Exemplars of how interdisciplinary research responds to international challenges** include Peters' Clean Cooling Congresses (World Bank, BEIS, and Sustainable Energy for All) which developed a Global Roadmap for Clean Cooling to meet the UN's Sustainable Development Goals. Our 'Cold Energy' **Policy Commission** established cooling at the **forefront of the climate change agenda** and, as a founding partner in the Centre for Sustainable Cooling, our work is aligned with the Paris Agreement, the Kigali Cooling Efficiency Program and the Montreal Protocol to support developing counties transition to clean energy.

**International development** is a major driver. In line with UN Sustainable Development Goals in Climate Action, No Poverty, Gender Equality and Industry, Innovation and Infrastructure, Burrows' research led to new roads in Sub-Saharan Africa (UKAID, UN, World Bank) and contributed to gender mainstreaming and sustainability in transport (UKAID). Digital solutions to road maintenance and asset management are being developed with Liberia's Ministry of Public Works (UKAID), and the Gambia Roads Authority (UN). BCRRE's global partnership portfolio includes DFID-funded work to assess railway infrastructure in low-income countries and low-carbon traction solutions for Sub-Saharan Africa.

**Sustainability** is the focus of research on clean transport in Jordan (Steinberger-Wilckens), water shortages in Egypt (Al-Dadah), food security in Somaliland (Davies, Innovate-UK/DFID), clean cold chains in India (Dearn, Innovate-GCRF/DBT & IIT Bombay), and energy storage in Mexico (Radcliffe, BEIS Newton Institutional Links, with the Instituto Nacional de Electricidad y Energías Limpias). We are establishing a Global Centre for Excellence in Rural Roads with India's Ministry of Rural Development (Burrow), and supporting Bosnia and Herzegovina incorporate climate resilience into road management (World Bank). With International Solar Alliance, BEI is providing solar and solar-hybrid energy cooling for agricultural use in India, Egypt and Brazil (EPSRC Eight Great Technologies Capital Programme).

In the UK, *Railway Engineering* is setting the **decarbonisation** agenda via the Rail Industry Decarbonisation Task Force, 2019 (Hillmansen). We initiated Policy Commissions in 'Technology-Critical Materials' (Walton) and '**Energy from Waste and the Circular Economy'** (Peters and Freer, Physics), which are changing local government and industry practice and increasing employment in the region. Leeke advised the Ellen MacArthur Foundation on the New Plastics Economy.

#### International knowledge exchange

International knowledge exchange is vital to developing our research. Funding from a joint research fund established between the University of Illinois at Urbana-Champaign and UoB (BRIDGE, REF5a-2.1.8) facilitated 13 projects. Other programmes brought internationally leading academics to Birmingham, including a Newton Advanced Fellowship (Royal Society) to Prof. Sun, Sichuan University (China). We hosted five Brazil Visiting Fellows, a Rutherford Fellow, and Prof. Xu, Wuhan University of Technology (China), and Dr Buist, University of Eindhoven (Netherlands) as Institute of Advanced Study Vanguard Fellows. Antoniou was invited as Overseas Expert to the National Key Laboratory on Radar Signal Processing (China). Sciacovelli and Nayak undertook Universitas 21 exchanges (Melbourne, Connecticut) and 14 PGRs visited eight international institutions via the scheme. Strategic partnerships for PhDs have been formed with SUSTech (China), the University of Melbourne and Trinity College Dublin.

48% of our 5,051 journal publications are co-authored with international scholars, and staff held over 40 honorary roles and visiting professorships around the world. We acted as external examiners to over 300 higher degrees globally.

#### Visiting speakers

We have hosted events by world-leading researchers, such as Professor Sir Harry Bhadeshia (Cambridge) and Dr Sylvia Johnson (NASA Ames Research Center). Between 2015 and 2019, the annual Clark Lectures, which are open to the public, were given by Dr Jean Venables (Chairman of Crane Environmental), Professor Tim Broyd (UCL), Professor William Powrie (Southampton), Dr Sarah Buck OBE (Director of BSW Consulting) and Professor Phil Blythe (GCSA Department for Transport). We have also hosted speakers from Oxford, Cambridge, Imperial College London, UCL, Warwick, Max-Planck Institute, Illinois and Missouri (for example), and leading companies, including Siemens, Tata Steel, MAPAI and Rolls-Royce.

