Institution: The University of Manchester
Unit of Assessment: 12 (Engineering)
1. Context and mission

1a. Overview

Engineering in the University of Manchester (UoM) has made significant improvements since REF2014. We have created integrated Schools of Engineering and of Natural Sciences, established the Henry Royce Institute (Royce), and developed strong interdisciplinary themes guiding our research. The vitality of the Unit is evidenced by the following highlights from the REF period:

- Selected to lead Royce and host the Royce Hub Building (5,618 m^2, £215m total), based on our strength in advanced materials research.
- £552m investment in state-of-the-art infrastructure including a new single-site Manchester Engineering Campus Development, MECD (18,940 m^2 research laboratories, £425m), the National Graphene Institute, NGI (7,500 m^2, £62m), Graphene Engineering and Innovation Centre, GEIC (3,058 m^2, £50m), and refurbished materials laboratories (2,000 m^2, ~£15m).
- Appointment of **Withers** as inaugural Regius Professor of Materials and Chief Scientist of Royce.
- Tyndall-Manchester's Local Carbon Budget Tool used by 250 local authorities, approved for inclusion in the UN Race to Zero initiative (REF2021 Impact Case Study, ICS).
- EPSRC award of £12.2m for Robotics and Artificial Intelligence for Nuclear, which led to 10 deployments of robots into active facilities, four subsystems bought to market, and two spin-out companies.
- Award of £8.0m in Prosperity Partnerships and £16.7m in programme grants
- Award of RAEng Chair in Emerging Technologies to **Lennox** and four RAEng Research Chairs with companies: **Prangnell** with Airbus, **Kinloch** with Morgan Advanced Materials, **Connelly** with EDF, and **Xiao** with Rolls-Royce.
- Host of EPSRC Supergen Bio-energy Hub, and then host to co-directors of three Supergen Hubs (2018-22): Bio-energy, Offshore Renewable Energy, and Energy Systems; £4m EPSRC investment into National Grid High Voltage Laboratory.
- GCRF FutureDAMS award with **Harou** as Research Director of £8.2m consortium, supporting an ICS in system-scale design for hydropower systems around the world.
- Lead of the Energy and Water-Energy Science themes for phase 1 and phase 2 of the UK Catalysis Hub; **Hardacre** Director of the Hub.
- 15 new spin-out companies.
- Queen's Award for Enterprise (Innovation Category, 2016) to Mettler Toledo Safeline for metal detection technology led by **Peyton**; Institute of Physics Business Innovation award (2020) to Advanced Hall Sensors for magnetic sensor commercialization with **Missous**.
- Election of **Hinduja**, **Lennox**, **O'Brien**, and **Soutis** as Fellows of the Royal Academy of Engineering (FREng, 16 in place within period) and **Withers** as Fellow of the Royal Society (FRS, seven in place within period); award of a CBE to **O'Brien** and MBEs to **Azapagic** and **George**; Royal Society Wolfson Research Merit Award to **Kiss**; and >45 institutional and learned-society medals to staff.
- 2014 Royal Institution Christmas Lectures by **George**.
- Total £385m research income; average annual income 69% greater than in REF2014.
- Total 1,460 PGRs completed; average annual number of doctorates awarded 7% greater than in REF2014.

1b. Unit structure

Research is framed by Faculty, Schools, and Departments, with Institutes cutting across these structures to facilitate interdisciplinary research objectives. At the start of the REF period, the Faculty of Science and Engineering (FSE) comprised nine separate Schools. To advance our strategic aims, especially interdisciplinary collaboration, we restructured the Faculty in 2018 by creating a School of Engineering and a School of Natural Sciences, with nine constituent Departments. As a result, School leadership and budgets span disciplines, allowing research areas to be prioritized and research quality and impact to be increased.

The submitted Unit is drawn from the two new Schools with its 326 academic staff from one of four Departments: Chemical Engineering and Analytical Sciences (CEAS), Electrical and Electronic Engineering (EEE), and Mechanical, Aerospace and Civil Engineering (MACE), all in the School of Engineering, and the Department of Materials (MATS) in the School of Natural Sciences.

The School Heads of Research (SHoR) provide strategic research leadership and work with Departmental Heads of Research (DHoR), to enable and monitor progress through Departmental Research Committees. The SHoRs, DHoRs, and Research Institute Directors belong to the Faculty Research Strategy Group, which facilitates communication and debate on research, encourages interdisciplinary activities, and oversees Faculty research strategies.

The four Departments of the Unit provide local support, guidance, and operational implementation of strategic objectives. Each research group in each Department has a critical mass of researchers working within one or more of the five overarching themes described in §1c.3. Group leadership is usually established by consensus, not seniority, to allow flexibility and opportunity for early career researcher development.

The Faculty's Research College, which spans the two Schools, was created during the Faculty restructure to promote the FSE research agenda, including postgraduate research (PGR) and infrastructure, and share best practice on grant submissions, outputs, and impact.

The University's interdisciplinary Research Institutes provide further support for collaborative research (§1f.1, REF5a §2.iii).

1c. Research within REF period

1c.1 Overview

This submission combines five Engineering units returned in REF2014. The alignment of the submitted research plans laid the foundations for subsequent developments. A recurring theme was the importance of interdisciplinary research and the opportunities available with the two new Schools, the Royce Hub building, and MECD.

The REF2014 plans identified five generic goals, reviewed in the sections cited:

- Appoint strategically to underpin excellence and encourage interdisciplinary research (§2a).
- Invest in building internationally excellent doctoral training programmes (§2b).
- Diversify sources of funding, particularly from industry and international sources (§3a).
- Invest in physical infrastructure and facilities, forming platforms of excellence (§3b).
- Cultivate new strategic collaborations with industry and internationally (§4a).

The REF2014 plans also shared an ambition to exploit emerging themes in advanced materials and processes, bioengineering, energy, environment, and integrated systems. These themes were nurtured over period and shape this submission (§1c.3).

1c.2 Research excellence

The Unit's achievements in this REF period included marked improvements in research income and citations; recognition by national academies; and honours and awards. Over the period, the average research income per FTE increased by 47%, including three Prosperity Partnerships. Staff published 7,178 journal articles, of which 1,516 (21%) were in the Scopus top 10% field-weighted percentile, including 7 *Science*, 10 *Nature*, and 52 *Nature*-family papers. The average number of doctorates awarded per year was 209, with a 5-year completion rate of 79% for 2014 entries. The Unit had 22 Fellows of national academies with 16 FREng and 7 FRS, including 5 new Fellows, two staff awarded MBEs, and one a CBE (§4b).

