Institution: University of Leeds

Unit of Assessment: UoA12—Engineering

1. Unit context and structure, research and impact strategy

a. Overview

This submission represents four of the eight Schools in the Faculty of Engineering and Physical Sciences, together with the closely aligned Institute for Transport Studies in the Faculty of Environment. The Schools, the Heads of Schools, and the number of academics (not all returned in this UoA) are:

- Chemical & Process Engineering (CHEM): Professor Elaine Martin OBE FREng, 58 academics.
- Civil Engineering (CIVIL): Professor Muhammed Basheer FREng, 45 academics.
- Electronic & Electrical Engineering (ELEC): Professor Robert Kelsall, 44 academics.
- Mechanical Engineering (MECH): Professor Harvey Thompson, 56 academics.
- Transport Studies (ITS): Professor Simon Shepherd, 37 academics.

The University's 2015–2020 strategic plan (REF5a) underpinned an unparalleled period of investment in research infrastructure and personnel in this Unit, supporting the Schools not only to deliver, but exceed, the ambitions presented in their REF2014 submissions, discussed below by School. A common focus across the Unit has been to promote and grow interdisciplinary research to address technological and societal challenges through internal and external partnerships, both nationally and globally; indeed, over one half of our outputs in REF2 are collaborative with at least one international co-author. This has been achieved through the development of major externally-funded collaborative research centres, e.g. in medical technologies and in infrastructure materials, as well as through major University capital investment delivering, e.g. our new Sir William Henry Bragg Building and the new Bragg Centre for Materials Research. Major investment in personnel has been made into early career researchers through, e.g. our University Academic Fellowship (UAF) scheme, as well as into senior leadership chairs, with many appointments made jointly between Schools within, and external to this Unit. This has embedded interdisciplinarity, and further improved the quality and volume of our research outputs, and the breadth and depth of our research impact.

The formation of the single Faculty of Engineering and Physical Sciences in 2019 through the combination of the former Faculty of Engineering and Faculty of Mathematics & Physical Sciences has further consolidated our goal of driving interdisciplinary working, by opening new opportunities for research networking and communication, and through development of co-located and consolidated research facilities.

b. Research objectives during the assessment period and over the next five years

A detailed and evidenced discussion on how we met, and exceeded, our REF2014 research objectives is provided here by School, followed by our vision for the Unit over the next period. Reference to selected REF2 outputs (e.g. CHEM-1) and impact case studies (e.g. ICS-1) are indicated. Colleagues with outputs in this submission are named in **bold**.

School of Chemical and Process Engineering

Research structure of the School

Following a £38M refurbishment completed in this period, we re-organised into three externally-facing divisions to support the research goals outlined in our REF2014 submission:

Advanced Materials Engineering (AME) (lead: **Bell** FREng FIEEE; 17 FTE) conducts research into the characterisation and control of microstructure-processing-property

relationships during materials/device fabrication, and in engineering applications.

Innovative Manufacturing and Products (IMP) (lead: **Roberts** FREng; 17.5 FTE) develops new manufacturing routes and methods, allowing better control of product functionality, consistency, and quality.

Sustainable Systems and Processes (SSP) (lead: **Jones**(**J**); 19.5 FTE) integrates research into the design, operation and life-cycle analysis of sustainable chemical and energy systems.

Overview of the School's research objectives and achievements since 2014

In REF2014 we set a goal to increase our leadership and participation in major national and international materials research infrastructure. **Advanced Materials Engineering** has achieved this through leading on the formation of the University's Bragg Centre for Materials Research (§3(b)), through founding membership of the Henry Royce Institute, and by developing closer links via new joint appointments with SuperSTEM (**Ramasse**), Diamond (**Schroeder**), and the Advanced Photon Source (**Mishra**). Research highlights include: production of the world's thinnest 2D gold (CHEM-105); elucidation of *p*/*n* graphene doping mechanisms (CHEM-37); and, visualisation of catalyst dynamics at single atom levels (CHEM-80) and in hierarchical porous networks (CHEM-42). Resolving longstanding structural ambiguities in a variety of energy materials (CHEM-81,92), we discovered a new class of relaxor multiferroics (CHEM-44). We developed high performance lead-free electroceramics (CHEM-24), commercialised a new high-temperature ferroelectric for process monitoring (CHEM-8), and achieved homogeneous laser-doping of photonic glasses (CHEM-36). Newly developed materials characterisation methods include nanoscale vibrational spectroscopy (CHEM-91), *in situ* X-ray Raman scattering (CHEM-95), and hydrogen bonding spectroscopy (CHEM-11).

Our 2014 goals included the development of new molecular product design approaches and digital process manufacturing technologies for the pharmaceutical, food and personal care sectors. To achieve this, **Innovative Manufacturing and Products** focused its vision around an interdisciplinary 'Molecules to Product' research concept, enabled via strategic industrial partnerships, and appointed new tenure-track UAFs (**Warren**, **Hondow**). Highlights include development of side-effect-free iron food supplements (CHEM-2), and micro-encapsulate delivery strategies for volatile additives (CHEM-28) and targeted drugs (CHEM-93). Industrial impact was achieved through development of digital design and manufacturing processes including: particulate spray drying (CHEM-29); self-optimised flow reactions for pharmaceuticals (CHEM-63,50,90), leading to rapid cancer drug delivery to market (ICS-5); and, rapid cell-screening methods for biopharma production (CHEM-23). A further 2014 goal was to develop understanding of nanoparticle toxicity, which we have achieved through identification of: zinc oxide nanoparticle toxicity mechanisms (CHEM-4); pathways for intestinal nanoparticle uptake (CHEM-20); a new nanoparticle tracking method in cell populations (CHEM-9); and, improved prediction of inhaled drug-delivery efficiency (CHEM-13).

In 2014, we aimed to consolidate critical-mass research in renewable energy and nuclear engineering, and build on industrial links. This has been successful, with highlights from **Sustainable Systems and Processes** including the development of new production methods for high quality chemical products and biofuels from low quality biomass (CHEM-43,74) and algae (CHEM-30,45), as well as carbon nanotubes/hydrogen from waste plastics (CHEM-76). Whole energy-system integration approaches have quantitatively assessed biomass-driven decarbonisation in global steel industries (CHEM-86) and roof-top solar energy at city-wide levels (CHEM-19). Our investment in nuclear research has included new active-handling laboratories leading to new remediation technologies for active water (CHEM-65), and new mechanistic understanding of microstructural changes in irradiated graphite moderators (CHEM-10) and particle behaviour in waste-flows (CHEM-89), with adoption by

UK nuclear waste management and decommissioning.

School of Civil Engineering

Research structure of the School

In this period, we restructured into three interconnected groups to deliver our REF2014 research plans and to respond effectively to national priorities and international opportunities such as the UN Sustainable Development Goals.

Water, Public Health and Environmental Engineering (**WPE**) (lead: **Stewart**(**D**); 13.3 FTE) integrates physical, biological, chemical, social and economic sciences to inform delivery of robust and effective infrastructure and systems.

In **Materials and Structural Engineering (MSE)** (lead: **Bernal-Lopez**; 12 FTE), world-leading research in infrastructure materials combines nanomaterials science with the measurement and modelling of full-scale structures, informing the design of future built environments.

In **Cities, Energy and Sustainable Buildings (CESB)** (lead: **Rees**; 14.5 FTE), systems and socio-economic approaches are coupled with the physics of the built environment. We inform sustainable, energy efficient and resilient infrastructure design.

Overview of the School's research objectives and achievements since 2014

In 2014, we planned to build on our success in understanding airborne infection, develop integrated approaches to water and sanitation challenges in the developing world, and tackle remediation and resource recovery. In **Water, Public Health and Environmental Engineering** our global analyses produced the first international models of plastic pollution (CIVIL-84) and faecal sludge management in rapidly urbanising environments (CIVIL-44), underpinning methods for measuring progress against UN Sustainable Development Goals (ICS-1). Collaborative activities in fluid dynamics led to patents for 3D-printed heat exchangers with BAE Systems (CIVIL-76) and world-first real-time airflow simulation for indoor environments (CIVIL-15). Our stochastic infection-risk models directly linking air, surface and hand contamination to hospital design (CIVIL-11) have informed international Covid-19 responses via our SAGE membership (ICS-8). Collaborative international research on bio-geo-chemical processes included the first explanation of the fate of nutrients in thermally-treated biomass (CIVIL-25,30), and seminal advances in coupled physico-chemical models for groundwater flows (CIVIL-34). We recruited **Beretta** and **Trigg** to address global issues on flood risk (CIVIL-65), a further 2014 goal.

Materials and Structural Engineering research advanced fundamental understanding of the performance and durability of materials to inform low-carbon, sustainable and resilient design. We recruited to reflect international interest in the impact of cementitious materials (**Basheer**, **Bernal-Lopez**, **Garcia-Taengua**, **Barbhuiya**). Highlights include the first coherent models both for the structure of calcium silicate hydrate binding phases in cement (CIVIL-10), and for the role of slag chemistry in cements that utilise industrial by-products (CIVIL-7,71). Fundamental work underpinning international design codes includes: the first full-scale demonstrations of the structural effect of edge restraint (CIVIL-70); and, the first explanations of the contribution of individual components in masonry-infilled frames and lightweight steel systems to earthquake response (CIVIL-62). Structures research has contributed world-first applications of quasi-steady aerodynamic theory to bridges (CIVIL-3) and models of splitting risk in reinforced concrete (CIVIL-16).

A particular goal in our 2014 REF submission was to develop analyses of the complex interplay between resilience and technical infrastructure performance, supporting innovations for energy efficiency and sustainable building design. In the **Cities, Energy and Sustainable Buildings** group we have pioneered new systems approaches combining economic, environmental and

engineering analyses for assessing energy and infrastructure resource lifecycles (CIVIL-4,54,66), and a web-based tool for tackling multi-stakeholder approaches to maintaining urban infrastructure (CIVIL-83). This led to national leadership of the UKRI Resource Recovery from Waste Programme, and leading roles in two UKRI Circular Economy Centres and the ISCF Foundation Industries Network Plus. We invested in high-speed rail research capacity (§3(b)) in response to global transit strategies, recruiting **Woodward** and **Connolly**. Our new energy systems investments have yielded: unique statistical approaches for assessing risk in mega-projects and energy infrastructure (CIVIL-33) that directly inform BEIS strategy; and, a gold-standard data set for modelling geothermal heat exchange systems (CIVIL-60). We have also invested in architectural engineering, including through recruitment of **Selim** and **Sarhosis**.

School of Electronic and Electrical Engineering

Research structure of the School

Since 2014, the School restructured its research into three institutes to reflect a growing focus on robotics and autonomous systems, to integrate research on communications and power networks and, to broaden the scope of its activities in optoelectronics and (bio-) nanotechnology.

The **Pollard Institute (Pollard)** (Lead: **Wälti**; 18 FTE) explores high frequency electronics from GHz to THz frequencies, quantum electronic devices, semiconductor nanotechnology, and bio-nanoelectronics.

The **Institute of Communications and Power Networks (ICaPNet)** (Lead: **Elmirghani** FIEEE; 9 FTE) carries out research on communications, smart energy systems, signal processing, control systems and instrumentation, and engages with all major telecommunication companies.

The **Institute of Robotics, Autonomous Systems and Sensing (IRASS)** (Lead: **Valdastri**; 10 FTE) undertakes research in the fields of robotics, autonomous systems and sensing, with a strong focus on the translational impact of its discoveries.

Overview of the School's research objectives and achievements since 2014

In our REF 2014 submission we planned to develop optoelectronic components and sub-systems, with a focus on terahertz frequency quantum cascade lasers (THz QCLs), and underpin development of nanoscale electronics for future high frequency devices. Highlights in the **Pollard Institute** include: the first electrically-pumped THz topological laser (ELEC-95); the first measurement of the switch-on dynamics of a frequency-tuneable semiconductor laser (ELEC-74); the first THz self-mixing near-field microscope (ELEC-29); fully phase-stabilized THz QCL frequency combs (ELEC-88); and, locking of a THz QCL to an optical comb reference (ELEC-58), and ultimately to the GPS primary frequency standard. We demonstrated the first lasing of a direct bandgap Group IV semiconductor (GeSn) on Si (ELEC-16), leading to ultra-low threshold lasing in tensile-strained GeSn alloys (ELEC-96). We also explored the physics of skyrmions (ELEC-55), artificial spin ices (ELEC-77) and domain-wall logic (ELEC-84).

We also planned to integrate biological functionality into nanostructured electronic devices to develop new functional materials and devices, targeting therapeutic delivery. Highlights include: (i) the demonstration of label-free biosensors leading to commercial spin out (ELEC-28); directed self-assembly of RecA nucleoprotein filaments (ELEC-2); and, the observation of RecA-mediated homology searching (ELEC-61); (ii) the use of nano-tweezers for trapping single molecules within a single cell (ELEC-78) and delivery of individual protein oligomers into living cells (ELEC-34); (iii) new suturing techniques for fetal surgery (ELEC-37), and development of organ-on-chip models of the human endometrium (ELEC-47); and, (iv) cell separation using surface acoustic waves leading to commercial spin out (ELEC-46).