#### Engagement with research users

We currently lead five ERDF-funded Business Support Programmes which allow us to partner with SMEs, direct research towards pressing challenges and enhance the Midlands region. The **Advanced Materials Characterisation and Simulation Hub** supported over 180 businesses with materials science-related projects. **Advanced Manufacturing Technologies to Create, Activate & Automate (Smart Factory Hub)** supported 53 SMEs in additive, subtractive and hybrid manufacturing, laser and plasma processing, robotics and healthcare technologies. **Alternative Raw Materials with Low Impact** supported 92 SMEs, created employment in low-carbon and sustainable construction and developed waste processing facilities. **Digital Rail Demand-Led Demonstrator** will assist 215 SMEs and has facilitated R&D partnerships with 63 companies to develop digital rail products and processes to date. Finally, **Data-Enabled Medical technologies ANd Devices Hub** (established 2020) will facilitate medical technology development and support clinician-patient-user experience.

We contribute expertise to two ERDF projects in Physics and Astronomy. The **Centre for Innovation in Advanced Measurement in Manufacturing** supported 20 SMEs to use quantum technologies and **Accelerating Thermal Energy Technology Adoption** assisted 122 businesses in the region, generating over £25M for the local economy. It led to Innovate and BEIS funding for projects with clients (Ouadi, Tsolakis). We also promote the translation of healthcare products as partners in **MD-TEC** and members of the public invested in research into antimicrobial resistive treatments using honey (Cox's 2018 UoB Philanthropic Research Project Award).

**Public engagement** is a vital pathway to impact. As well as organising and presenting at events such as the UK Green Film Festival and the Big Bang Fair, we have been interviewed on BBC Radio 1, 4, 5 Live, WM and the World Service, BBC TV (The One Show, Midlands Today) and



Sky News. Staff won awards for engagement activities, including best presenter at 'Soapbox Science' 2014. We have contributed to the University's annual Girls in STEM day since its inception in 2013 and the Daughters of Invention project encourages girls from underrepresented backgrounds to aspire to become engineers. Green won The Engineer's Trust Stephenson Award for encouraging young people to study engineering.

# Wider contributions to the economy and society

We are heavily invested in the **sustainability of the local region**, in particular supporting Birmingham City Council's ambition to be carbon neutral by 2030. BEI is an active partner in the Birmingham Route to Zero Taskforce, a cross-party response to the climate emergency, and contributes to the **West Midlands Regional Energy Policy Commission. The** *Birmingham Centre for Cryogenic Energy Storage* is establishing a legal framework for the Energy Innovation Zones recommended by this Policy Commission, via the Carbon Trust.

Our activities with the **Thermal Energy Research Accelerator (T-ERA)** enabled collaboration with MTC to develop the International Thermal Energy Manufacturing Research Accelerator (ITEMA), which uses Industry 4.0 and other novel manufacturing approaches to scale production of novel technologies for transfer to market ('Factory in a Box'). We are also supporting industry to undertake composite recycling (EPSRC, £1.4M), on which Leeke advised UK government.

Staff are actively involved in **Knowledge Transfer Partnerships** with a value of £2.9M. These include collaborations with Aggregated Micro Power Holdings, Recycling Technologies, Westley Plastics, Webster and Horsfall (Holdings), Blue Sky Bio, Cogitare, Cobra Biologics, Ionotec, Brandenberg (UK), Strip Tinning, RS Hydro, Truflo Marine, and KUKA Robotics UK. Work with Abtus won a Railway Industry Innovation Award (2019). **13.5% of our publications since 2014 were co-authored with industrial partners.** 

The establishment of eight **spin-out companies**, Aqualo (Davies), Smart Antenna Technologies (subsequently Novocomms, Gardner), MoniRail (Roberts, Stewart), EneRail (Roberts, Hillmansen), Susteen UK, Susteen Canada (A Hornung), Sensors and Composites (Fernando) and Microforce Measurement UK (Z Zhang), is testament to the entrepreneurial culture of the UoA.