1c.3 Interdisciplinary Research Themes

Figure 1 shows the development of the Unit's five interdisciplinary Research Themes. Details are given in the following sections with achievements of specific REF2014 plans indicated and 'ICS' referring to a submitted REF2021 Impact Case Study (see §1e, Figure 2).

Advanced Materials and Processes

This theme focused on the understanding and control of materials from their atomic structure to macroscale properties, novel manufacturing routes, and applications. It is supported by collaborations enabled by Royce, characterization facilities, and investments in UoM's Research Institutes and Centres (§1f.1), namely the BP International Centre for Advanced Materials (bp-ICAM), National Graphene Institute (NGI), Graphene and Engineering and Innovation Centre (GEIC), Thomas Ashton Institute (TAI), Manchester Environment Research Institute (MERI), Manchester Institute of Biotechnology (MIB), Photon Science Institute (PSI), and Tyndall Manchester. Highlights included metallurgy activity ranked top in Europe in the Academic Ranking of World Universities (ARWU, 2018), five spin-outs from 2D-materials activity (§3b.1), two Prosperity Partnerships (§3a.3), and 47 Clarivate ESI^{SM} Highly Cited Papers.

2D Materials. Exploiting opportunities with the NGI and GEIC (REF2014), we made significant progress in characterization, production, composites, electrochemistry, photonics, membranes, and sensors, leading to eight *Science/Nature* papers. Funding sources were broadened with £8.6m (to Unit) from Government and charities, ERC Fellowships (e.g. MATTERDESIGN, £1m), ERC Grants (Graphene Flagship, UoM £7.8m), and EPSRC, along with £5.8m industrial funding from BP, Petronas, YKK, and others. Our work on sporting goods with Inov8 has reached the market (G-Grip™, §4a.4). The NoWNANO Centre for Doctoral Training (CDT) has prepared the next generation of 2D materials scientists (REF2014) with a new approach to enterprise supported by the competitive Eli and Britt Harari Enterprise Award (£70k/year) for founding 2D-related spin-outs, with three in the Unit (e.g. Nanoplexus).

Advanced Manufacturing. We consolidated and built on innovative manufacture research (REF2014) in additive production of multiple-material components, micro/nano fabrication, and digital and sustainable manufacture. An illustrative outcome is the first 3D printing with multiple metallic and functionally graded metallic/non-metallic materials. **Hinduja** was elected FREng in recognition of his work on tooling technology for SMEs.

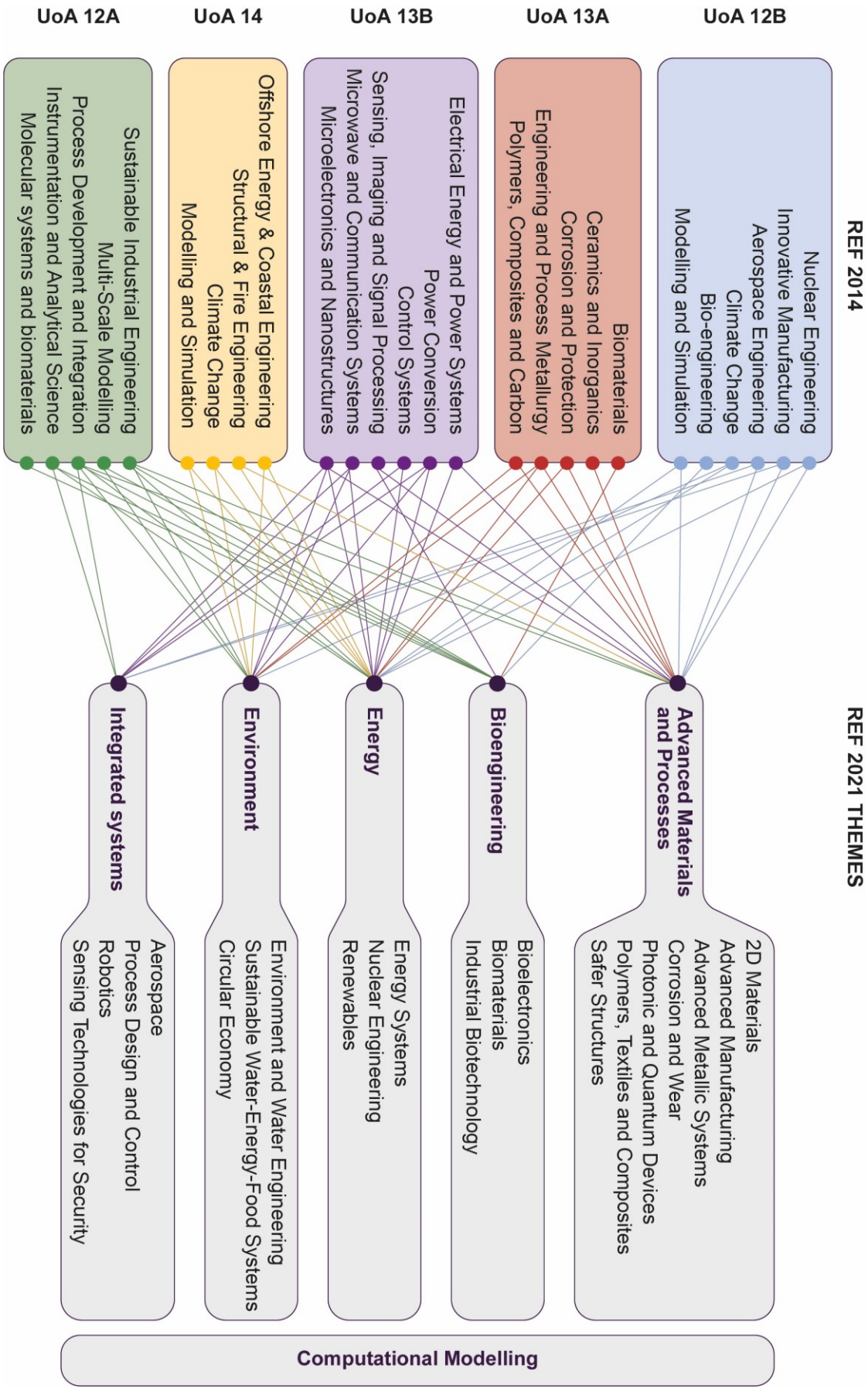

Figure 1. Main developments of REF2014 research into Unit's overarching Themes.