In 2014, we planned to design energy efficient optical networks, content distribution networks and data centre architectures. Highlights in the **Institute of Communications and Power**

Networks include passive optical network designs for data centres (ELEC-26) leading to commercial spin out, new distributed progressive processing for greening big data networks (ELEC-62) and, use of distributed energy efficient clouds over core networks (ELEC-6), leading to IEEE standards (§4(c)). We also expanded activity to encompass smart energy systems through the appointment of one Chair (**Li**(**K**)) and four lecturers (**Aristidou**, **Azizi**, **Lawey**, Schiffer).

In 2014, we proposed exploiting functionalized microbubbles for targeted therapeutic delivery, exploiting our expertise in ultrasonics, signal processing and embedded systems. We have: explored liposome-loaded microbubbles for subharmonic imaging (ELEC-43); investigated gold nanoparticles for focused ultrasound therapy (ELEC-60); and, demonstrated high frame-rate contrast-enhanced echocardiography (ELEC-80). We expanded into surgical and medical robotics, and with the appointment of two overseas chairs (**Valdastri**, **Xie**) joint with MECH, and three UAFs (**Mazomenos**, **Zaidi**, **Zhang**(**Z**)), we established the new Institute, the **Institute of Robotics, Autonomous Systems and Sensing**. Highlights include the demonstration of closed-loop micro-ultrasound imaging in the bowel using intelligent magnetic manipulation (ELEC-87), with the additional introduction of robotic assistance (ELEC-104) reducing the burden on surgeons through autonomous control.

School of Mechanical Engineering

Research structure of the School

As planned in our 2014 REF submission, we divided our former large Institute of Engineering Thermofluids, Surfaces and Interfaces into the two new Institutes of Functional Surfaces (iFS) and Thermofluids (iTF). The School is now organised into four research institutes.

With a vision of '50 active years after 50', the **Institute of Medical and Biological Engineering (iMBE)** (Lead: **Wilcox**; 11 FTE) comprises engineers, scientists, medics and clinicians, and aims to make a lasting impact on improving the quality of life of an ageing population.

The **Institute of Functional Surfaces (iFS)** (Lead: **Neville** OBE FRS FREng; 8 FTE) carries out challenging research from basic science through to application in tribology and surface engineering, corrosion, and flow assurance, with impact on energy, transport and healthcare industries.

Institute of Thermofluids (iTF) (Lead: **Wilson**; 14 FTE) develops powerful experimental and modelling techniques for understanding of flows and processes with impact in healthcare, combustion, transport, sustainability, energy and manufacturing.

Institute of Design, Robotics and Optimisation (iDRO) (Lead: **Richardson**(**R**); 17 FTE) focusses on theoretical and experimental research in mechatronics and robotics in infrastructure and healthcare technologies, hybrid manufacturing, design sciences, and energy efficient automotive and aerospace structures.

Overview of the School's research objectives and achievements since 2014

Within the **Institute of Medical and Biological Engineering** our 2014 goals were to increase our natural joint simulation capabilities, grow our research on biological scaffolds and regenerative interventions, and extend our computer simulation and modelling capabilities to all human joint systems. Highlights include: the first six axis natural knee simulator for in-vitro studies of natural joints (MECH-31), providing insights on mechanical cartilage degradation (MECH-74); the first quantification of non-directly measurable mechanical behaviour of fibrous tissues (MECH-23), and; development of a hydrogel for disc regeneration that mimics natural tissue behaviour (MECH-41). Furthermore, we developed the first processes for decellularisation of porcine superflexor tendon as an acellular scaffold for anterior cruciate ligament repair (MECH-53), and established new bioprocessing techniques for the efficient

removal of genetic content from porcine tendon (MECH-15).

To capitalise on the growth of our corrosion/tribology/surface engineering research, we set the objective to develop a UK centre of excellence on functional surfaces. We have achieved this through the **Institute of Functional Surfaces** and highlights include: the first *in situ* synchrotron study of corrosion products growth (MECH-75); development of bespoke equipment for *in situ* study of tribochemistry processes (MECH-27,56) underpinning unique mechanistic (MECH-44), and multiscale numerical (MECH-18) models; and, the first demonstration of the role of mixed-metal coupling on tribocorrosion at the femoral stem-cement interface (MECH-13). Additionally, we developed the first 3D nanoprinting system using triboreactive materials (MECH-89), and a robust coating strategy of flexible substrates to boost the Hydrogen Evolution Reaction performance (MECH-113).

The **Institute of Thermofluids** was launched in 2014 to focus on key thermofluidic phenomena in combustion and optimization. During this REF period: we showed for the first time that water inclusion must be considered in the combustion of future ethanol-based fuels (MECH-5); we developed an advanced optimisation process for maximising aero-engine thermodynamic cycle performance (MECH-51); and, we developed a new method for assessing dynamic surface tension and transient shear viscosity in nozzles/jets (MECH-14). In addition, new interdisciplinary research led to: enhanced oilfield scale prevention through inhibitor adsorption on carbon nanotubes (MECH-55); and, the first direct experimental evidence of the impact of extensional flow on protein stability (MECH-65).

As planned in our 2014 submission, we refocused the **Institute of Design, Robotics and Optimisation** to be a hub for advanced design and manufacturing of innovative robotic systems for industrial and medical applications. Our stated goal to become an international centre of excellence in robotics has been enabled through formation of the Robotics@Leeds network (§3(b)) in collaboration with the IRASS Institute in ELEC, the School of Computing, and wider. Highlights include: the first meta-model and benchmark for product system definitions (MECH-11); the first implantable soft system for restoring cardiac output (MECH-62); the first soft inductive tactile sensor which exploits an inductance-transducer mechanism based on the eddy-current effect (MECH-80); and, the development of a portfolio of unique techniques to manage tether kinematics (MECH-10). Furthermore, we developed new capability in hybrid manufacturing through recruitment of **Harris**, **Kay**, **Lee**, and **Saleh**. Achievements include low cost, efficient infrared nanosecond laser textured surfaces for chemical sensing (MECH-42), and development of multifunctional metal matrix composites with embedded printed electrical materials fabricated by ultrasonic additive manufacturing (MECH-59).

Institute for Transport Studies

Research structure of the Institute

ITS moved into a new £4M building in 2017, and undertakes multi-disciplinary research at the interface between academia, policy and practice with researchers belonging to one of five discipline-based research groups; our Social and Political Sciences group is returned to UoA14. The other four groups are:

The **Choice Modelling** group (Lead: **Hess**; 2.8 FTE) develops mathematical models to understand the drivers of individual activity and travel choices, ranging from long-term choices such as residential location through to short-term choices such as route and even motorway lane selection.

Economics and Appraisal (Lead: **Smith**(**A**); 7.2 FTE) develops understanding in the economics of transport demand and supply (both passenger and freight) and the economic appraisal of transport investments and policy interventions, and how these impact on individual

travel decisions and the overall business case for transport investment and wider interventions.

Human Factors and Safety (Lead: **Merat**; 5.5 FTE) researches road users' interactions with transport systems and technologies to advance transport safety, using field operational tests, naturalistic driving studies, and laboratory studies.

Spatial Modelling and Dynamics (Lead: **Watling**; 11.2 FTE) develops and validates mathematical models and simulation tools for representation, analysis and optimization of traffic and transportation systems with a focus on use of big data in new modelling approaches.

Overview of the Institute's research objectives and achievements since 2014

Within the **Choice Modelling** group, we have delivered on our 2014 plans to develop enhanced methodologies for choice modelling, contributing fundamental theory as well as applications to practical problems using new data sources such as GPS (ITS-12,28,33,39). We developed new methodology for estimating origin-destination matrices using mobile phone records from 2.87 million anonymized users in Dhaka (ITS-4).

In this period, the **Human Factors and Safety** group aimed to grow research in intelligent vehicles, refocussing around automation and safety, and building on our evolving 'Virtuocity' simulator assets (§3(c)). To enable this, we hired new chair (**Romano**) and drew on our successful partnership with Jaguar Land Rover, EU projects, and development of our driving simulator (ITS-41,44). This has resulted in the first understanding of driver behaviour and braking, and validation of simulators with Volvo (ITS-17,23), together with understanding of human factors around the transition to automation (ITS-26,37), and driver workload (ITS-3).

In 2014, a goal of the **Economics and Appraisal** group was to develop our rail economics research to deliver major policy impacts. We led work around values of travel time savings that have been taken into policy guidance (ICS-7), materially affecting the HS2 business case and resulting in recommendations that have driven £85M per annum through the Schedule 8 regulatory regime of the British passenger rail industry (ITS-15,16,24). Our research into structure and operations has influenced the UK and EU rail operations (ITS-10,19,40), and has informed railway franchising in UK and Norway (ITS-5). We diversified into road transport, developing the benchmarking club for road maintenance (ITS-51).

In this period, we planned to deliver improved methods for modelling complex transport networks in the **Spatial Modelling and Dynamics group**. Our work on network modelling (ITS-14) developed algorithms now implemented in commercial software developed by the Danish company Rapidis, which has been adopted in the Danish National Model, and in the European Union's Transtools 3 software forming the new standard for European network policy assessment. We responded to new challenges such as the 'diesel-gate' scandal and how pollution impacts asthma in children. We also took the opportunity to strengthen our electric vehicle research through appointment of **Anable** who worked on market segmentation and uptake of electric vehicles informing European Climate Foundation and US Department of Energy, fulfilling our ambition to increase presence in the transport and energy area.

Vision and Future Research Strategy of the Unit

Our research objectives over the next five years focus on cross-cutting challenges enabled by the Unit's critical mass of interdisciplinary expertise, exceptional experimental and computational facilities, and international research leadership. Central to our vision is the development of effective physical and digital infrastructure systems that underpin lives and work. Current and future energy, transport and water infrastructure must be efficient, resilient and able to support the transition to a zero-carbon future. We will expand and diversify our research into healthcare technologies, improving patient outcomes and well-being, and build upon the remarkable breadth of research and innovation across the Unit and wider. We will capitalise on the

significant internal and external investment over this REF period (§3) including our new £96M Sir William Henry Bragg Building incorporating the £20M Bragg Centre for Materials Research, both opening in Spring 2021, and our new ten-acre £23M Infrastructure Innovation Park opening in 2022 which, in the first phase of occupancy, will house our new £50M Institute of High-Speed Rail and System Integration, and the £16M National Centre for Infrastructure Materials.

- We will commission our Infrastructure Innovation Park, and build our new Institute of High-Speed Rail and System Integration to be the most advanced centre in the world for high-speed rail planning, design, construction and testing. We will develop further major new facilities in field robotics, city simulation, and energy-intensive foundation industries. We will re-house and re-develop our Virtuocity suite of fully-immersive truck, car and pedestrian simulators and build capability in distributed simulation to support the development of UK transport policy and on the introduction of autonomous vehicles. We will lead research in the whole life performance of cleaner infrastructure systems from material supply to end-of-life disposal of decommissioned installations, integrating these considerations into design processes. Furthermore, we will expand our research on infrastructure economics, to understand better the funding, finance and political economy of infrastructure.
- We will reduce the carbon footprint associated with electrical energy consumption, developing new methodologies for smart grids encompassing renewable energy sources, providing new approaches for efficient data centre operation, and implementing new spintronic, ferroelectric, and high frequency (RF and terahertz) device technologies. We will grow our leadership of national facilities, such as Super-STEM and Diamond, and develop new partnerships through our leadership of the Royce Institute and our Bragg Centre for Materials Research, building on our expertise in *in situ*/transient measurements, *operando* studies, and interfacial properties. A focus will be on intelligent and sustainable material design, informed by product and component specifications, and end-of-life degradation and recycling, connecting through to digital manufacturing processes, for example in the pharmaceutical sector.
- We will develop the next generation of healthcare technologies, growing our successful partnerships with clinical practitioners, the NHS Trust, and industry, including the development of joint replacements with consistently excellent outcomes, functional decellularized scaffolds, and robust preclinical testing and simulation systems. We will address emerging opportunities around technology convergence and the integration of digital technologies into new therapies and evaluation systems, including the development and integration of sensors and biomarkers for point-of-care diagnostics and personalised therapy, sustainable and effective minimally invasive surgical robotic systems, and organ-on-chip and microfluidic capabilities for testing drug efficacy. Clean water is an urgent global requirement, with its unavailability linked to poverty, ill-health and marginalisation. We will contribute to sustainable water, sanitation, and waste management services, as well as healthcare screening platforms and robot-assisted rehabilitation methodologies to improve infrastructure and services for the most marginalised members of global society.

c. How the Unit has enabled research impact, and is ensuring the vitality and sustainability of our impact

In this period, the Unit has enabled a wide range of national and international impact in industry, public health and wellbeing, public policy and practice, standards and guidance, and outreach. Specialized research and innovation development managers (RIDMs) in the Faculty, and centrally, work with researchers to find/build strategic stakeholder partnerships, undertake early development of exploitation (including through strategic allocation of e.g. School, IAA and HEIF funding for pump-priming explorative work), and support development of e.g. Knowledge

Transfer Partnerships and Innovate UK projects, and ERC Proof of Concept awards (§3(a)). The exchange of personnel between academia, industry and public sector bodies (§2(e) for examples and mechanisms), together with consultancy, are important mechanisms to facilitate impact. Furthermore, our engagement with technical and regulatory bodies supports the development of standards, and influences future directions. School workload models reflect significant research and impact commitments through reduced teaching and administration duties. Large research grants, CDTs, and ITNs include industrial partners to help direct and facilitate research impact.