#### 4.2. Leadership, indicators of wider influence and contributions to the research base:

Our leadership shapes research and funding landscapes nationally and globally. Testament to its excellence is Davenport's OBE for her services to electrochemistry and corrosion science and Cannon's OBE for leading UK research in extreme space weather. Leadership in microencapsulation technologies and in energy storage led to the election of Zhang and Ding as Fellows of the Royal Academy of Engineering, bringing our cohort of elected Fellows to ten. 45% of our research papers are in the top 10% of journals and a further 20% are in the top 10% most cited worldwide.

# Fellowships

Senior staff are elected Fellows of the following learned societies: Royal Society of Chemistry (6); Institution of Chemical Engineers (10); Institution of Mechanical Engineers (11); Institute of Materials, Minerals and Mining (7); Institute of Electrical and Electronics Engineering (5); Institution of Engineering and Technology (5); Institution of Civil Engineers (2); Royal Metrological Society (1); Geological Society (2); Institute of Physics and Engineering in Medicine (1); and Institution of Rail Signal Engineers (2).

In addition to industry fellowships (section 2.1), externally funded fellowships include UKRI FLFs (Cox, Knowles), EPSRC New Investigator Fellowships (Faramarzi, Thomas-Seale, Cox, Windows-Yule), a Turing Fellowship (Cai), three UKRI Future Leaders Fellowships (Cox, Knowles, Kelly) and two prestigious RAEng Fellowships (Goldberg-Oppenheimer, Knowles). We



hosted 37 Marie *Skłodowska*-Curie Fellows (early stage, senior and individual), an NC3Rs Training Fellow and an i4i Fellow.

Senior fellowships include El Haj's ERC Advanced Fellowship, Soo's RAEng Distinguished Visiting Fellowship, Feresidis's RAEng-Leverhulme Trust Senior Research Fellowship, Bowen's Research Fellowship in Nuclear Structural Integrity (Office of Nuclear Regulation), Sterling and Metje's Walsh Fellowships (Agriculture & Food Development Authority), and fellowships from the Leverhulme Trust (Butt), Rutherford Strategic Partnership (Tsolakis), EPSRC (Wu), and Royal Society (ZJ Zhang).

# Leadership and advisory roles

Staff occupy over 200 leadership and advisory positions at national and global bodies, including the REF2021 Panel (El Haj, Fryer). Positions at *national and international societies* include **presidencies** of the European Ceramic Society (Binner), IOM3 (Binner), IChemE (Seville), American Association of Wind Engineering (Kopp), Bioengineering Society (El Haj), **vice presidencies** of International Union of Railways Universities Alliance (Jack), International Association of Engineering Geology (Jefferson), Scandinavian Society for Biomaterials (Bassett), and International Union of Radio Science (Cannon), and **founding Chairman** of EMSIG: UK Radar Society (Cherniakov). We **chair** the UK Magnetics Society (Walton), Heads of Chemical Engineering Excellence Panel (Rogers), UK Automatic Control Council (Dixon), the IET Railway Technical Network (Easton), the Railway Division of IMechE (Schmid), the IChemE Catalysis SIG (Wood), and the Wind Engineering Society (Sterling), and sit on multiple RSC, IMechE, IEEE, IChemE and SCI boards and special interest groups.

Positions in *industry* are numerous. Jefferson, Soper, Theophanus, Sterling, Metje, Dirar, Kopp and Kaewunruen have served on steering committees including BSI, ASTM and ASCE, and many European standards committees. Jack sits on the Technical Advisory Board of the International High Speed Rail Association. Roberts sits on the UK rail industry Technical Leaders Group and the Technical Advisory Panel to Singapore Metro. We sit on technical committees including ISSMGE, Sustainable Geotechnics, and the Geospatial Commission's National Underground Asset Register.