Advanced Metallic Systems. We developed industry interactions (REF2014) with an Airbus RAEng chair and the LightForm programme grant (£4.8m, 16 industrial collaborators). The Advanced Metallics CDT (with Sheffield) was renewed with a direct industrial contribution for every PhD student (REF2014). By the end of period, the metallurgy research portfolio was £14m with three Institute of Materials, Minerals and Mining (IOM3) awards.

Corrosion and Wear. We strengthened existing alliances (REF2014), e.g. with AkzoNobel, which led to a Prosperity Partnership (SuSCoRD, £5m) awarded with Sheffield (§3a.3) and the AkzoNobel Chair (£0.7m in period) being extended. The Materials for Demanding Environments (M4DE) CDT, begun in 2014, seeded a Core Research Theme of Royce. Close collaboration with Rolls-Royce led to an ICS on barrier coatings (**Xiao**) and award of an RAEng Chair with £3.1m industrial funding.

Photonic and Quantum Devices. Cross-disciplinary research and improving physical infrastructure (REF2014) were realized though investment and integration with the PSI (§3b.1). Since 2014 we have secured a >£18m portfolio of UKRI-funded research central to Royce's Atoms to Devices theme. Collaboration with UK SME Ionoptika produced the commercial Q-One tool for quantum technology.

Polymers, Textiles, and Composites. Supporting the research environment (REF2014), UoM invested ~£2m in new polymer chemistry laboratories underpinning research in other areas on anti-corrosion coatings, polymer recycling, and medical devices. Industrial collaborators included Airbus, SAFRAN, Collins Aerospace, GE Dowty, Sigmatex, DSTL, and Teijin. The composites activities led work in 3D Weaving (US 2015/0107715A1) and robotic multiaxial fibre placement (ICS **Potluri**). **Young** won the Institute of Materials, Mining and Metallurgy (IOM3) Platinum Medal.

Safer Structures. Structural and fire engineering research was expanded (REF2014) aided by new research facilities (UKCRIC National Centre for Infrastructure Materials - Extreme Loading Facilities, EPSRC, £3m), with new industrial impacts (influencing Eurocodes for fire resistance, 3 EN 1993-1-2 and 4 EN 1994-1-2), and broadening research scope to include resilient supply chains for construction materials.

Bioengineering

Collaborations between life sciences, biology, materials science, and engineering research delivered new manufacturing routes and healthcare technologies, enabled through MIB, Royce, and MERI (§1f.1). Highlights included a polymeric peripheral nerve guide conduit that successfully passed phase 1 clinical trials, spin-out Manchester BIOGEL, and an RAEng Enterprise Fellowship that helped found biosurfactants spin-out Holiferm, which attracted £1m investment from a Dutch venture capital firm.

Bioelectronics. We capitalized on increasing interest in bioelectronics by applying our expertise in sensing and biomaterials to address smart wearables, flexible tattoos, sensor innovation in healthcare and agriculture, and regenerative medicine. Illustrative outputs in the Scopus top 2% field-weighted percentiles are https://doi.org/10.1016/j.actbio.2014.02.015 and https://doi.org/10.1039/C7TC03669H.

Biomaterials. Investing in research excellence in biomaterials (REF2014) resulted in two ESPRC Fellowships (£1.2m and £2.3m), one of which licensed IP to BIOGEL, and a £1.6m grant in injectable microgels. Other outcomes include the EPSRC Advanced Biomedical Materials CDT with Sheffield and national leadership of Royce's Biomaterials theme (**Cartmell**) and Philip Leverhulme Prize (**Miller**). Building on an institutional healthcare

strategy (REF2014), UoM is a hub partner in the EPSRC UK Regenerative Medicine Platform and partner in Health Innovation Manchester.

Industrial Biotechnology. Funding was attracted by the Centre for Synthetic Biology of Fine and Speciality Chemicals (BBSRC, £10.2m) and Future Bio-manufacturing Research Hub (EPSRC £8.7m). **Dickson** co-founded the UK Network in Bioprocessing BioProNET2 (BBSRC/EPSRC £1.8m, 10 UK industrial groups) and was awarded the UK BioIndustry Association 2017 Peter Dunnill Lifetime Achievement Award.

Energy

This theme addressed energy generation (nuclear and offshore renewables) and storage, conversion, distribution, resilience, and demand. Highlights included £10m EPSRC funding on nuclear research, an international standard on transformer liquids adopted by National Grid (NG), an ESRC award for the Centre for Climate Change and Social Transformation (CAST) tackling energy demand, and investment in the High Voltage Test laboratory and the Rolls-Royce University Technology Centre (UTC).

Energy Systems. Addressing EPSRC's focus on Whole Energy Systems, a portfolio of Tyndall Manchester projects (£2.7m) enabled a systems perspective (ICS **McLachlan**), expanding the Energy Theme to include £1.3m of EPSRC funding on transport energy systems (ICS **Larkin**) and £1.4m on social change including the CAST centre. **Panteli** led a national resilience assessment with NG. We integrated expertise and EPSRC capital funding in power systems, energy conversion, sensors, control systems, and communications (§3b.1). Our research on reduced use of fossil-oil insulating transformer liquid and advances in high-voltage cable systems led to two ICSs (**Z. Wang**, **Rowland**) and a 2015 IET Innovation Award (Built Environment Category). Our digital technologies research enabled Scottish Power Energy Networks to achieve savings of £0.9m in six new digital substation bays. Our aim to increase international collaborations (REF2014) led to joint appointments with the University of Melbourne, work with the University of Chile and Chilean electricity coordinator, and partnerships with universities in Zambia (§4a.1).

Nuclear Engineering. Nuclear engineering research was consolidated and extended (REF2014). Our expert advisory partnership was renewed with the Office for Nuclear Regulation (ONR) in 2018 (£4m over period) and our Modelling and Simulation Centre expanded from founding partner EDF to include the National Nuclear Laboratory (NNL) and Jacobs Group. We led or contributed to several multi-partner collaborations including EPSRC MIDAS (£3.8m) and PACIFIC (§3a.2), EPSRC CDTs Next Generation Nuclear (2015-24) and Guaranteeing Reliable Economic Energy from Nuclear (GREEN, 2019-28), five Department for Business, Energy & Industrial Strategy (BEIS) Nuclear Programme projects (£3.7m). A novel treatment of irradiated nuclear graphite has attracted initial investment (£300k) from SME MARAD to develop this technology towards process-scale implementation.