The achievement of impact in **commerce**, the **economy**, and **production** (ICS-4, 5, 9, 10) is particularly supported through the University's Commercialization Services. The University provides formal IP protection/management, market scoping, due diligence and exploitation plans, and later stage commercialisation through licencing and spin-out. The Commercialization team includes case managers, patent and contracts administrators, and a corporate solicitor. A budget covers filing of UK/PCT patent applications, management of search reports and patent office actions, and proof-of-market/concept funding to provide market validation.

Seven companies were spun-out of this Unit in this period: Acuity Robotics (MECH); Cell Lane, Celltron Networks, and Relitect (ELEC); Free Running Buildings (CIVIL); and, Optimus Vitrum, and Ultramatis (CHEM). These complement a further eleven companies spun out pre-2014 period and still active in this REF period, including: Industrial Tomography Systems (CHEM); Instrumental (ELEC); Ionix Advanced Technologies (CHEM); and, Tissue Regenix (MECH) (ICS-2). **Bourne**'s secondment to AstraZeneca on RAEng Industrial Fellowships facilitated ICS-5; similarly, Hunter(I)'s RAEng Chair with Radio Design enabled ICS-9.

Impact on **public policy** and on the **environment** (ICS-1, 6, 7, 10) is particularly enabled by School funding to buy-out academic time and support engagement, including travel/visits, with policy makers. This approach supported **Carsten**'s work with the EU on the benefits of intelligent speed assistance in vehicles (ICS-6), and **Batley**'s engagement with the Office of Rail and Road, and the UK Department for Transport (ICS-7). ICS-1 was enabled by **Evans**' international leadership in global sanitation, including through e.g. membership of the UN WHO/UNICEF Joint Monitoring Programme Strategic Advisory Group, with Bower's secondment to Mott MacDonald supporting ICS-10. International policy impact is further supported by e.g. our legal, contracts and research ethics teams, and WUN membership.

Impacts on the **health and wellbeing** of people (ICS-1–3, 8) have been enabled through company spin-out and commercialization (ICS-2), and collaborative proof-of-concept projects with industry, regulatory and clinical end-users e.g. NHS Blood & Transplant, NHS Leeds Teaching Hospital Trust. **Jennings** was Chair of ISO TC150/SC4 Bone and Joint Replacements standards (ICS-3). **Fisher** led the Leeds City Region Science and Innovation Audit in 2019, commissioned by BEIS, to guide investment for medical technologies and facilitate impact acceleration in the Leeds city region. **Noakes**' release from University duties to join the government SAGE committee informed international Covid-19 responses (ICS-8).

We are adapting our approach to support the vitality and sustainability of research impact though, e.g. the University's innovation hub ('Nexus') and the Infrastructure Innovation Park. Nexus consolidates, coordinates and expands our commercialization and corporate relationship teams, as well as providing incubator laboratories/space. Through this approach new research collaborations have been initiated, including by embedding partners on campus (e.g. Jiuli Group laboratories, Connected Places Catapult), as well as supporting new PGR training opportunities (e.g. Key Engineering Solutions, partner in Marie Skłodowska-Curie Nu-SPINE ITN). The Infrastructure Innovation Park provides capacity for large academic and industrial programmes, and will house our new Institute of High-Speed Rail and System Integration and National Centre for Infrastructure Materials from 2022 (§3(b)), with further major research facilities in robotics,

city simulation, and energy-intensive foundation industries to follow.

The University's media team promotes our research and impact, and engage in national debate, with many statements/articles/interviews in national media during this period on topics ranging from plastic waste in oceans (**Velis**, BBC News at Ten, 23 July 2020) and endoscopic robotics (**Valdastri**, The Times, 13 October 2020), to autonomous vehicles (**Merat**, Daily Mail, 5 February 2020) and the transmission of coronavirus (**Noakes**, Financial Times, 23 September 2020). The 'Public Engagement with Research' team support delivery of outreach to schools and national science fairs, e.g. an exhibit on terahertz technology at the Royal Society Summer Exhibition 'Discovery Hub', July 2019.

d. The Unit's approach to supporting interdisciplinary research

The Unit supports and pursues interdisciplinary research within Schools as well as through leadership of, and participation in, interdisciplinary research centres that work across traditional School and Faculty disciplinary boundaries (§3(b)). Such centres arise organically through identification of shared interests, approaches, and facilities (e.g. Robotics@Leeds), but we also develop centres strategically to address a national/international research and impact challenge that capitalizes on research excellence in the Unit (e.g. Institute of High-Speed Rail and System Integration). The vitality and sustainability of the centres are enabled through the appointment of a Centre Director with workload buy-out, a representative management committee that includes early-career researchers, provision of dedicated RIDM support, and funding for events/seminars and pump-priming research. We reserve EPSRC DTP studentships to support interdisciplinary projects distributed both at Faculty level and aligned with interdisciplinary initiatives e.g. the Bragg Centre for Materials Research internal CDT comprising 20 studentships over four years. Our approach and strategy for generating research income, including large interdisciplinary awards, is discussed in §3(a).

Interdisciplinarity is further supported and embedded through the academic background of researchers (e.g. in ITS alone, this ranges from mathematics and engineering, to psychology and economics), through shared PGR students, and through joint appointments. Such appointments include: **Smith**(**A**), **Toner** (50% ITS, 50% Leeds University Business School); **Wang**(**J**) (20% ITS, 80% CIVIL); **Choudhury** (80% ITS, 20% CIVIL); **Mao** (50% CHEM, 50% CIVIL); **Cockerill** (60% MECH, 40% CHEM); **Ramasse** (20% Physics, 80% CHEM); **Wadud** (50% ITS, 50% CHEM); **Valdastri**, **Xie** (40% MECH, 60% ELEC); **Bourne**, **Muller** (50% CHEM, 50% Chemistry); **Zhang**(**Z**) (70% ELEC, 30% MECH); **Collins** (60% CHEM, 40% Chemistry); **Mazomenos** (50% ELEC, 50% Medicine). In the UoA12 Schools, but submitted elsewhere, these also include: Roelich (49% CIVIL, 51% Earth and Environment); Tillotson (33% CIVIL, 33% Geography, 33% Earth and Environment); Blacker, Nguyen (50% CHEM, 50% Chemistry); Bale, Taylor (50% Earth and Environment; 50% CHEM); Edwards (45% MECH, 55% Biomedical Sciences); Morganti (50% ITS, 50% Food Science).

The formation of the single Faculty of Engineering and Physical Sciences in 2019 supports interdisciplinary research by opening new opportunities for networking and communication, and through development of co-located and consolidated laboratory facilities.

e. How the Unit is progressing towards an open research environment, and gone beyond the REF open access policy requirements

The five Schools in this Unit adopted a robust approach to open research in March 2014, commensurate with REF 2021 Open Access policy announcement. Exceeding the requirement of this policy, authors were obliged to deposit all journal and conference papers (not just those anticipated to feature in this submission) and where appropriate, other research outcomes, ahead of the mandatory deadline set by the HEFCE. We introduced a quarterly communication with authors to confirm compliance, together with individual support to inform and mitigate

problems. A dedicated appointment oversees research compliance. All outputs in this submission, and published while an author was employed at Leeds, are available openly via our institutional repository except where a publisher's policy intervenes.

The University implemented its Research Data Management Policy in 2017 to ensure research data can be shared, reused and cited beyond the end of the project, and to comply with funder policies. Our Institutional Data Repository holds deposited data for a minimum of ten years and the datasets are associated with digital object identifiers referenced in the relevant publication.

The University encourages all research-active staff, including PGRs, to use an ORCiD ID, ensuring work is clearly identified by individual and organisation.

f. How the Unit supports a culture of research integrity, and conducts research according to ethical, legal and professional frameworks, obligations and standards

We uphold the principles in the Concordat to Support the Career Development of Researchers to support research integrity, which are embedded in the inductions given to new academic and research staff, and reinforced through School staff meetings, School Research and Innovation committees, the Faculty Research and Innovation Committee, and during individuals' annual Staff Review and Development Scheme (SRDS) meetings and Annual Academic Meetings (AAMs) (§2). Principles in the EPSRC's Framework for Responsible Innovation are taught in, e.g. our CDT and other PGR training programmes.

All colleagues with leadership responsibility undertake training and must follow the University's leadership excellence behaviours. Our formal Open Access and Research Data Management policies support transparency in the open sharing of research results and research data, which themselves comply with the requirements of major research funders.

The Faculty ethics committee provides guidance, audits compliance, and appraises research proposals that include significant ethical dimensions, in particular involving human participants, field work in developing countries, use of medical and biological samples, and research with the potential for adverse impact upon the environment. All externally funded grants and contracts undertake a risk review before submission, including appraisal of ethics, safety, data management, anti-bribery, export control legislation, and potential conflicts of interest.

We seek and are awarded audited external quality assurance for our facilities, including ISO 9001 certification in ITS and MECH, and ISO 14644-1 in CIVIL. Complementing the University's highest OHSAS and RoSPA accreditation and awards, the former Faculty of Engineering has separately held 18001 accreditation from 2013 (now transitioning to 45001 certification), as well as receiving five consecutive RoSPA Gold Awards, and three RoSPA commendations.

We uphold professional standards by encouraging, and financially supporting, staff affiliation with professional societies and national academies, as well as through colleagues' contributions to: research council committees and peer-review grant evaluation; industry/regulatory bodies, and technical committees; and, through journal editorial boards and refereeing publications (§4(e)).

2. People

Staffing strategy and staff development

a. The Unit's development strategy for all staff pursuing a career in research.

In line with the University's Employment Policy for Research Staff, we implement the principles of the Concordat, as indicated below for the 2019 Concordat: **C1** Environment and culture (a supportive and inclusive research culture); **C2** Employment (researchers are recruited, employed and managed under conditions that recognise and value their contributions); and, **C3** Professional and career development (enabling researchers to develop their full potential).

Staff development occurs throughout an academic career including informally through membership of research groups/institutes, and formally via probation discussions, the annual Staff Review and Development Scheme (SRDS) meetings, and the Annual Academic Meeting (AAM). The University's mentoring scheme will pair any colleague who requests, or is recommended, with an experienced academic mentor.

New tenure-track staff and PDRAs join the University's probation scheme and jointly agree academic targets, typically for two years, with an academic mentor/probation advisor and Head of School [C2]. New tenure-track staff supported by externally-funded five-year University Research Fellowships (URFs), and those appointed on our University Academic Fellow (UAF) scheme, are provided with a five-year developmental programme, leading to Associate Professor (Reader) status, with probation stages at year 3 and 5, with targets agreed with the Fellow.

Established staff benefit from the annual SRDS meeting with their Institute/Centre Director, Head of School, or Dean. This developmental discussion identifies needs, goals, support and methods to achieve ambitions, including promotion [C2]. This complements the AAM between each member of staff and their Head of School, Director of Research & Innovation, Director of Student Education, and Institute/Centre Director, which appraises their research, student education, and administration activities, and includes discussion of future research plans. This informs the individual's workload profile, in which significant research and impact commitments are balanced by reduced teaching and administration duties [C1]. All Schools employ teaching assistants to alleviate research staff workload.

The University's training and development opportunities are led by the Organisational Development and Professional Learning (OD&PL) unit [C3]. This complements specialized training arranged by other university services, including the Library (e.g. open access, research data management, thesis and journal paper writing), and the Research and Innovation Service (RIS) (e.g. grant preparation, interview practice, research impact, commercialization). Staff are further supported by local training in e.g. health and safety requirements associated with specific laboratory facilities [C3]. Colleagues taking up expert roles, e.g. the research ethics committee, receive bespoke training.

We proactively identify and support staff at all career stages in e.g. securing promotion, research fellowships, and prizes [C2]. For major external opportunities (e.g. EPSRC fellowships), and those where an internal selection is required (e.g. RAEng URFs), candidates prepare an expression of interest for the Faculty Research and Innovation Committee. Those who align with the fellowship specification are supported by a series of workshops organized by OD&PL and RIS, and internal peer review; unsuccessful candidates receive feedback and guidance. Colleagues invited to grant/fellowship interviews receive training [C3].

The University participates in national surveys to monitor progress in meeting its research training and development objectives, and we review feedback in appropriate discussions (e.g. School PGR–staff forums) [C1]. Such surveys include the Postgraduate Research Experience Survey (PRES) for research students, the Careers in Research Online Survey (CROS) for research staff, and the Principal Investigators and Research Leaders Survey (PIRLS).

b. The Unit's staffing and recruitment policy with evidence of its effectiveness

Our staffing and recruitment policy is broadly divided into two approaches. The first focusses on supporting, sustaining and developing areas of strength and critical mass, with the second focussing on the development of new, and especially cross-disciplinary, research activity.