Official roles with *governments and intergovernmental organisations* include Stolkin's election as Chair of the global Nuclear Energy Agency (OECD) Expert Group on Robotics and Remote Systems, representing 33 nations. Fryer was a member of the MOD Defence Scientific Advisory Council (2014-2017) and Thomas of the MHRA Clinical Trials, Biologicals and Vaccines Expert Advisory Group. Cannon is a member of BEIS's Severe Space Weather Steering Group, the Space Environment Impacts Expert Group, the Cabinet Office Space Weather Project Board, and the Blackett Review Committee on Satellite-derived time and position.

Further *governmental advisory positions* include Founder Member and Chairman of the UK Graphite Technology Advisory Group to the Office of Nuclear Regulation (Bowen), member of the Lead Expert Group of the UK government Foresight Future of Cities Project (Rogers), advisor to the Met Office's UK Climate Predictions 2018 Project (Quinn), and RAEng representative to the House of Commons Science & Technology Committee (Goldberg-Oppenheimer). Walton advised the Cabinet Office (POSTnote) on critical materials. Tight advised the government's Foresight Future of Mobility report. Jack was Special Advisor to the Parliamentary Select Committee on Transport (2018). Papaelias contributed to the UK Parliament COVID-19 Outbreak Expert Database (Life Beyond COVID) and Burrow is a panel member for the FCO's £28.5M Research for Community Access Partnership.

Internationally, staff acted as advisors to United Nations agencies, the World Bank, WHO and NATO. Walton led the European Rare Earths Competency Network Rare Earth Recycling Working Group. Ding's role on the steering committee of the Royal Society large-scale energy



storage study led to the adaptation of *policy and regulation* to recognise the role of energy storage in the UK's energy system. Radcliffe is shaping government policy on emissions reduction through roles with the House of Commons Science and Technology Select Committee, and UKRI Scientific Advisory Committee for Energy.

# Membership of national international grants committees

We contribute **strategic input to the direction of UK research** through membership of EPSRC Strategic Advisory Teams (Grover, Healthcare Technology; Kendrick, Physical Sciences (2016-2019); Binner, Engineering (Chair, 2018)). Davenport chaired the Science and Technology Facilities Council's Science Board and was a member of Innovate UK's Advanced Materials Leadership Council. El Haj is Deputy Director of the Engineered Cell Environment Regenerative Medicine Platform (BBSRC, EPSRC, MRC). We chaired multiple UKRI panels (Rogers, Cassidy, Fryer). Further memberships include the ERC (El Haj, Fryer), EU COST actions (Baniotopoulos, Feresidis), the EU SET-Plan Implementation Group (A Hornung) and EU European Technology and Innovation Platform: Smart Networks for Energy Transition (Y Ding).

# Editing and peer review

The majority of staff are involved in management and peer-review at leading journals. We are editors of 12 (*American Geophysical Union*, *Biosensors* (editor-in-chief), *Cogent Engineering*, *Energy Storage Science & Technology*, *Frontiers in Medical Technology*, *Frontiers in Transportation and Transit Systems*, *Journal of Experimental Nanoscience*, *Powder Technology* (editor-in-chief), *Radio Science*, *Sports Engineering*, *Tunnelling* and *Underground Space Technology*), associate editors of 28, editorial board members of a further 126, and peer reviewers for over 400 different titles. We also guest edited 41 special editions.

#### Grant peer review

38 staff are full members of the EPSRC Peer Review College (14 are associates) and staff have peer reviewed for funders including UKRI, NHS, Royal Society, Royal Academy of Engineering, and major charities. Jayaweera was twice recognised for outstanding contribution to EPSRC peer review. Internationally, staff sit on panels or peer review for funding bodies in over 28 countries, and peer review for the ERC, EU, and the World Bank's Strategic Research Programme.