Renewables. We expanded research on sustainable and low-carbon energy systems (REF2014). Having hosted the EPSRC Supergen Bio-energy Hub, we then hosted as co-directors three Supergen Hubs (2018-22): Bio-energy, Energy Systems, and Offshore Renewable Energy. Research in offshore energy was consolidated (REF2014) by adding elements of offshore wind to marine and wind research. The programme grant HOME-Offshore (£1.8m, §3a.2) advanced remote inspection and asset management for offshore wind farms in partnership with other institutions and the ORE Catapult. An earlier project, STEP-WEC (2012-16), led to international collaborations including a CONACyT fellowship 2017-18 and agreements for offshore wave-device demonstrators in Australia and China. UoM

academics have been integral in establishing the UK Catalysis Hub. **Hardacre** led the energy theme in phase 1 and the water-energy theme in phase 2 of the Hub as well as the UK Catalysis Conference. He is the UK Catalysis Hub Director.

Environment

This theme brought engineering approaches to environmental preservation (atmosphere, water, land) and sustainable food chains. It is supported by MERI (§1f.1) and Tyndall Manchester (§1f.1), which expanded its energy focus during the period with £2.7m in non-capital grants on land and food systems. Highlights included the GCRF FutureDAMS award (£2m to Unit), collaborating with UoM social scientists in the Global Development Institute, £1.4m EPSRC Tyndall grant on the Water-Energy-Food Nexus, and a spin-out agri-sensors business Fotenix.

Environment and Water Engineering. Our commitment to water engineering (REF2014) for economic, social, and environmental benefit was advanced with the FutureDAMS project, which led to three NERC projects (£0.6m), **Harou**'s ICS, and reinforced international collaborations and EU ties (e.g. visiting Professorship at Jülich Research Centre).

Sustainable Water-Energy-Food Systems. Tyndall Manchester's expanded portfolio addressed interconnections between water, energy, and food with techno-economic assessments (ICS **Welfle**), a £1.4m Water-Energy-Food EPSRC Sandpit (£0.3m in Unit), **Hoolohan**'s Presidential Fellowship, and the co-direction of the £5.7m EPSRC-funded UK Centre in Sustainable Energy Use in Food Chains (2013-19). Over £17m on food-system-related funding was secured in period with Tesco, the Norwegian Research Council, EC, and UKRI. In Electronic Engineering in Agriculture (e-Agri) we developed e-devices for reducing waste, increasing yields and energy efficiency, and improving nutrition, attracting £2.9m of UKRI funding.

Circular Economy. We have combined diverse groups across UoM to tackle the challenge of securing a more sustainable future. For example, the Rethinking Resources and Recycling (RE3) collaboration (UKRI £0.8m) brings groups together to seek solutions to plastics pollution through an integrated approach. RE3 laid the foundation for the Sustainable Materials Innovation Hub (ERDF, Royce £10m) in the Royce Hub Building. In another major initiative, the EPSRC LightForm project worked on alloys for closed-loop recycling (see Advanced Metallic Systems earlier).

Integrated Systems

This theme addressed the intersection of electronics, communications, and mechanical and control systems to deliver integrated engineering solutions. Highlights included land-mine detection with the charity Find a Better Way, an RAEng Emerging Technology Chair, the first-ever aircraft manoeuvred in flight using supersonically blown air ('MAGMA' drone with BAE), and two ESI^{SM} Highly Cited Papers.

Aerospace. We strengthened and accelerated aerospace research (REF2014) with new appointments (§2a.1) and funding including a £2m Horizon 2020 award for technologies enabling satellite operation in very low Earth orbits, and sustained BAE support for unmanned-autonomous-vehicles research.

Process Design and Control. We developed techniques for digital manufacturing and Industry 4.0 (REF2014) centred on the Pilot Plant facility (§3b.1). Industrial collaborators included Unilever, BP, Astra Zeneca, Johnson Matthey, AWE, Sellafield/NNL. Our advances in process integration found widespread industrial usage and led to an ICS (**Jobson**). Our work

on energy-management systems was recognized by the 2019 Energy and Buildings Best Paper Award.

Robotics. Our research in technologies needing minimum human intervention (REF2014) delivered robot applications for the nuclear industry, facilitated by UoM's purpose-built off-site laboratory in Cumbria (REEL Lab, §3b.1). Major funding included capital investment of £4.1m for the ISCF RAIN Hub (§3a.2), £4.1m programme grant, and an RAEng Chair in Emerging Technologies (£2.7m), with other academic appointments (§2a.1). Outcomes included strategic relationships with Sellafield Ltd and NNL, the deployment of robots on site (§4a.2), and **Lennox** elected FREng.

Sensing Technologies, Communications, and Signal Processing. Our commitment to advancing electromagnetic modelling in new sensing and signal-processing areas led to applications in steel production and reactor-core inspection. Major funding included £3.5m from the land-mine-detection charity Find a Better Way and £0.8m through the EPSRC Centre in Non-Destructive Evaluation. Our collaborator Rapiscan Systems has applied our research with walk-through scanners for detecting and classifying metal objects.

Computational Modelling

This cross-cutting theme focused on engineering modelling underpinning other activities. To expand our research in smoothed particle hydrodynamics, SPH (REF2014), we appointed new lecturers (§2a.1) and extended SPH activity, achieving acceleration by massive parallelization and first steps with novel quantum computing. We made multiple releases of the jointly developed open-source SPH code DualSPHysics (https://dual.sphysics.org/), with subreleases approaching 10,000 downloads and growing adoption in motorsport, wastewater treatment, and nuclear waste management, aided by four industry-sponsored PhDs. This research led to three international prizes, seven keynote lectures, a Leverhulme/RAEng Fellowship, Leverhulme and EPSRC funding (£1.2m at period end), and papers in the Scopus top 1% field-weighted percentile (https://doi.org/10.1080/00221686.2015.1119209 and https://doi.org/10.1016/j.cpc.2014.10.004).