The first approach typically concentrates on the recruitment of early-career researchers, including UAF/URFs and new lecturers, and the promotion and development of existing junior colleagues. By embedding them within and alongside existing critical mass activities, we

develop them to become the research leaders of the future and provide sustainability to the activity. As an example, since the inception of our UAF scheme in 2015, 26 UAFs have been recruited into this Unit comprising 11 internal and 15 external appointments: in CIVIL–**Bernal-Lopez**, **Loveridge**, **Trigg**; in CHEM–Bale (in UoA7), **Hondow**, **Mishra**, **Warren**; in ELEC–**Actis**, **Freeman**, **McLaughlan**, **Mazomenos**, **Pensabene**, **Valavanis**, **Zaidi**; in MECH–**Alazmani**, **Brockett**, **Lee**, **Khodaparast**, Mangolini, **Ruprecht**; in ITS–**Rezaei**. **Zhang**(**Z**) is joint between ELEC and MECH; **Collins** is between CHEM and Chemistry; Roelich is between CIVIL and Earth & Environment; Edwards is between MECH and Biomedical Sciences; Morganti is between ITS and Food Science; **Mazomenos** is between ELEC and Medicine. As evidence of the effectiveness of the support and appointment policy, all UAFs passed their first stage probation, and there have been six early promotions to date (before the end of the five-year probation period): Bale, **Brockett**, **Hondow** and Roelich to Associate Professor, and **Bernal-Lopez** to Chair, in Leeds, with **Ruprecht** and Mangolini appointed to Chairs at Hamburg University of Technology and the University of Texas at Austin, respectively. **Valavanis** and Bale subsequently received a UKRI Future Leaders Fellowship and an EPSRC Early Career Fellowship, respectively. Since 2015, this UAF cohort has collectively achieved over £37M of research funding (total consortia value) as PI/Co-I across 83 successful grants, providing further evidence of the effectiveness of our UAF scheme.

The second approach typically concentrates on recruitment of established outstanding researchers and their teams to grow a strategic new area rapidly (including through consolidation of existing activities). As an example, in this period we identified opportunity to develop significant new activity in high-speed rail research, headhunting **Woodward** and his team, and consolidating this with the activities of 14 existing staff across CIVIL, MECH, and ELEC. Further chair appointments including **Li**(**K**) and his team strengthen our expertise in smart energy systems, which complements this vision. The University invested £23M to create the new ten-acre Infrastructure Innovation Park to facilitate new industrial and academic collaborations nationally and internationally for this activity, and is committed to ten new academic appointments (§3(b)).

A rigorous interview process, usually over two-days, is employed for tenure-track appointments, including candidate seminars to ensure transparency [C1,2]. We use research and professional networks to reach out to a diverse set of potential applicants and ensure diverse recruitment panel membership with training in unconscious bias and ED&I.

Since 2014, our FTE increased from 141 to 199 to support the ambitious objectives identified in our REF2014 submissions (§1(a,b)), with investment across all career stages to balance strategic development of new activity with succession planning. 97% of our Category A staff have open-ended (permanent) contracts. A number of Category A staff hold part-time positions, providing flexibility for their personal circumstances.

	Chair	AProf / Reader	Senior Lecturer / Lecturer	UAF / URF
July 2013	66	17	41	28
July 2020	83	53	52	25

We recruit experimental officers and technical staff on permanent contracts, following probation, enabling long-term career paths to be developed. Trainee technicians are trained in analytical, mechanical and electronic skills before moving into Faculty or School laboratories and workshops [C3]. Since 2017, all trainees undertake apprenticeships and are supported to study for qualifications such as the HNC apprenticeship or part time degree. The success of our approach is evidenced by our retention of all but one of the eleven trainee technicians recruited in this REF period.

c. How individuals at the beginning of their research careers are supported and integrated into the Unit

The Schools' Institutes and Research Centres provide a critical mass of staff and shared research infrastructure to support individuals at the start of their research careers, and help them integrate into the research culture [C2]. The Institutes/Centres engender researcher collaboration and provide: a forum for interaction between staff at different career stages; focus and critical mass for sustainability and infrastructure development; seminar series, delivered by national and international speakers, which help staff develop contacts; and, support for grant and fellowship applications including peer review.

Colleagues at the beginning of their careers are helped with reduced teaching and administration duties, and priority for EPSRC DTP and School-funded PGR studentships [C1]. The annual SRDS and AAM meetings identify and agree needs, goals, support and methods to achieve ambitions for all staff, but are particularly valuable to individuals at the start of their careers, as are the probation meetings for PDRAs and those newly recruited [C2]. Early career researchers benefit from the University's training and development opportunities discussed above, which includes targeted support for grant and fellowship applications [C2].

Networks provide opportunities to share experience and best practice, and to have a combined voice; e.g. in MECH, the Early Career Academics Network hosts inspirational senior academics to share experience on career development, and speakers from funding bodies. Early career membership of University research committees is built into their terms of reference.

We develop individual career paths for our PDRAs through regular academic and pastoral meetings with their supervisory team, and via training and development activities [C2,3]. A University international mobility fund allows PDRAs to apply independently to attend conferences and for collaborative visits. Support in applying for, and securing, research fellowships is provided as discussed above, and PDRAs can be named as a researcher co-investigator on grants. PDRAs develop their academic skills, as well as contributing to the Unit, through opportunities to support PhD, MSc and undergraduate projects, and to contribute to research-led teaching through undergraduate and masters demonstrating.

A formal meeting, six months before the end of each PDRA's contract, explores future opportunities, including priority for University positions via redeployment [C2]. Bridging funding enables continuity of contract between research grants.

d. Research and sabbatical leave

School workload models reflect significant research and impact commitments by reduced teaching and administration duties, as well as providing time for personal research and generation of grant applications, tailored to individuals' needs and career stage [C1]. Where possible, Schools concentrate staff teaching timetabling into one term, or on certain weekdays, to free blocks of time for research and impact activity. Schools support research/sabbatical leave, usually up to one semester, and secondments to industry (§2(e)), and financial support for travel and for pump-priming activities can be requested. These arrangements are available for all academic staff with both teaching and research responsibilities with open-ended contracts (full- and part-time) and who have progressed beyond probation. We encourage colleagues, including PDRAs, to apply for external competitive funding for research leave.

e. Procedures to stimulate and facilitate exchanges between academia and business, industry, public and third sector bodies

In addition to many colleagues having previous experience outside academia, we actively recruit directly from outside academia at all career stages [C3], facilitating industry and third sector engagement and translation of industrial practice and needs (e.g. **Bayly**, **Hanson**, **Muller**,

Romano, and **York**). **Evans** formerly at the World Bank, was a consultant with UNICEF, WHO, and WaterAid before joining CIVIL—see ICS-1. We write job descriptions to appeal to, and enable, talented engineers who have followed a non-academic career path to be competitive (e.g. without a PhD). Joint academic and PDRA appointments with overseas institutions (e.g. **Wen** with Beihang University), and with industry (e.g. RSSB and SNCF, **Smith**(**A**)), open opportunities for collaborative work and exchanges.

We encourage and support colleagues to undertake secondments to industry (e.g. **Bourne** to AstraZeneca supported by an RAEng Industrial Fellowship, ICS-5), or government bodies (e.g. **Tate** seconded to Transport for London), and to engage through e.g. non-executive directorships (e.g. **Clarke**, Murphy Group). Some transition to an industrial position, but maintain a part-time role in the Unit (e.g. Bower to Mott MacDonald–ICS-10). Industry staff are seconded (or have visiting positions) to the Faculty: e.g. George (Syngenta) was seconded to CHEM for 50% over 2018–2020.

We also encourage and support colleagues with strong industrial engagement to apply for e.g. RAEng Industrial Research Chairs (e.g. Hunter(I) with Radio Design (ICS-9), **Kapur** with GSK, **Schroeder** with Infineum) and Senior Research Fellowships (**Bourne** with AstraZeneca, **Williams**(**S**) with dePuy). **Schroeder**'s RAEng Chair is also joint with the Diamond Light Source; other joint appointments with major infrastructure facilities include **Mishra** with the Advanced Light Source at Argonne National Laboratory, and **Ramasse** with SuperSTEM at Daresbury.

Many research grants include industrial and public sector partners, and benefit from formal industrial advisory boards, as do our research centres. Visiting Chairs stimulate and facilitate exchanges through participation in School industrial advisory boards, and by speaking in research seminars and research-led undergraduate modules. Competitive funding obtained from e.g. EC Marie Skłodowska-Curie Research and Innovation Staff Exchange (RISE) (**Williams**(**P**), Schiffer, **Aristidou**) / Industry-Academia Partnerships and Pathways (IAPP) (**Jha**) programmes have further supported staff and skills exchange.

f. Recognition and reward for carrying out research and for achieving impact

The University's Recognition Scheme is open throughout the year and includes options for one-off payments to recognise exceptional contribution, including in research and impact [C2]. The annual University Reward Scheme provides the ability to award additional or discretionary salary increments [C2]. The annual AAM meetings reflect on staff progress and achievement, and identify cases for promotion as the principal mechanism for recognising and rewarding research and impact [C2]. These are complemented by the annual SRDS meetings, which identify the support needed by colleagues to achieve their ambitions. In addition to achieving promotion through research excellence alone, the application, translation and impact of research beyond academia are criteria for promotion at all academic levels (e.g. **Forth**'s promotion to chair in this period). 88% of the 85 academic promotion applications in this period were successful.

The University also recognises research and impact excellence through nomination and support of staff for national awards, fellowships, and prizes [C2] (§4(e)).

The support provided to enable staff to achieve impact from their research is described in §1(c) and includes: use of workload models to reflect and enable significant research and impact commitments; support from RIDMs in the Faculty and centrally, as well as from our central commercialization and corporate relationship teams; and, strategic allocation of pump-priming funding for explorative work.

Research students

a. The Unit's approach to doctoral research student recruitment and evidence of studentships from major funding bodies

We recruit PGRs through the relevant Faculty Graduate Offices ensuring that each applicant is addressed in a timely, consistent and fair manner [C1,2]. We advertise PGR positions widely, and host open days and recruitment events. Prospective PGRs are invited to see facilities and discuss aspirations, and candidates are interviewed by prospective supervisors either in person or remotely, following training in e.g. unconscious bias. Successful candidates are supported through registration, with the University International Office helping with visas. Many PGRs are recruited from our undergraduate/MSc base, encouraged by our policy to embed project work in research laboratories and through our provision of competitive summer laboratory placements (School funded, or via e.g. the EPSRC vacation bursary).

Studentships are funded through a variety of mechanisms including: research councils (DTP, CDT programmes, and on ERC grants); international scholarship schemes; EC ITNs; co- or fully-funded by industry; and, self-funded by the candidate/candidate's home government. We have also established School/University funding schemes to support training of the best post-graduates [C2] in core research areas (e.g. underpinning large research grants), areas that we wish to grow, and to support new and early career colleagues.

Exemplars of studentships from major funding bodies include:

- EPSRC/UKRI Centres for Doctoral Training – we are leading on five centres newly awarded in this period comprising a total cohort of around 250 PGRs in: Bioenergy (EP/L014912/1), Complex Particulate Products (EP/L015285/1); Molecules to Product (EP/S022473/1); Water and Waste Infrastructure Systems (EP/S022066/1); and, Tissue Engineering and Regenerative Medicine (EP/L014823/1). We are furthermore partners in Centres led in other Leeds UoAs (e.g. Fluid Dynamics (EP/S022732/1) in UoA11) or other Universities (e.g. Nuclear Energy (EP/S022295/1, EP/S022295/1) and Aerosol Science (EP/S023593/1). We also led on Centres extant in period, but awarded before 2014 in: Low Carbon Future (EP/G036608/1); Molecular-Scale Engineering (EP/J500124/1); and, Tissue Engineering and Regenerative Medicine (EP/F500513/1). We ring-fence EPSRC DTP awards to create strategic internal CDT cohorts e.g. twenty studentships over four years commencing in 2020 to support the Bragg Centre for Materials Research.
- Marie Skłodowska-Curie ITN/EJD/IAPP – 14 centres extant in period (H2020 and FP7) with nine newly awarded (of total consortium value €37M), including co-ordinating programmes in: green tribology and sustainable engineering (GreenTRIBOS); quantum communications (QCall); laser dental surfacing (LUSTRE); and, nano-electrochemistry (SENTINEL).
- International schemes – During this period, we have increased our internal scholarships budget to leverage the number of scholarships provided by overseas Government funding schemes, including CSC in China, CONACyT in Mexico, Brazil, Malaysia, Indonesia, Pakistan, Thailand, Nigeria, Iraq, Libya, Kuwait and Saudi Arabia. Through partnerships with international universities in Asia, South America and Europe, we have established externally funded research training structures that are developing into dual PhD programmes (e.g. with the Federal University of Rio de Janeiro and the University of Sao Paolo, funded by BG Group; CSC funded scholarships with South West Jiatong University; Horizon-2020 funded scholarships with Universities of Ljubljana/Lulea/Coimbra etc).
- Direct Industry and CASE awards – During this period, studentships have been supported by e.g.: Parker Hannifin, Shell, Network Rail, Jaguar Land Rover, Arup, Transport for London, AstraZeneca, GlaxoSmithKline, P&G, Pfizer, Sellafield, Nuclear Decommissioning

Authority, National Nuclear Laboratory, National Physical Laboratory, DePuy Synthes, Radio Design, KeySight Technologies, Thales, and Syngenta.

b. Monitoring and support mechanisms for doctoral research students

Each PGR is assigned at least two supervisors who undertake formal supervision training. Regular supervision meetings review progress, determine goals, and identify/rectify problems. The University's web-based Graduate Record of Achievement and Development system records all interactions between supervisors and students, including supervision meetings and feedback, training, progress reports and assessment, ensuring compliance and standardisation of experience [C1]. The School Postgraduate Tutor meets each PGR annually. The Faculty Graduate Office provides, or signposts, further resources to support PGRs in their personal needs such as financial hardship, wellbeing and mental health [C1].