# Conferences

Staff have organised over 150 conferences and panels, from focused symposia to major international events such as the 69th International Academy for Production Engineering General Assembly (2019), co-organised by Soo and Hood in Birmingham, which featured on the BBC's One Show. Further events include the Advanced Composites in Construction conference (2019), the International Symposium on Mixing in Industrial Processes (2017), the UK Particle Technology Forum (2017), the RSC Biomaterials Science Meeting (2016), the Liquid Metal Processing and Casting Conference (2019), and the IEEE International Conference on Intelligent Railroad Transportation (2016, 2018). Staff are on the Technical Programme Committees of IEEE RadarCon, IEEE/IET International Radar Conference, International Radar Symposium, and the IET International Conference on Railway Engineering, amongst many others. Significant chairing roles include RAEng Everywoman Academy and IAM Women in Infrastructure discussion panels, UN workshops and multiple international congresses.

#### Invited talks

All staff engage in research dissemination through national and international events. Nearly 700 invited and keynote talks occurred at conferences, universities, and industry events in 37 countries. Select examples include Jack's plenary at the World Congress on Railway Research, Milan (2016), Metje's invited talk at the Civil Engineering Forum, Canada (2017), Basoalto's



address to the ECCOMAS Thematic Conference, Glasgow (2019), Mendes's lecture at the RSC Conference Challenges in Nanoscience, San Diego (2014) and Grover's at the European Society for Biomaterials, Dresden (2019).

# Prizes

REF-eligible staff won over 90 prizes, reflecting the originality and impact of our research. Select examples include El Haj's MRC Suffrage Award for leading women in STEM, Mendes' 2016 IChemE Global Award for prostate cancer research (*Healthcare*), and Adams's Tribology Trust Silver Medal for outstanding achievement (2016, *Formulation*). Basoalto and Brooks's multiscale approach to phase transitions in additive manufacturing won 1<sup>st</sup> Prize in the NIST AM-Bench 2018 Challenge and Collins won the Silver Medal at the 2020 IOM3 Awards (*Advanced Manufacturing and Materials Processing*). An MoU with the British Geological Survey helped secure the EPSRC Assessing the Underworld project (Rogers, £5.8M), the impact of which was recognised by the ICE Midlands in the 'Research & Studies' and 'Overall' awards (2018, 2019, 2020), and Street Works UK's Best Collaborative Work award in 2017 (*Infrastructure*).

BCRRE was named one of the Midlands' most innovative businesses as part of 'Innovation 50' and HydroFLEX won the BusinessGreen's Transport Project of the Year 2020 (*Rail*). Cherniakov won the Christian Hülsmeyer award for his internationally leading work in radar (German Institute of Navigation, 2017, *Communications and Sensing*). Davenport won the Uhlig Award for the Corrosion Division of the Electrochemical Society (2019, *Materials for Challenging Environments*). Peters' Innovate UK Inspirational Innovation Award was presented by Jo Johnson MP (2016) and Y Ding won three 2019 IChemE Global Energy Awards (*Energy*).

ECRs were also recognised, e.g. Du's Royal Society of Chemistry CSCST UK Emerging Talent Prize (2015), Iordachescu's World Biomaterials Congress Young Scientist Award (2016) and Alberini's EFCE Young Researcher Award in Mixing (2018).

# Collaborative PGR training

The majority of our CDTs are collaborative, enabling students to access a wide variety of facilities and expertise: Fuel Cells and their Fuels (with Nottingham, Loughborough, Imperial College and UCL); IMPaCT (Leicester, Nottingham); Sustainable Hydrogen (Nottingham, Loughborough, Ulster); and Carbon Capture and Storage and Cleaner Fossil Energy (Nottingham, Sheffield and Loughborough). The DTP in Structural Metallic Systems runs with Cambridge and Swansea and the lifETIME CDT partners Glasgow, Aston and CÚRAM – Science Foundation Ireland. Its Birmingham-centred activities run from the HTI, at which a new course in medical innovation (with Trinity College Dublin) is planned.

# 4.3. Concluding remarks:

Our research environment is one that promotes collegiality and equality to support and develop world-class researchers to lead and influence the discipline of Engineering nationally and internationally. Our emphasis on collaborations with governments, industry and healthcare providers, and our unique ability to traverse the full translational pipeline, positions us to achieve the economic and societal impacts needed to address the challenges of the 21<sup>st</sup> century.