In other areas, we built fully parallelized GPU-based pore-network simulators and lattice Boltzmann simulators for porous materials applications (REF2014), including two-phase flow, reactive transport, and electrokinetics. This work led to influential publications (e.g. in *Nature*, *Scientific Reports*, and *PNAS*), invited presentations to industry (e.g. BP, Bosch, Pall, Ballard, Equinor) and conference presentations (Gordon Research Conference 2016, InterPore Conferences 2017, 2019), and research collaborations with Cornell, Princeton, and Stuttgart Universities.

1d. Research aims and objectives over next five years

Our overarching aims are these:

1. To nurture a diverse and inclusive generation of outstanding engineers to maintain our world-leading expertise and develop core capabilities that address new engineering challenges and underpin our long-term competitiveness.
2. To strengthen our contribution to internationally agreed targets on clean water, air, and soil and help the transition to clean-energy systems by applying engineering solutions in partnership with colleagues across the sciences and humanities.
3. To capitalize on major investments in the current period including MECD, Royce, and high-performance computing by expanding interdisciplinary research and its enabling infrastructure.
4. To widen impact by cultivating long-term strategic relationships with regional, national, and global engineering stakeholders.

Objectives for our thematic areas follow:

Advanced Materials and Processes

We will exploit our investment in advanced materials (including in Royce, NGI, and PSI) and improve pathways from fundamental research to full-scale applications.

- We will create multidisciplinary teams from engineering to economics to produce new materials for a sustainable future, drawing on Tyndall Manchester and MERI. We will achieve increased lifetimes with e.g. corrosion control, greener precursors, more energy-efficient processing, easier recycling, and less environmental damage.
- We will take a multidisciplinary approach to complex, engineering challenges, such as the transition to a hydrogen economy, by better understanding metal embrittlement, catalysts, and transport in nanoporous materials.
- We will expand our involvement in computational platforms. We will make greater use of machine learning, expert systems, and data mining to optimize materials performance and endurance limits. We will coordinate processing and applications across whole life cycles, exemplified by closed-loop use of light alloys.
- We aim with regional government to deliver on the Greater Manchester Local Industrial Strategy to establish an Advanced Materials/Manufacturing Alliance. We will continue to develop our national engagement with DEFRA, BEIS, and HMRC.

Bioengineering

We will promote activities that span bioengineering, biomanufacturing, biomechanics, biomaterials, and biomedical devices and monitoring. In particular, we will leverage the MIB, co-locate researchers, and establish new facilities within MECD to support our growth in health-related engineering.

- We will take advantage of the devolution of NHS healthcare budgets in the Manchester metropolitan area. We will work with clinicians to inform our research direction and improve exploitation through the TAI (§1f.1), Health Innovation Manchester, and the ERDF Research and Innovation Health Accelerator.
- We will advance our work in pharma, including manufacturing biologics (biopharmaceuticals, cell and gene therapies), optimizing formulation technologies, sensors, and drug-delivery systems.

Energy

We will continue to deliver research helping to ensure safe and affordable energy while eliminating greenhouse gas emissions. MECD presents a unique opportunity to bring together researchers from different disciplines including climate change, energy supply (fission, fusion, solar, wind, bio, tidal, and wave), also power systems, energy storage, transport, materials light weighting, infrastructure, energy demand, negative emissions technologies, and energy policy.

- We will work with the Greater Manchester Energy Innovation Agency to deliver research across the areas of climate change, energy systems, and transport to accelerate our transition to net zero and beyond, supporting our regional partners in creating sustainable industries and jobs.
- We will apply our research expertise in subsurface engineering to energy system transitions, the subsurface in energy storage (compressed air, hydrogen, thermal) and in nuclear-energy schemes.
- We will focus on delivering catalytic science and engineering coupled with process engineering to address the Government's goal of reaching net zero by 2050. This will be

part of a UK wide initiative through the UK Catalysis Hub (§1c.3), which will shape the future for catalysis for several decades.

- We will determine how future nuclear provision will affect the energy system transition when deployed with other maturing technologies e.g. large-scale tidal and wave energy systems.
- We will address how policy, regulation, and business-model innovation can expedite energy system transition and identify routes to societal acceptance of new technologies. We will collaborate with policy@manchester (REF5a §2.iv) and support the TAI (§1f.1) in areas such as safe operation of offshore energy assets.

Environment

We will apply engineering solutions to further address UN sustainability goals. We will foster enhanced interdisciplinary research through MECD and by stronger interactions with natural sciences, humanities, and health researchers.

- We will enhance engineering for the environment and our engagement with relevant policy and society.
- We will work through MERI (§1f.1) to identify challenges and engineering solutions and through Royce and NGI (§1f.1) to advance materials approaches, e.g. membrane technologies for clean air and water.
- We will exploit opportunities to integrate our approaches in anticipation of Government prioritizing links between energy and environment.

Integrated Systems

We will build on our investments in robotics, autonomous systems, and AI.

- We will strengthen our collaboration in Cumbria with Sellafield Ltd, the Nuclear Decommissioning Authority (NDA), NNL, and UK Atomic Energy Authority (UKAEA) to deliver new robotics and AI technology into the decommissioning sector. With UKAEA, we will develop remote handling systems for the UK's next generation of fusion reactors (STEP) and advanced modular fission reactors (AMRs).
- We will integrate UoM's autonomous systems, robotics, and AI communities, and establish a robotics hub in MECD. With investments in this Unit and in Computer Science, we will increase collaboration between the Faculty's 50 researchers in these areas to expand applications, e.g. to autonomous flight technology, biomimetics, and micro-robots, with potential impact in aerospace, hydrodynamics, and healthcare.
- We will further integrate research on AI, Control, and Software Engineering in our Computational Modelling Theme (§1c.3), incorporating societal benefits of trustworthiness, security, and sustainability.

1e. Enabling research impact

Impact is enabled through support, funding, and staff-development mechanisms. This section describes the first two mechanisms and their relationship, summarized in Figure 2, to our 13 ICSs selected for submission. Staff development is discussed in Section 2.