Every PGR joins a research group/institute within their home School, which integrates them into the research culture and broadens their appreciation of the wider research agenda [C1]. As well as being provided with necessary research and computing equipment, consumables and facility access, funds are available for conference attendance, with additional competitive funding for research visits and conferences. Industry and academic placements are embedded into CDT programmes. PGRs have representation on School and Faculty committees, and opportunity to build teaching expertise through paid undergraduate supervision and demonstrating.

All first year PGRs undertake compulsory training, including discipline-specific courses [C3]. Students agree a personal development plan with their principal supervisor within one month of starting, using a training needs analysis tool based on the UK's Researcher Development Framework. CDT programme training is available to aligned non-CDT PGRs also. The Leeds Doctoral College brings together the central support services, networking, and formal training to enhance each PGR's research and well-being, and leads on activities to celebrate the importance of PGRs to the University. Within the Unit, School-based events such as PGR conferences, often organized by senior PGRs, provide training in presentation skills, as well as opportunities for communication, feedback, and networking.

All PGRs write an outline report/literature review at six months, reviewed by their supervisors, followed by a formal report at the end of their first year, assessed by viva voce examination including an independent examiner, before progression. A further viva including an independent examiner, with a review of the thesis plan and an example/draft publication, takes place at the end of the second year. Training plans and supervision arrangements are reviewed at each stage [C2,3].

We awarded 813 PhD degrees over this period, 79% greater per annum than at REF2014. A number of our PGRs are recognized through international prizes, e.g. the Eric Pas Dissertation Prize (Calastri, 2017), the IEEE Communications Society Competition (Nonde, 2016). 60% of the outputs in this submission have a PGR co-author.

Employment destinations for our PGRs, in addition to academic positions in the UK and internationally, include: AstraZeneca, Johnson and Johnson, DePuy Synthes, Pfizer, Unilever, Sanofi, Jaguar Land Rover, Johnson-Matthey, Ricoh, Tata Steel, British Steel, Infineum, Radio Design, KeySight Technologies, Sky, Google, Hitachi, Teledyne LeCroy, Ericsson, Mott McDonald, Sonova, National Nuclear Laboratory, International Energy Agency, Environmental Agency, National Air Traffic Services, Ernst & Young, BEIS, Department for Transport.

Equality and diversity

Evidence of the Unit's commitment to equality and diversity in the recruitment and support of research staff and students

In 2016, the University of Leeds was the first UK university to achieve a Silver Athena SWAN

award across all of its engineering/computing schools. The Silver Award was retained in 2019, with the Faculty of Environment (ITS) also awarded Silver, building on their previous Bronze award. In 2017, we restructured our Equality and Inclusion (E&I) approach, creating a dedicated project support role and allocated workload allowances, to use our Athena SWAN success as a catalyst to develop a sustained agenda addressing all protected characteristics.

Recruitment actions, including compulsory E&I training, active monitoring of shortlist diversity, and gender balance on panels [C1,2], ensure that our recruitment is unbiased and special circumstances are considered (e.g. career break, disability). This led to an increase in female staff from 17% in 2014 to over 22% in 2020 across the Unit. Revision to job adverts and online material, including our online 'Footsteps' initiative showcasing inspirational colleagues from under-represented groups and at different career stages, have had a positive impact on diversity; surveys captured for our Athena SWAN 2019 submission show unbiased recruitment and positive interview experiences.

We played a key role in revising the University promotions scheme in 2016, providing clearer routes to senior roles through teaching and leadership achievements, and explicitly including outreach, E&I, and mentoring/support activities. Promotion workshops include role models from diverse backgrounds, who also provide mentoring and peer support. Of the 85 academic promotion applications in this period, the success rate for female and male applicants was comparable (89% and 88%, respectively).

Flexible working policies support staff with caring responsibilities or ill health. Further support, including for those returning from leave (maternity/parental, illness), includes financial support to attend conferences/training courses, priority for PhD studentships, access to a wellbeing room (including facilities for medication and baby feeding) and reduced teaching workload [C1].

Our approaches have had significant influence on wider University strategy, including direct input to policies (e.g. promotion, shared leave) and expansion of initiatives developed within the Unit. These include: our Career Architect scheme (**Fisher**) to support PGR career development into academia and industry, which is now adopted across the University; the Women at Leeds Network (**Noakes**) expanded from STEM to cover all Faculties in 2016; and, Wellness programmes to support mental health through exercise, developed by Engineering HR colleagues. The Women Rising programme (funded initially by EPSRC, now by the Faculty) was created to support female PGRs; all 17 from the first cohort remained in academia (indeed over 30% of our PGRs are female, above the national benchmark).

Staff support groups focussing on protected characteristics offer opportunities for networking and peer support, and our Breaking Boundaries in STEM events (e.g. our annual LGBT+ Research Day, Ada Lovelace Day, Black History Month, UK Disability History Month) provide vehicles to promote, and discuss, issues affecting these groups and include role models from academia and industry.

We play a major role in the EPSRC 'Northern Power Inclusion Matters' project to support researchers from underrepresented groups, and provide mentoring and leadership development. Our joint activities with industry (e.g. 'Building Equality' and Leeds LGBT+ Pride, both with Arup, and outreach activities with Northern Rail) challenge societal perceptions of diversity in engineering and provide role models. We target underrepresented groups in outreach with our partner schools and colleges, and are expanding our geographical reach through digital activities and resources.

The preparation of this submission has been undertaken in accordance with the University's REF2021 Code of Practice. All individuals involved in the REF2021 decision making process undertook tailored E&I training [C1]. Periodic equality impact assessments were undertaken to ensure due regard to equality considerations. These have, and will, allow us to: understand the

representation of the eligible and submitted staff against our academic staff profile; understand how the selection of outputs represents the diversity of the eligible and submitted staff community; and, identify where further progress on diversity considerations is needed to strengthen delivery of the Unit's and University's research and innovation strategy.

3. Income, infrastructure and facilities

a. The Unit's research funding and strategies for generating research income

The Unit secures research income from a wide range of funders including AHRC, MRC, BBSRC, NERC, EPSRC, ESRC, EC/ERC, Wellcome Trust, NIHR, Innovate UK, NGOs, and industry. A selection of major/prestigious grants awarded by external bodies on a competitive basis includes:

- EPSRC Programme, Platform and Grand Challenge Grants – 13 extant in period, with nine newly awarded (of total consortia value £46M) in: terahertz instrumentation (EP/P021859/1); infrastructure robotics (EP/S016813/1, EP/N010523/1); surgical robotics (EP/R045291/1); tribology (EP/R001766/1); advanced manufacturing (EP/P027687/1), crystallisation (EP/R018820/1); 6G LiFi (EP/S016570/1); and, tissue engineering (EP/P001076/1). We also received a £2.5M EPSRC Prosperity Partnership on corrosion and tribology with BP (EP/R00496X/1).
- GCRF Grants – seven awarded in period from EPSRC, NERC, BBSRC, ESRC, and the Royal Society (of total consortia value £31M) including in: bioenergy and fertilisers (BB/S011439/1); food resilience (BB/P027784/1); sustainable microgrids and energy harvesting (EP/R030243/1); ultra-low-cost endoscopy for gastric cancer screening (EP/P027938/1); advanced glasses (RS IC170195); and, resilience to water variability (NE/P016146/1), as well as the Water Security and Sustainable Development Hub (ES/S008179/1). We also received an AHRC Newton award on sustainable conservation in Jordan (AH/S011609/1).
- EC FP7 Collaborative Projects, H2020 Research & Innovation Actions/Innovation Actions – 20 awarded in period (of total consortia value €210M). Major programmes include €46M L3Pilot (Project 723051, coordinated by Volkswagen AG) on automated driving, and €26.5M AUTOPILOT (Project 731993, coordinated by ERTICO) to investigate IoT-connected driving. FET-Open awards include: optoelectronic devices based on Bose-Einstein condensation (Project 737017) and generation of ultrashort terahertz pulses (Project 665158).
- ERC – seven projects awarded in period of total value €14M: Advanced Grants to **Neville** and **Romano**; Consolidator Grants to **Hess**, **Valdastri**, and **Wen**; and, Proof-of-Concept Grants THEMIS (Project 727541) on terahertz imaging and APOLLO (Project 875692) on choice model estimation. These complement four further Advanced Grants and one Starting Grant extant in period. EC Marie Skłodowska-Curie programmes are discussed in §2.
- Large centres awarded and led in period include: £3.5M Medical Technologies IKC (EP/N00941X/1); £4.5M National Centre for Infrastructure Materials (EP/P017169/1); £7.2M EPSRC National Research Facility for Advanced Electron Microscopy (SuperSTEM Daresbury, NS/A000057/1); £5.7M EPSRC Centre for Innovative Manufacturing in Medical Devices (EP/K029592/1); and, £3.1M Point-of-Care Diagnosis for Reduction of Antibiotic Misuse (MR/N029976/1).
- Innovate UK – 23 KTPs awarded in period (of total value £4.2M) including with: Procter & Gamble, British Glass Manufacturers Confederation, Industrial Tomography Systems, Ilke Homes, Ardent Ltd, Sandvik Limited, DePuy International, and Produmax. A further

six Innovate UK awards were made, including Digital Design in the Pharmaceutical Sector of consortium value £20M (Project 14060).

- Fellowships awarded in period include: EPSRC (**Bell**, **Bernal-Lopez**, **Colombo**, **Fuentes**, **Loveridge**, **McLaughlin**, **Markkula**); UKRI Future Leaders (**Choudhury**, **Valavanis**); RAEng (Chair: Hunter(I), **Kapur**, **Neville**, **Schroeder**; Senior Research Fellow: **Bourne**, **Williams**(**S**); Industrial: **Kim**); and, Leverhulme Trust (**Charpentier**, **Dawson**).

Our grant portfolio has supported the high-quality research output and impact described in §1; over 4,400 outputs have been published in primary archival international refereed journals by researchers in this Unit during this REF period.

Our strategy for generating research income is underpinned by our approach to staff recruitment and development. We hire outstanding early-career researchers, including UAFs and new lecturers, to support, sustain and develop areas of strength and critical mass, and we recruit excellent established researchers and their teams to grow strategic new areas of research rapidly (for examples, see §2(b)). Opportunities to increase and embed cross-disciplinary research, and the funding opportunities that this creates, are enabled through e.g. joint appointments (§1(d)), and through the development of, and investment in, interdisciplinary research centres (§3(b)).

The University Research and Innovation Service (RIS) and the specialized research and innovation development managers (RIDMs) horizon scan UK and international funding opportunities, and facilitate workshops to develop large research proposals, and convene consortia with e.g. industry and public sector organizations. Our industry collaborations provide direct research income as well as supporting grant proposals with both direct and in-kind support, and alignment with end-user needs. We work with, and are members of, national research institutes, research council and other funding body committees, and professional organizations (§4(e)), providing leadership to help define and direct national funding priorities, and provide visibility for our strengths and infrastructure.

Researchers are supported by RIS, the Organisational Development and Professional Learning (OD&PL) unit, and their home Schools in preparing successful grant applications through e.g. peer review of draft proposals, mock interviews for large grants, matched equipment funding and PGR studentship contributions to grants, and pump-priming funding. University and Faculty finance, contracts and EU Grant offices support consortium agreements, audits, and financial reporting. Researchers (especially ECRs) applying for externally-funded fellowships receive a bespoke programme of support and mentoring throughout their application (§2(a,c)).

b. Organisational infrastructure supporting the Unit's research and impact, and areas where there has been significant investment

Organizational mechanisms to support research and impact include our leadership of, and participation in, University interdisciplinary centres that span School and Faculty boundaries and which present critical mass to national and international partners. They enable new collaborations to be established, support large interdisciplinary grant applications, and consolidate and enhance experimental facilities, providing a platform to increase research funding, quality, outputs and impact.

We highlight two such Centres initiated in this period that have received significant investment, followed by four examples of further centres/clusters that illustrate the breadth of our interdisciplinary organization and research. In all cases, the Centres are facilitated by the appointment of a Director with workload buy-out, dedicated RIDM support, and funding for events/seminars/publicity and pump-priming research activity.