Impact Case Title	Lead	KTP/IAA	Long-term stragetic relationships	IP: Patents and Spinouts	Policy and Governments	Interdisciplinary Networking Through Institutes.
Increasing productivity in the process industries through the use of artificial intelligence and machine learning for the optimisation of distillation operations	Jobson	●		●		
Financial and environmental benefits through the development and transfer of control and monitoring technology in the process industries	Lennox			●		
Increasing renewable energy and reducing customer bills: using managed connections and flexible demand response controls in the electricity network to support decarbonisation with the minimum infrastructure investment	Li				●	●
Reducing usage of fossil-oil-based insulating liquids in power transformers to deliver environmental, safety, and financial benefits	Wang		●			
New industrial electromagnetic sensor systems improve safety processes and optimise capabilities in the UK's energy, rail and manufacturing sectors	Peyton			●		
Improved designs of high voltage overhead lines enable increased transmission capacity, providing environmental and financial benefits	Rowland		●			
Reducing climate change caused by shipping and aviation	Larkin				●	●
System-scale design of water resource systems improves water security and resilience	Harou		●		●	
Manchester's independent graphite research for the Office for Nuclear Regulation has been instrumental in improving the safety, security and reliability of the UK's nuclear industry	Jones				●	
Empowering local climate change action and shaping local authority policy through their adoption of carbon budgets	McLachlan		●		●	
Providing the scientific foundations to grow a sustainable, low-carbon UK bioenergy sector	Welfie		●		●	
Innovative performance evaluation techniques assure the safe operating limits of Thermal Barrier Coatings for improved jet engine performance	Xiao		●			
Robotic and mechatronic manufacturing of 3D shell-shaped textile products to deliver medical and structural textile reinforcements	Potluri	●		●		

Figure 2. Enabling mechanisms supporting the submitted Impact Case Studies.

1e.1 Knowledge Transfer Partnerships (KTPs) and Impact Acceleration Accounts (IAAs)

Our dedicated University Knowledge Exchange team work closely with staff and companies to establish KTPs. UoM held the highest number in GB at the census date, with 42 KTPs over the period supported by £4m from companies. The ICS with Cygnet-Texkimp (**Potluri**) exemplifies how KTPs enable transfer of trained engineers and experience to generate new products. Our 118 EPSRC IAA projects (£4.1m EPSRC, £2.6m company contribution) have spanned all company sizes (38% SME, 62% Large) and enabled EPSRC research to create impact. For example, IAA funding underpinned Tyndall Manchester's two ICSs (**Larkin**, **McLachlan**). Another IAA led to CARMA, the first autonomous nuclear decommissioning robot installed at Sellafield and identified as a world-leading technology in the Government's 2020 R&D roadmap (https://www.gov.uk/government/news/government-fires-up-rd-across-the-country-to-cement-the-uk-as-science-superpower). A KTP project with Nuvia aims to commercialize CARMA.

1e.2 Building long-term strategic relationships

Opportunities and relations are targeted through dedicated support for business engagement (§1e.2) including an Associate Dean, professional service (PS) managers for key companies, and six Faculty academic champions (five within the Unit) to encourage cross-Faculty solutions. Departments have External Advisory Groups, comprising senior industrial staff from a range of companies who advise on industrial direction.

The UoM professional Business Engagement (BE) team (REF5a §4.1) supports growth sectors, providing a single point for commercial project research enquires which they pass on to academics, guiding the relationship to contract and project start. For example, since the NGI opened in 2015, the 2D materials BE team has handled ~1,500 enquires and supported ~70 projects, leading to >£12m of industrial contracts (e.g. Petronas, Sony, Tetra Pak).

With BE's support, staff cultivated long-term relationships with Governmental and industrial partners (e.g. AkzoNobel, Airbus, AstraZeneca, BAE Systems, BP, EDF, Infineum, NG, Petronas, Rolls-Royce, and Unilever), delivering against joint industrial and UKRI funding within framework agreements. For example, our strategic relationships with NG since 2003 led to **Rowland**'s and **Z. Wang**'s ICSs, and **Xiao**'s 22 year-long collaboration with Rolls-Royce to his ICS.

Our Prosperity Partnerships (§3a.3) are both an outcome of our long-term relationships and an enabler of their continuation.

1e.3 IP generation: patents and spin-outs

The UoM Innovation Factory (UMIF) provides guidance on IP including contract negotiations, protection, and exploitation. UMIF was restructured within the period by assigning IP scouts to particular research fields to identify, assess, and protect inventions more quickly. UMIF supports patenting (101 patent families) and licensing (e.g. 2D Tech, Inov8). Alternatively, staff can spin-out their research. Within period they launched 15 companies (AEH Innovative Hydrogel, Atomic Mechanics, Fotenix, Grafine, Holiferm, ICE-9, LIG Nanowise, Manchester Biogel, Manchester Robotics, Molymem, Nanoplexus, Pentabee, Signal Wizard Systems, SmartIR, and StreamBio). UMIF offers support to these spin-outs, including pump-priming (e.g. £275k to MolyMem in 2019), fund-raising, attracting board members, and business-case development.

1e.4 Policy and governments

We have worked closely with policy makers and governments to create economic, health, and environmental impact. Policy@Manchester (REF5a §2.iv) has cooperated with the Unit to produce

reports on energy, net zero, AI, and robotics, and to engage in events such as panels with MPs at UK party conferences and receptions in the House of Commons. Policy@Manchester has supported academic workshops on working with parliamentarians and civil servants.

The Tyndall Centre's explicit policy-relevant remit underpins the continuing relationship with policy and industry stakeholders, supported by a full-time Knowledge Exchange Fellow. Outcomes include ICSs on shipping and aviation climate-change reduction (**Larkin**), local-authority policy and climate change (**McLachlan**), and a sustainable low-carbon UK bioenergy sector (**Welfle**).

1e.5 Interdisciplinary networking through institutes

Solutions to real-world problems, and thus impact, often require a multidisciplinary approach. Benefits from our interdisciplinary networks and institutes are discussed in §1f.

1f. Interdisciplinary research

Interdisciplinarity is intrinsic to our engineering Research Themes (Figure 1) but collaboration beyond the Unit is essential to success. Some larger interdisciplinary projects are these:

- The Centre in Advanced Fluid Engineering for Digital Manufacturing (CAFE4DM, Prosperity Partnership, §3a.3), which involves the Unit, Chemistry, the Business School, the Dalton Nuclear Institute (DNI), MIB, Unilever, and Cambridge University (Mathematics).
- The TORONE project (§3a.2), which involves the Unit, NNL, and Digital Electronics at Lancaster University.
- The EPSRC Supergen Hubs (§1c.3), comprising Bio-energy, Energy Systems, and Offshore Renewable Energy.
- The FutureDAMS project (§3a.2), which involves the Unit in water-energy engineering, economics, food security, climate change, finance, and ecology.

Our interdisciplinary collaborations are targeted strategically, aided by Research Institutes and Centres, interdisciplinary PhDs, joint appointments, and networking activity, as follows.

1f.1 Research Institutes and Centres

The UoM Research Institute (UMRI) governs and helps develop UoM's interdisciplinary Research Institutes and Platforms, which along with Centres bring together academic teams across the Faculties to address key challenges. Institutes and Centres cut across Research Themes, as shown in Figure 3. They are launched with either University seed-corn funding or strategic external grants. For example, the TAI was pump-primed through UMRI with £240k, resulting in a Lloyd's Register Foundation 5-year funded programme (£1.1m). The GEIC was funded with £15m from HEFCE RPIF, £30m from Masdar (UAE company), and £5m from Innovate UK.

The Institutes and Centres relevant to the Unit and its interdisciplinary activities are as follows:

- **Henry Royce Institute** (Chief Scientist **Withers**). UoM led the bid for Royce with six other University partners. The bid capitalized on UoM's success in advanced materials, especially in 2D materials research, its characterization equipment bids (RPIF, £17m, 2013 and ONSIDE, £4.3m, 2013), and bp-ICAM. The peer-reviewed award resulted in UoM hosting the national hub (EPSRC £46m equipment, £105m estate) with other partners as spokes. Royce provides a national focus in advanced materials with UoM leading the 2D Materials, Biomedical Materials, Materials for Demanding Environments, Nuclear Materials themes, and other partners leading Advanced Materials Processing (Sheffield), Atoms to Devices (Leeds/Imperial College), Energy Storage (Oxford), and Materials for Energy Efficient ICT (Cambridge).

Research Area	Advanced Materials & Processes	Bioengineering	Energy	Environment	Integrated Systems
Henry Royce Institute (Royce)	●	●	●	●	●
National Graphene Institute (NGI)	●				
Graphene Engineering and Innovation Centre (GEIC)	●				●
The Thomas Ashton Institute for Risk and Regulatory Research (TAI)					●
Dalton Nuclear Institute (DNI)		●	●		
Manchester Environment Research Institute (MERI)		●	●	●	
Manchester Institute of Biotechnology (MIB)				●	
Photon Science Institute (PSI)	●		●		
Tyndall Manchester				●	
BP International Centre for Advanced Materials (bp-ICAM)	●		●		

Figure 3. Interactions between Research Institutes and Centres and the Unit's Research Themes.

- **BP International Centre for Advanced Materials** (Director **Matthews**, then **Haigh**). bp-ICAM brings together capabilities from BP and four leading universities with UoM as the hub and the Universities of Cambridge, Illinois at Urbana-Champaign, and Imperial College as the spokes. It was founded in 2012 and renewed in March 2020 to 2027 with the Centre's focus moved from fossil fuels to renewables. Over fifteen years, BP and UoM have invested £18.7m and £6.5m respectively in bp-ICAM at UoM.
- **National Graphene Institute**. NGI acts in a hub-and-spoke model for 2D material groups at UK universities, cooperating with institutions overseas and engaging with businesses (§4a.3)**.** It houses 110 researchers from physics, chemistry, life sciences, electrical engineering, and materials to develop the fundamental science and engineering of 2D materials.
- **Graphene Engineering and Innovation Centre** (Acting Chief Scientific Officer **Sampson**). GEIC opened in 2018 to accelerate the application of 2D materials from TRL3 to TRL5 (§3b.1) through its industrial partners, spin-outs, and University academic expertise.
- **Thomas Ashton Institute** (Co-Director **Bourne**). TAI established in 2018 brings together UoM and the Health and Safety Executive to deliver research, learning, and regulatory insights for a better working world.

- **Dalton Nuclear Institute** (Associate Director **Taylor**). DNI is the largest nuclear academic community in the UK which, uniquely, covers the whole nuclear fuel cycle. The DNI coordinated the GREEN CDT and four successful University-led capital bids (£15m) across three of UoM's submitted Units. Its staff sat on >7 Government advisory committees.
- **Manchester Environment Research Institute** (Theme Leads **T. Foster**, **Grieve**, **Lea-Langton**). MERI was launched in 2018 to integrate cross-University research and promote inter-disciplinary environmental research. MERI is associated with 716 academics, 157 in this Unit.
- **Manchester Institute of Biotechnology**. MIB has expertise in industrial biotechnology and is helping to further the UK's strategic development of biomanufacturing, specifically in the areas of pharmaceuticals, value-added chemicals, advanced materials, and next-generation biofuels. Seven of its 40 academics are in this Unit.
- **Photon Science Institute** (Director **Curry**). PSI delivers high quality fundamental and applied research in materials, devices, and spectroscopy, providing underpinning University capability in advanced materials, energy, industrial biotechnology, and cancer. It has ~100 resident researchers and >250 regular University users from four submitted Units. It operates several national research facilities (NRF) including the EPSRC National EPR service, the HMXIF/XCT, XPS, and SIMS capability, and forms part of UoM's contribution to Royce. In 2020, we were selected to host the hub of the new EPSRC £10m NRF for Laboratory X-ray Computed Tomography.
- **Tyndall Manchester** (Director **McClachlan**). Tyndall Manchester is a founding partner in the Tyndall Centre for Climate Change Research and hosted the Tyndall Centre directorship 2018-19. Its expertise forms one strand of the training for the GREEN CDT. A focus has been sustainable water and the management of energy-water-food systems, enabled by the FutureDAMS project (§3a.2).

1f.2 Interdisciplinary PhDs

Our PGR strategy engenders interdisciplinarity, with co-supervision across disciplines stimulating collaboration between academics. The NoWNANO CDT (with Lancaster) and Advanced Biomedical Materials CDT (with Sheffield) supervise biology, medicine, and engineering students, with NoWNANO requiring PhD supervisory teams from two different disciplines. Cross-Faculty PGR studentships were enabled through the EPSRC and MRC CDT in Regenerative Medicine. Our BBSRC DTP allocations led to eight projects with the Faculty of Biology, Medicine and Health on biofluids, engineered spiral grafts, tissue engineering, drug delivery, and bio-sensors.

The PhD scholarships listed in §2b.2 encouraged cross-disciplinary research, with 13 PhDs since 2018 joint between the Unit and Chemistry and Earth & Environmental Sciences (EES). PhD project funding schemes also enabled access to national facilities at the Diamond Light Source (DLS) with projects on imaging in Materials and Modelling.