The Bragg Centre for Materials Research

The Bragg Centre for Materials Research (Director: **Linfield**) was inaugurated in January 2019 and comprises over 200 researchers from all Schools in the Faculty of Engineering & Physical Sciences, and from the Faculties of Biology, Medicine & Health, and Environment. The creation of £20M 2,300 m^2 of shared and future-proofed laboratories in the new Sir William Henry Bragg Building opens opportunities for new ways of working, collaboration and interdisciplinary thinking. £10M investment in equipment and specialist facilities has already been secured (EP/P022464/1), together with funding (EP/R00661X/1, EP/S019367/1, EP/R02524X/1) to enable promotion of, and access to, our materials facilities by UK academia and industry. Further University investment includes three UAFs (including **Collins** between CHEM and Chemistry), an internal CDT of 20 interdisciplinary studentships, and funding for events/seminars/pump-priming research. The Centre complements our leadership of research activities in SuperSTEM at Daresbury, the Diamond Light Source at Harwell, the ISIS neutron facility, and the CMAC EPSRC Future Manufacturing Hub, and houses the Leeds activity of the UK's Henry Royce Institute, in which we are a founding partner and leading the 'Atoms-to-Devices' theme with Imperial College London.

Institute of High-Speed Rail and System Integration

The University has invested £23M in a new ten-acre **Infrastructure Innovation Park** ten miles from the Leeds city centre, completing the site purchase in April 2019. This will house our new Institute of High-Speed Rail and System Integration (IHSRSI) (Director: **Woodward**, together with 14 existing staff and 10 planned appointments) providing substantial new research opportunity across the University and the Leeds City Region, and to facilitate industrial and academic collaborations nationally and internationally. For example, it will support a step-change in ELEC's energy, electrical power systems, power electronics and sensing/control systems activities, building on the track record of the new Smart Energy Systems Chair (**Li**(**K**)), as well as extending ITS's capabilities in automated signal controls and simulation (**Liu**) and passenger comfort (**Romano**). Phase 1 of the IHSRSI will comprise two substantial components, an Infrastructure Testing Facility and a Vehicle Testing Facility, with an estimated value of £39M. Phase 2 will support an £11M Systems Integration and Innovation Centre. Before being temporarily paused by the Covid-19 disruption, Phase 1 was due to be completed in Spring 2021 with a £13M contribution from the West Yorkshire Combined Authority. Phase 2 was due to be completed by Spring 2022 funded by UK-RPIF with £29M in industry matched funding, demonstrating significant industry interest to use the facilities for R&D, consultancy and testing, as well as further research into systems integration and passenger experience.

The Infrastructure Innovation Park will also host our new National Centre for Infrastructure Materials (CIM), which builds on CIVIL's £4.5M UKCRIC/EPSRC capital award (**Black**, EP/P017169/1) as well as a further £12M University investment, providing state-of-the-art structural materials degradation and characterization facilities. It will also rehouse elements of our £4.3M EPSRC National Facility for Innovative Robotic Systems.

Examples of other centres that illustrate the breadth of our interdisciplinary organization and research include, but are not limited to:

- **Leeds Institute for Fluid Dynamics** (Co-Director **Noakes**) established in 2018 brings together over 200 researchers across twelve academic departments to provide interdisciplinary perspectives to complex flow challenges. LIFD leads the EPSRC CDT in Fluid Dynamics (EP/S022732/1, renewed 2019), has strong partnerships with industry (e.g. Sellafield Ltd, Dupont Teijin Films, Parker Hannifin, Shell, MPI, BAE Systems) and the public-sector (Met Office, PHE, NHS, NCAS), and over 50% of papers include an international collaborator, from over 85 countries.

- The University's **Robotics@Leeds** network (Director: **Valdastri**) was formed in 2017 and brings together over 100 researchers across nine academic departments focussing on: field robotics (for infrastructure and exploration); medical robotics (assistive, rehabilitation, and surgical); artificial intelligence for robotics (learning, perception and manipulation); and, underpinning science and technology (communications, sensing, and manufacture). The Centre benefits from unique manufacturing and laboratory capabilities (e.g. our £4.3M EPSRC National Facility for Innovative Robotic Systems) consolidating equipment and personnel, and will open new facilities in both the Sir William Henry Bragg Building and the Infrastructure Innovation Park in the next period.
- There is a remarkable breadth and depth of health technology research and innovation across the Unit, with close collaboration with the Faculties of Biology, Medicine & Health, the Leeds Teaching Hospitals NHS Trust, industry and national and international collaborators. The **Healthcare Technologies Innovation Centre** brings together over 140 academics and 50 clinicians to develop new healthcare technologies to improve patient well-being. The academic leadership group includes **Wälti** (ELEC) and **Wilcox** (MECH).
- **Energy at Leeds** (Directors: **Cockerill**, Taylor in UoA7) comprises over 200 researchers with interdisciplinary expertise in whole energy systems in bioenergy, nuclear science and engineering, upstream oil and gas, transport energy systems, energy demand and efficiency, and low carbon transitions. A dedicated £12M Energy Building houses bespoke laboratories. We have close relationships with industry and government including Arup, Alstom, Drax, Northern Gas Networks, and Leeds City Council. We are a partner in e.g. the UK Energy Research Centre, and are supported by two EPSRC CDTs (EP/L015390/1, EP/S022295/1).

c. Operational and scholarly infrastructure supporting the Unit's research and impact

The Unit hosts significant experimental infrastructure; a selection of our particularly unique and large (TRAC-funded) facilities is given here.

- Our dedicated £2M Medical & Biological Engineering Building houses the world's largest academic facility for joint replacement research. The facility includes over £5M of experimental simulation equipment in >500 m^2 class 2 cleanroom laboratories, a dedicated imaging & metrology facility and retrievals laboratory, and an imaging suite with two microCT scanners. A dedicated laboratory for the processing and storage of orthopaedic retrievals supports development of pre-clinical simulation capabilitites.
- Our £6M state-of-the-art class 100 Nanotechnology Cleanroom comprises a full suite of equipment for optical lithography, and hosts the £3M JEOL 6300-FS EPSRC Regional Facility for electron-beam lithography. The cleanroom also provides hands-on training for PGRs and undergraduate research projects.
- Leeds Electron Microscopy & Spectroscopy Centre (LEMAS) with an equipment base of ~£10M has an international track-record with, per annum, >400 users from ~30 Leeds institutes, ~32 UK universities, and ~20 companies. As an EPSRC-funded facility (since 2008), eligible UK researchers enjoy pump-priming access, feeding into national infrastructure (e.g. SuperSTEM). Investment in this period includes new £2M Royce-funded Versatile X-ray Spectroscopy Facility. LEMAS, together with the cleanroom, will move into the Sir William Henry Bragg Building in 2021 and both will be expanded.
- The Dowson Tribology Laboratory consolidates surface analytical techniques to study the complexities of surface processes in corrosion, tribology and flow assurance research. The facility has been expanded by 400 m^2 in this period, with a £1.1M upgrade to the PVD coating system (EP/R02524X/1). Our capability to handle complex

corrosive gases under extreme conditions is unique in the UK.

- The £5M Terahertz Photonics Laboratory comprises nine optical bench systems for femtosecond pulsed, and quantum cascade laser, terahertz imaging and spectroscopy. It hosts the EPSRC national high-field terahertz facility. The facility is supported by eight cryostats including a 12 T cryogen-free dilution refrigerator, and a £2M MBE facility comprising two growth systems for opto-electronic III-V semiconductor device growth. A 1.1 THz network analyzer complements our associated microwave laboratories.
- Our £4.5M EPSRC National Facility for Innovative Robotics Systems (EP/P017169/1) provides over £1M robotics facilities, over ten large autonomous aerial drones, two large mobile ground robots, 3D printers, and precision water/laser jet cutters. During this REF period, we have invested in a dedicated 140 m^2 state-of-the-art Hybrid Manufacturing Processes research laboratory.
- 'Virtuocity' is a unique, immersive, human-in-the-loop simulation and visualization facility for city simulation and co-design, powered by academic models and industry software. It comprises three simulation laboratories (Driving Simulator, Truck SIM, and the Highly Immersive Kinematic Experimental Research (HIKER) laboratory), which can be connected for participants to interact in a single multi-'player' environment. The new £650k pedestrian laboratory (EP/R008833/1) enables interactions between pedestrians and drivers to be tested safely, including exploring automated vehicle design, warning system design, and intersection configuration.
- Our public health laboratories include facilities for the analysis of water and waste, and a class II microbiology lab and a clean laboratory for molecular biology work, including for the characterization of microbial populations in environmental samples. Bioaerosol sampling equipment is available for both laboratory- and site-based studies, including a class II aerobiology chamber for room-scale bioaerosol experiments.

Throughout the REF period, the University has invested heavily in High Performance Computing, in accordance with a longstanding strategy of biennial hardware upgrades (most recently £2M in 2019) and maintaining a specialist support team. Since 2019 this has been supplemented through recruitment of a new Research Software Engineering team (including Leng in the School of Computing who received an EPSRC RSE Fellowship (EP/R025819/1)). Together these support research throughout this Unit, including fluid dynamics, materials modelling and image analysis. We benefit from partnership with national supercomputing centres: e.g. NICE and JADE2, which received significant investment in 2020.

These, and our other, facilities are supported by experimental officers and technical staff with permanent contracts enabling long-term career paths to be developed. As part of the Sir William Henry Bragg Building, the University is investing in a new £2M electrical and mechanical workshop, providing state-of-the-art infrastructure and development opportunity for technical staff.

d. How the Unit supports equality and diversity in acquiring research funding and accessing research infrastructure

All researchers are supported in preparing successful grant applications through: local mentoring within Schools and research groups, and our diversity networks; School and Faculty peer review and mock interviews; and, grant writing workshops (typically 40% female attendees). We actively encourage fellowship applications through open calls and directly approaching staff, including those who may not actively put themselves forward. Analysis presented in our 2019 Silver Athena SWAN award illustrates the positive impact of this support on women who were associated with 24% of the total value of funding in Engineering

(compared to <20% eligible), and were more likely to be Principal Investigator.

We enable flexible working to support staff with caring responsibilities or ill health, including working from home, to enable research grant preparation *inter alia*. We support those returning from a significant period of leave (maternity/parental, illness), and for those with caring responsibilities, via financial support and a reduced teaching workload to visit collaborators or attend conferences/workshops, as well as funding for an accompanying partner, and through priority for PhD studentships to help pump-prime research proposals.

Alongside the measures detailed in §2, we support individuals with particular needs through the University's occupational health and disability services, and drawing on e.g. the government's 'Access to Work' scheme, including adapting offices, provision of specialist lab furniture, provision of specialist computing equipment and extra assistance (e.g. support to a visually impaired colleague through provision of a 0.6 FTE teaching and research assistant).

e. How the Unit uses its infrastructure, facilities and expertise in relation to impact activities

Infrastructure: The University's innovation hub 'Nexus' consolidates, coordinates and expands our previous commercialization and corporate relationship teams. Nexus colleagues have enabled new research collaborations, helped embed industrial laboratories on campus (e.g. Jiuli Group with MECH), and importantly used their critical mass and expertise to drive major new impact opportunities, e.g. securing the significant local and national investment for the Institute of High-Speed Rail and System Integration (§3(b)). Nexus provides incubator laboratories/space e.g. the Connected Places Catapult have taken space to work closely with ITS. Furthermore, specialized RIDMs in the Faculty, and centrally in Nexus, work with researchers to find/build strategic stakeholder partnerships, and undertake early development of exploitation (§1(c)).

Facilities: Researchers and PGRs use our TRAC-funded experimental facilities in collaborative research with industry. External users benefit from the infrastructure through contract research, accessing the facilities themselves or having work performed by our technical staff. For example, the materials characterisation facilities in CHEM (including the Leeds Electron Microscopy & Spectroscopy Centre, and the Versatile X-ray Spectroscopy Facility), are routinely used to facilitate industrial impact with large (e.g. AstraZeneca, GSK, Syngenta, P&G, Unilever, Pfizer, Infineum, Thales) and small companies (e.g. Keighley Labs, Burgoynes). As a further example, MECH hosts the world's largest independent academic facility for the pre-clinical wear simulation testing of artificial joint replacements to verify and validate evidence, support regulatory approval (FDA and CE marking), and fulfil the requirements for industry-recognised methods and standards. Recent industry collaborators using these ISO 9001 accredited facilities include Mathys, Corin, DePuy, and JRI.

Expertise: Researchers' expertise underpins impact through pursuing research informed by end-user requirements; large research grants, CDTs, and ITNs include industrial partners to direct and facilitate research impact. Secondment of staff between academia and industry, public and third sector bodies, and consultancy are important mechanisms to facilitate impact, as is our engagement with industrial, technical and regulatory bodies to develop standards and influence future directions (§2(e), §4(e)). Colleagues exploit their expertise with industry and with major infrastructure facilities through e.g. industrial Research Chairs and industrial Research Fellowships (§2(e)). We develop impact through policy advice to government (e.g. **Noakes** is a member of the SAGE Covid-19 committee and Convenor/Chair of the Environmental and Modelling SAGE sub-group, **Tate** provided oral evidence to the Commons Select Committee on diesel emissions, and **Evans** is chair of DFID Sanitation and Hygiene Research Consortium Advisory Group, and member of the UN WHO/UNICEF Joint Monitoring Programme Strategic Advisory Group). Expert witness activities include: **Anable** in 'dieselgate',

Brydson advising in High Court patent disputes between GSK and Vectura, and between Coloplast and Salts, and **Fisher** in High Court defence of DePuy Pinnacle Ultimet Products.

f. Specialist research infrastructure: the Unit's engagement with major research facilities

A selection of our specialist research infrastructure was presented in §3(b,c), and our large collaborative research projects such as Programme Grants naturally involve cross-HEI use of such research infrastructure. Here we outline examples of national research facility use and collaboration in the UK and overseas.

Daresbury Laboratories: **Brydson** and **Ramasse** lead the EPSRC National Facility for Advanced Electron Microscopy (SuperSTEM), founded in 2002, supported by >£25M and currently involving a consortium of six UK Universities. This internationally leading instrumentation attracts both UK and major international users. The national facility is underpinned by University LEMAS facilities, where £3.5M of EPSRC awards over the period have established low-dose analytical cryo-TEM, cryo-FIB, and 3D confocal light microscopy for soft matter characterisation.

Diamond Light Source: Our Leeds-Diamond Collaboration centred on the soft X-ray beamline B07, is augmented by a joint Royal Academy of Engineering Bragg Centenary Chair in Synchrotron Science (**Schroeder** co-funded by RAEng, Diamond and Infineum), laboratory space in the Harwell Research Complex, and also a new Leeds EPSRC £1.2M (EP/R042683/1) SAXS/WAXS facility sited at Harwell. In addition to major Diamond usage across this Unit (including **Barker**, **Bell**, **Black**, **Milne**, **Morina**, **Neville**, **Roberts**, and **Wälti**), **Mishra** has a joint Leeds-DoE position at the Advanced Photon Source at Argonne National Lab in USA, and **Schroeder** is on the ESRF Strategic Advisory Committee.

Rutherford Appleton Laboratory: On-going collaborative projects include e.g. development of satellite-borne instrumentation based on terahertz frequency quantum cascade lasers for astronomic and atmospheric gas sensing (**Davies**, **Linfield**, **Valavanis**), in conjunction with STFC RAL Space, UK and European Space Agencies, and the Centre for Earth Observation Instrumentation and Space Technology. In addition, collaborative programmes with the **National Physical Laboratory** are establishing standards for microwave/terahertz frequency waveguides and feedhorns (**Cunningham**), and high frequency measurement of 2D and topological materials and devices.

We host a number of national facilities for the benefit of external users, including e.g. the EPSRC National Facility for Innovative Robotics Systems, the National Centre for Infrastructure Materials, and SuperSTEM Daresbury (above).

g. Significance of major benefits in-kind

The majority of our research programmes and grants are collaborative with, or supported by, industrial and other end-users of our research, providing not only direct research income and PGR sponsorship, but also in-kind support. This can include access to bespoke facilities and proprietary samples, opportunities for PGR placements and supervision, and staff secondments. Two examples of major **equipment donations** in this period include:

- A state-of-the-art £1M *da Vinci* surgical robotic system was donated by Intuitive to ELEC (**Valdastri**) to enable world-leading research in the field of robotic minimally invasive surgery. We are working to automate repetitive parts of surgical procedures enabling the surgeon to focus on the most delicate steps. Robotic automation in surgery will also enable improved and more reliable outcomes, thus enhancing the patient experience and reducing the NHS costs. This is the only *da Vinci* robot available in an academic anatomy laboratory, with access to human cadavers for experimentation, in the world.

- Our 'Virtuocity' city simulation and visualization facility (**Romano**) has received multiple in-kind contributions from industry (totalling £725k) including: access to Arup's simulation models; the 'Omnideck' virtual reality pedestrian deck from the Transport Systems Catapult; truck and car cabs, and monitoring equipment, from Volvo, Jaguar Land Rover and Seeing Machines; and, other in-kind contributions from Nexteer, Belron, Highways England, and Aimsun. Our transport research also benefits from UK and EU partner collaborations with donations of vehicles (ECODRIVER), a Daimler truck, a BMW car, three Fiat Group vehicles, and research vehicles from CTAG, IKA and IFSTTAR.

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

a. The support for, and effectiveness of, the Unit's research collaborations and indicators of their success

We lead numerous national and international research collaborations, networks and partnerships (§3). These are supported financially and operationally through: investigator workload buy-out; matched funding for, and direct purchase of, equipment; laboratory refurbishment; and, dedicated University Academic Fellow (UAF) positions and PGR studentships. Local, and central, university research and development managers (RIDMs) support programme reporting, consortia organization, and help develop sustainability through e.g. identifying further industrial and academic collaboration. Faculty funding to support development and sustainability of collaborations, and for membership of networks (e.g. ERTICO – European intelligent transport systems) and professional/standards bodies (e.g. RILEM – construction materials, systems, and structures) facilitate research and connect with industry. University and Faculty finance, contracts and EU Grant offices support consortium agreements, audits, and financial reporting, and communications and marketing teams disseminate research to press and other media outlets, and via social media.

We give three examples to show how such support has underpinned the growth, effectiveness, and sustainability of collaborations, networks and partnerships in this period:

- Building on long-term international industrial research collaborations (e.g. Infineum UK, Total France, Komatsu Japan, SKF Netherlands), the **Institute of Functional Surfaces** in MECH (**Bryant**, **Morina**, **Neville**, **Wilson**) established the EPSRC Integrated Tribology CDT (EP/L01629X/1, with Sheffield) in 2014, co-funded by industry and the School. This developed the research base leading to multidisciplinary/multisectoral partnerships supported by Programme and Prosperity Partnerships Grants (EP/R001766/1; EP/R00496X/1), industry (e.g. BP, Parker Hannifin, Schlumberger) and **Neville**'s ERC Advanced Grant (INTELLICORR), and by 2017 had significantly strengthened the fundamental understanding of surface degradation and its consequence in a wide range of applications. Recruitment of four new School lecturers in 2018/2019 (**Ghanbarzadeh**, **Kosarieh**, **Pessu**, **Yang**(**L**)) expanded the research scope and developed new collaborations (e.g. EP/T024542/1 with the School of Design and TMD-Friction Gmbh in 2020). This increased critical mass led to new collaborations with e.g. Caltech, Max Planck Institute for Intelligent Systems, and Ljubljana, supported by an EPSRC Centre-to-Centre award (EP/S030476/1), and a Marie Curie ITN 'GreenTRIBOS' to explore tribology as an enabling technology in energy harvesting, advanced manufacturing, and green tribology.
- Critical mass **nuclear engineering research** into fuel recycling, reactors and decommissioning centred in CHEM (**Fairweather**, **Hanson**, **Harbottle**, **Hunter**(**T**)) has developed over 20 years, supported by a full-time technology manager and administrator. Award of the Sellafield Ltd Sludge Centre of Expertise (2011–2022) led, in this period, to: partnership in two multi-University CDTs in 2014 and 2019

(EP/L015390/1, EP/S022295/1); School investment (£500k) in a Nuclear Laboratory suite with active handling capability (2015); and, new collaborations on cements and modular reactors with CIVIL and ultrasonic monitoring with ELEC. This contributed to the formation of the Energy Leeds network (Directors: **Cockerill**, Taylor (UoA7) supported by dedicated RIDM and administrator investment), and the Leeds Institute for Fluid Dynamics and associated CDT (EP/S022732/1). This has further enabled £25M of collaborative projects (EPSRC/EU/BEIS/Industry) with five UK Universities including Manchester and Imperial College (e.g. EP/S011935/1, EP/P013600/1, EP/L018616/1). Beyond the UK nuclear industry, this support has enabled funded projects with ten international institutions (e.g. BARC and IGCAR (India), CEA (France), KAIST (South Korea)).

- Long-standing support for **terahertz electronics and photonics research** in ELEC (**Davies**, **Linfield**, **Cunningham, Dean**), including >£5M internal funding for MBE growth, cleanroom fabrication and photonics infrastructure (§3(c)), enabled a number of EPSRC and EU awards, including a Programme Grant (EP/J017671/1, 2012–2017). This led, in this period, to further University support including two UAF positions (**Valavanis**, **Freeman**), underpinning: a further Programme Grant (EP/P021859/1) with Cambridge, UCL and Lancaster; a Career Acceleration Fellowship (EP/P007449/1, Burnett, in UoA8); establishment of the EPSRC national high-field terahertz facility (via EP/P001394/1); many international collaborations (e.g. Ecole Normale Supérieure, Queensland, and Nanyang Technological University) including two H2020 FET Open awards (737017, 665158); and, leadership of the UK 'TERANET' Network (EP/M00306X/1). The Network is now self-sustaining, attracting over 90 delegates annually representing 25 Universities, and it published the international terahertz roadmap in 2017 informing, *inter alia*, the EPSRC balancing capability exercise.

b. How the Unit's staff have developed relationships with research users to develop impact, and how this has enriched the research environment

Our ICSs explain how we developed relationships with research users and beneficiaries, and §1(c) and §2(e) describe, respectively, how we have sought to enable research impact and how we have stimulated and facilitate exchanges with industry, public sector, and end-user bodies. Here, we give further examples of how impact has been developed in three contrasting areas of the Unit, and how this has enriched the environment by creating new research directions, providing opportunities for new staff appointment and development, and in CDT/PGR research and training.

- The **Institute for Medical and Biological Engineering** (**Fisher**, **Wilcox**, **Williams**(**S**)) advances medical technologies by reducing technical, regulatory and commercial uncertainty, enabling downstream development of new medical devices by industry. In this period, we have collaborated with 202 user organisations of which 55 were industrial collaborators (e.g. via our second-phase Innovation Knowledge Centre (EP/N00941X/1), Catalyst-funded TRANSLATE programme, and the Grow MedTech Programme). Since 2014, 78 collaborative proof-of-concept projects have been supported, with 23 progressing beyond TRL-4 to receive over £50M downstream investment by industrial partners (e.g. DePuySynthes, Invibio, NHS Blood & Transplant, NHS Leeds Teaching Hospital Trust). In turn this has broadened the research base, leading to large new initiatives (e.g. the Tissue Engineering CDT EP/L014823/1; and EP/N02480X/1, EP/R003971/1), and we have recruited two UAFs (**Brockett**, Edwards) and a lecturer (**Herbert**). In 2019, we led the BEIS-commissioned Leeds City Region Science and Innovation Audit to guide the investment of £250M in the Leeds City Region's medical technology sector to strengthen the region's position as a global leader in health (**Fisher**).

- The **Institute for Process Research and Development** in CHEM and MECH (**Bayly**, Blacker in UoA8, **Bourne**, **Ghadiri**, **Kapur**, **Muller**, **Mullis**, **Roberts**, **Schroeder**) translates new reactor platforms, optimization methods, analytical capabilities and digital design, delivering Industry 4.0 approaches to chemical manufacturing. Our CDT in Complex Particulate Products (EP/L015285/1, 2014–2022) is supported by £1.1M investment from >20 multi-nationals/SMEs, with these partnerships underpinning further funding through three EPSRC Manufacturing hubs (EP/N007638/1, EP/P006566/1, EP/P006965/1) with a total of seventy industrial partners, and an EU public-private partnership association (SPIRE). It also enabled us to establish an advanced in-line process research group co-located at Harwell, award of industry-sponsored RAEng Chairs/Fellowships (§2(e), §3(a)), and a further CDT in 2019 (EP/S022473/1). This expertise allowed establishment of a £20M BEIS-funded Government/industry/academia collaboration (ADDOPT) to explore digital design in pharmaceuticals, and direct industrial funding including PGRs/PDRAs to deliver digital technology platforms at major UK pharmaceutical manufacturing sites e.g. Pfizer, Dr Reddy's, AstraZeneca, GSK (**Bourne**, ICS-5).
- The **Institute for Transport Studies** engages with **transport policy stakeholders** and industry to develop impact from research. Based on research into road cost benchmarking (**Wheat**), we established the Cost Quality and Customer (CQC) Efficiency Network in 2015, funded via subscription from 92 local government members, which enabled local authorities to progress new road investment strategies and obtain >£150M additional funding to improve road condition (CQC annual report, 2018). In rail, we were central in the 'Schedule 8' performance regime used by the Office of Rail and Road (**Batley**) to determine financial flow between Network Rail and Train Operating Companies (TOCs). Our research led to the industry 'Passenger Demand Forecasting Handbook' updates versions 5 and 6, and underpinned Schedule 8 compensation payments from Network Rail to the TOCs of £106M in 2015/16 alone. Partnerships with SNCF and RSSB provided two 50% joint funded PDRA posts (**Smith**(**A**)) on methodological and empirical advances in transport economics research to address key policy challenges. The emission performances of new (Euro 6/VI) cars, trucks and buses were evaluated as part of a secondment to Transport for London (**Tate**), leading to advice around low emission zones.

c. The Unit's wider contributions to the economy and society, not captured in the impact case studies

Our ICSs provide examples of our contributions to the health and wellbeing of people and society, commerce and the economy, and the environment. Here we provide three topical examples of our wider contribution, focussing on supporting standards, guidance and policy.

- We led the Wired Core and Access Networks (WCAN) working group of GreenTouch (2010–2015), which comprised 50 industrial and academic members aiming to **improve network energy efficiency** 1,000-fold. **Elmirghani** proposed five of the six core network energy efficiency improvement measures identified by GreenTouch, including the use of mixed line rates, energy efficient network virtualisation, energy efficient content distribution and energy efficient routing. These were recommended to all equipment vendors (e.g. Nokia, Huawei) and operators (e.g. France Telecom, Swiss Com, China Mobile, AT&T), and are being incorporated into industrial roadmaps. The methods developed are now being incorporated into IEEE standards, including P1925.1, P1926.1, P1927.1, P1928.1, and P1929.1.
- **Tate** was one of three experts invited to give oral evidence to the Commons Select Committee 'Vehicle Type Approval – evidence session' on 14 December 2015, owing to

his research in **real world emissions** (NO_x from diesel). A change to taxation policy was then recommended in a DEFRA-commissioned rapid evidence review of air quality actions in 2016 (Appendix 1 to project summary for contract AQ0959); we proposed the diesel car tax increase, and wrote the company car section. Following evidence by **Tate** to parliament, an increase in vehicle excise duty on diesel cars was applied in the Autumn budget 2017 along with a 1% increase on the diesel car 'Benefit-in-Kind' tax. Since 2017, diesel car sales have fallen from 50% to 30% market share. In conjunction with the West Yorkshire Combined Authority, and Transport for the North (formed in 2018), we supported bids including the successful DfT Transforming Cities Fund award (£317M) announced for the Leeds City Region in March 2019, which incorporates ideas around mass rapid transit, connected and autonomous vehicles, and use of 5G infrastructure to manage traffic better.

- **Locatelli**'s partnership with BEIS and the Department of Energy and Climate Change on the economics and financing of **small modular reactors** (SMRs) resulted in two co-authored policy reports, supported the 2018 parliamentary briefing on SMRs, and led to consultation on a 'Regulated Asset Base' (RAB) model for new nuclear projects (BEIS: July 2019); the RAB model has potential to reduce the cost of raising private finance for new nuclear projects, thereby reducing consumer bills and maximising value for money for consumers and taxpayers. The IAEA standard on Nuclear Energy Co-Generation recommends **Locatelli**'s approach for assessing technical and economic feasibility.

d. Evidence of the Unit's contribution to the sustainability of the discipline, interdisciplinary research, and responsiveness to national and international priorities and initiatives

Our breadth of research leadership, including in areas of significant societal relevance and benefit (e.g. in sanitation and waste in developing countries), enables us not only to respond to, but also importantly, influence national and international priorities and funding opportunities, contributing to the development and sustainability of the discipline. Four such examples are given here and sit within the context of wider frameworks such as the UN Sustainable Development Goals and HMG Industrial Strategy. Our approach to supporting interdisciplinary research is described in §1(d).

- **Velis**' systems-based tools to **quantify and manage solid waste** have been applied to 50 cities, and defined global strategy through authorship of the UN-Environment 'Global Waste Management Outlook 2016' and membership of the UN-Environment/UN-Habitat Joint Expert Group on Solid Waste Sustainable Development Group (SDG); SDG11.6.1 is directly supported by our 'Waste Flow Diagram' project funded by the German Development Agency GIZ GmbH. In addition to her substantial global impacts on faecal sludge monitoring (ICS-1), **Evans** leads **global sanitation** strategy as chair of DFID SHARE Sanitation and Hygiene Research Consortium Advisory Group, and as member of the UN WHO/UNICEF Joint Monitoring Programme Strategic Advisory Group, the GCRF Strategic Advisory Board, and the RAEng International Committee.
- Interdisciplinary collaboration between CIVIL (**Purnell, Camargo-Valero, Velis, Stewart**(**D**)), CHEM (**Williams**(**P**)**, Gale, Jha, Andrews, Tomlin, Dupont**), Leeds Business School, Mathematics, and Geography, with multiple national, industry and government partners has influenced the **national circular economy** strategy including around decarbonisation in complex infrastructure systems (NE/L014149/1), decarbonising foundation industries (UK CREDS EP/R035288/1, BEIS Glass Futures Industry consortium), developing the Hydrogen Economy (BEIS Hy4Heat projects, £9M Ofgem H21-LeedsCity Gate Project), and resource recovery from alkaline and mineral wastes. Work on phosphorus recovery from waste waters and reuse in food production

(BB/K011677/1, BB/N016033/1) led to collaborations with SMEs (Carbogen and Link2Energy) for pilot-scale testing. **Purnell**'s coordination of the £7M NERC Resource Recovery from Waste programme enabled integration across a national portfolio of projects, direct engagement with Defra, BEIS and the Treasury, and underpinned the £30M UKRI circular economy programme in 2020.

- Through our leadership of the Henry Royce Institute 'Atoms-to-Devices' core area (**Linfield**), over 220 representatives from academia and industry developed roadmaps identifying the necessary UK investments and interventions to meet the UK Government's net-zero emission targets for 2050 on topics ranging from materials for photovoltaic systems and low-loss electronics, to the low-carbon production of hydrogen.
- Our response to the COVID-19 pandemic has been wide ranging. **Noakes** (CIVIL) provided expert advice on SARS-CoV-2 virus transmission, underpinning all UK public policy guidance through her membership of the SAGE Covid-19 committee and directly to multiple government departments, including Number 10 (ICS-8). **Kapur** and **Culmer** (MECH) optimised continuous positive airway pressure ventilators, with more efficient oxygen utilisation, which were used by the Leeds NHS Trust in the first wave (ICS-4). On-going new and repurposed activity includes: development of fast COVID-19 antibody tests, through adaption of electronic biosensor assays (**Wälti**, ELEC); development of autonomous robotic systems for city infrastructure disinfection (**Purnell**, CIVIL, ELEC, MECH, ITS); and, development of ultrasound for detection of lung pathologies in COVID-19 patients with Leeds NHS Trust (**McLaughlin**, ELEC).

e. Indicators of wider influence, contributions to, and recognition by the research base

Bower, **Neville**, and **Noakes** each received an OBE for services to engineering, complementing the OBE and CBE previously awarded to **Martin** and **Fisher**, respectively. We have 16 National Academy Fellows: 13 FREng (seven new in period: **Basheer**, **Bell**, **Davies**, **Ghadiri**, Hunter(I), **Roberts**, Wilkins), two FRS (one new: **Neville**), and one FMedSci. These complement our EPSRC/UKRI, ERC, Leverhulme, and RAEng research fellowships (§3(a)).

Major prizes include: IoP Faraday Medal and Prize (**Davies**, **Linfield**, 2014); IOM^3 Verulam Medal and Prize (**Bell**, 2014); EPSRC RISE Fellow (**Neville**, 2014); IEEE Outstanding Service Award (**Elmirghani**, 2015); MRC Suffrage Science Award (**Neville**, 2015; **Wilcox**, 2015); Japanese Ferroelectrics International Award (**Bell**, 2015); Royal Society Wolfson Research Merit Award (**Linfield**, 2015; **Valdastri**, 2016); Queen Elizabeth Prize (**Neville**, 2016); Edison Award (**Elmirghani**, 2016); Royal Society Leverhulme Medal (**Neville**, 2016); IMechE James Clayton Prize (**Neville**, 2016); IMechE Donald Julius Groen Prize (**Morina**, 2016); IWA International Development Research Award (**Evans**, 2017); Kona Award from Hosokawa Foundation (**Ghadiri**, 2018); ICorr U R Evans Award (**Neville**, 2018); Tribology Silver Medal (**Neville**, 2019); RSC Industry-Academia Collaboration Award (**Fairweather**, 2020); RMS Mid-career Achievement Award (**Ramasse**, 2020); Fellow IAAM (**Basheer**, 2020); Fellow IEEE (**Bell**, **Elmirghani**, 2020); IEEE Outstanding Technical Achievement Award (**Elmirghani**, 2020); IOM^3 Rosenhain Medal and Prize (**Bernal-Lopez**, 2020); IOM^3 Chapman Medal (**Fisher**, 2020); RAEng President's Special Awards for Pandemic Service (**Noakes**, 2020).

Prestigious research paper prizes include: British Geotechnical Association Medal (**Yu**, 2015); IET Electronics Letters Premium Award (**Davies**, **Dean**, **Freeman**, **Linfield**, **Valavanis**, 2015); IMechE Thomas Hawksley Gold Medal (**Bryant**, **Neville**, 2018); ICE James Watt Medal (**Locatelli**, 2018); EMS Outstanding Paper Award (**Ramasse**, 2019); and, the ICE Parkman Medal (**Smith**(**N**), 2019).

We influence policy and help develop the national research agenda through membership of research council, national academy, and professional body committees. Examples include:

EPSRC Council (**Fisher**); EPSRC Strategic Advisory Teams (Hoyle, **McKay**, **Martin**, **Wilcox**); UK Government SAGE (**Noakes**); UKRI-GCRF Strategic Advisory Group (**Evans**); RAEng Trustee Board (**Martin**); RAEng Policy Committee (**Fisher**); Royal Microscopical Society (**Brown**, **Brydson**); European Microscopy Society Executive Board (**Brydson**); IoP Electron Microscopy and Analysis Group (**Brown**–chair); IMechE Tribology Group (**Morina**–chair); IOM^3 Materials Chemistry Committee (**Scott**); British Orthopaedic Research Society Executive Committee (**Brockett**); and, IChemE Energy Centre Board (**Hanson**).

Our membership of industry/regulatory bodies and technical committees supports the discipline through e.g. the development of international engineering standards. Examples include: ISO TC150/SC4 bone and joint replacements standards committee (**Jennings**–chair); ISO 14242-4 pre-clinical assessment of total hip prostheses (**Fisher**, **Jennings**); ISO TC22/SC39/WG8 driver ergonomics (**Merat**); ISO TC281 fine bubble technology committee (**McLaughlan**); ISO wear simulation of total ankle replacement (**Brockett**–UK lead); BSI TPR/001 committee (**McKay**); BSI standards sub-committee CH150/4 'Bone & Joint Replacements' (**Brockett**, **Jennings**–chair); IEEE UFFC Society Ferroelectrics Committee (**Bell**); IEEE Standards Association Green ICT Standards Committee (**Elmirghani**–chair); IEEE Comsoc Energy Efficient ICT Standards Working Group (**Elmirghani**–chair); IEEE Sustainable ICT Initiative (**Elmirghani**–co-chair); many RILEM technical committees (**Basheer**, **Bernal-Lopez**, **Garcia-Taengua**, **Sarhosis**); and, Air Quality Expert Group / Defra (**Tomlin**).

We contribute to the global engineering community through participation in, and organization of, national/international conferences, symposia and workshops. Major meetings organized and chaired include: European Microwave Week (**Robertson**–General Technical Programme Committee Chair, 2016); European Microwave Conference (Hunter(I), 2016); International Quantum Cascade Lasers School and Workshop (**Davies**, **Linfield**, 2016); and, the Leeds-Lyon Symposium on Tribology (**Bryant**, **Morina**, **Neville**, **Wilson**, 2014, 2016, 2018).

In addition to the many invited and contributed conference talks, a selection of our keynote presentations include: 10th International Conference on Chemical Kinetics (Chicago 2017, **Tomlin**); 17th Driving Simulation Conference (France 2018, **Merat**); 6th International Conference on Electric Vehicular Technology (Indonesia 2019, **Shepherd**); and, 18th European Conference on Surface and Interface Analysis (Germany 2019, **Schroeder**).

We support the vitality and integrity of our leading journals through membership of editorial boards and by refereeing manuscripts. Contributions as Editor-in-Chief include: Advances in Aerodynamics (**Wen**); Advances in Cement Research (**Black**); Journal of the Energy Institute (**Williams**(**P**)); Choice Modelling (**Hess**); Geomechanics and Geoengineering (**Wu**); Proceedings of the Combustion Institute (**Tomlin**); IEEE Ultrasonics, Ferroelectrics and Frequency Control (**Freear**); Cognition, Technology and Work (**Carsten**); Transportmetrica B – Transport Dynamics (**Watling**); Tribology – Materials, Surfaces & Interfaces (**Neville**).

Similarly, we support the vitality and integrity of UK/international research funding through grant peer-review, and through panel and EPSRC College membership. Examples of Panel Chairs include: EPSRC CDT (**Brydson**, **McKay**); IRC in Healthcare Technologies (**Fisher**); EPSRC Programme Grant (**Purnell**); EPSRC ICT Fellowships (**Elmirghani**); EPSRC Innovation Fellowships (**Anable**); EPSRC Global Challenges Research Fund (**Anable**); UKRI Future Leaders Fellowships (**Martin**); EPSRC Synchrotron X-ray Materials Characterisation National Research Facility Interview Panel (**Martin**); EPSRC Strategic Equipment Panel (**Schroeder**).

Our PGRs are supported and trained by a wide range of formal national and international schemes, including eight newly awarded EPSRC/UKRI Centres for Doctoral Training, and six new Marie Skłodowska-Curie ITN/EJD programmes, as detailed in §2. These programmes all include substantial co-operation and collaboration with partner universities, industry, and NGOs, enriching our research environment and the PGR experience. Leadership of other formal PGR

training collaborations include: EPSRC Dial-a-Molecule Summer School (**Bourne**, 2018, 2019); Annual Royal Microscopical Society Summer School in Electron Microscopy (**Brydson**, 2013–2020); and, SuperSTEM Summer School (**Ramasse**, 2015, 2017).