1f.3 Joint appointments

Investment in early career staff, including 19 UoM-funded fellowships, has been a priority in the REF period (§2a), with cross-disciplinary working a criterion in the assessment process. Appointments include five fellows collaborating with the DLS Facility, providing a bridge between fundamental science and engineering. Cross-departmental appointments and transfers have been made to facilitate collaborations and realize strategic objectives. A split appointment between the Unit and Chemistry and EES, led to the GREEN CDT (**Heath**). Other joint appointments include

ones with Computer Science (robotics), Mathematics (modelling), and Physics and Astronomy (graphene).

1f.4 Networking activity

To support future interdisciplinary activities, UoM provides seed funding of typically £200-300k for each network, for example:

- Industry 4.0 Innovation Lab is a collaboration in Advanced Materials and Processes between the Unit, Alliance Manchester Business School (AMBS), and the School of Environment, Education and Development to co-ordinate strategy and structure industry engagement.
- Advanced Materials in Medicine initiates, facilitates, and supports cross-Faculty activities to enhance collaboration in the area between FBMH and FSE, including biomaterials, bioelectronics, nanomedicine, and tissue engineering. Through workshops, awareness of funding calls and advice, it supported six grants (£8.6m), including the Advanced Biomedical Materials CDT.

1g. Open Research environment

We follow UoM policy on creating an open research environment (REF5a §4.3), detailed in its Position Statement on Open Research, in particular, transparency in research methodology, public availability and reusability of research data and code, and public accessibility and transparency of research communication. UoM's Open Research forum includes seven members from this Unit.

1g.1 Open Access publishing

Open Access is supported by UoM's research information system and publications repository PURE and the web-based Open Access Gateway, which verifies manuscript versions, checks journal and funder policies, and sets embargo periods on publication and support for Gold Open Access when not available from external funders. ORCID registration is required for all researchers. Open Access compliance is monitored by the Library with feedback to Directors of Research and REF Output Champions. Of our REF2021 outputs submitted, 98.4% were compliant.

1g.2 Open Research environment: data and software

Open research and reproducibility are incorporated into PGR and ECR training. For research proposals, the Library offers comprehensive support with outline checks or full reviews of data-management plans to ensure compliance with standards. UoM provides a repository for publishing data (Mendeley data, then Figshare) with DOIs.

In some projects we have made available freeware routines to help usage. Funded by EPSRC project LightForm, **Fonseca**'s team created software for running reproducible workflows, whose outputs can be automatically uploaded to data repositories (https://github.com/LightForm-group/matflow).

1g.3 Research integrity

UoM's Code of Good Research Conduct sets out our commitment to research integrity, along with the Code of Practice for Investigating Concerns about the Conduct of Research.

Online Research Integrity training was established in 2016. This course resulted in high levels of awareness of codes for good research conduct (77% University staff respondents) and University

ethical review processes (76%), with 83% of respondents agreeing that UoM supports a culture of ethical research.

Concordat. Complying with the UUK Concordat to Support Research Integrity, all research-active staff and PGR students take UoM's Research Integrity course (REF5a §2.v). Completion is monitored, with success necessary for staff to apply for research funding or supervise PhD students.

Ethical approval. Research Ethics Committees (REC) are in place across the Institution, reporting to the University REC. Departmental Leads act as gateways to procedures.

Export controls and NDAs. Effort has been invested in raising awareness among staff of their obligations to comply with export controls on data. All staff completed a training session on the implications of export controls for data management. The central legal team coordinates NDAs and data-sharing contracts.

2. People

2a Staffing strategy and staff development

Our staffing strategy is guided by UoM's strategic plan and commitment to the Researcher Development Concordat (§2a.3 and REF5a, §3.3.2). The intention is to provide a creative, ambitious, and supportive environment in which researchers, at every career stage, can progress into and succeed as leaders in their chosen fields.

2a.1 Recruitment

We have had a natural turnover of staff with most leaving for senior roles in other institutions, industry, or retirement. The Unit return comprised 112 professors, 36 readers, 67 senior lecturers, 81 lecturers, 3 senior research fellows, and 27 research fellows. Recruitment processes have been refined and improved in response to monitoring equality, diversity, inclusivity, and accessibility (EDIA) (§2c).

In the period over 23 professors, 7 senior lecturers, 56 lecturers, and 22 research fellows were recruited internationally.

Highlights of our recruitment within the REF period include the following, grouped by Research Theme (§1c.3). Delivery of REF2014 goals are indicated.

Advanced Materials and Processes

- To develop engineering applications in 2D Materials (REF2014), two professorial fellows were appointed, **Nair** as Royal Society University Research Fellow (RSURF) in membranes and **Koskun** ERC Fellow in electro-optical materials, and six ECRs: **Lewis** in 2D materials production, **Gorgojo** membranes, **Bissett** energy, **Barg** porous materials, **Vallés** composites, and **Kretinin** thermoelectrics (with Physics and Astronomy). **R. Young** took partial retirement.
- To support Photonic and Quantum Devices (REF2014) with retirement of **Hamilton**, **Curry** was appointed to provide leadership as Director of PSI, **Boland** and **Echtermeyer** as Lecturers**,** and **Illes-Smith** as Research Fellow.
- To underpin characterization infrastructure investments (§3b.1) and new *in-situ* and *in-operando* approaches, ECR appointments included **Eggeman** (RSURF), tomography expert **Burnett**, and NanoSIMs leader **Moore**. At UoMaH (§3b.4), **P Lee** (now UCL) and **Bourne** were appointed and seven research fellows, **Eastwood**, **Hunt**, **Mirihanage**, **Yan**, **Khan**, **Ma** and **Parlett**. NMR expertise was strengthened with Lecturers **D'Agostino** and **D. Lee**, helping to secure Tier 1 membership of UK analytical measurement science community (CAMS-UK).
- In Corrosion and Wear (REF2014), **Matthews** was appointed as Director of bp-ICAM (§4a.3) with **Haigh** assuming Directorship at period end. **Yerokhin** was appointed Lecturer as part of the long-term succession plan. **Mingo** received a Presidential Fellowship to develop new corrosion control mechanisms.
- In Advanced Manufacturing, our move into Industry 4.0 and Smart Manufacturing was accelerated by ECR appointments: **Bryan** in responsive manufacturing systems, **Kilic** in digital manufacturing, and **Y. Wang** to a Chair in Smart Manufacturing as part of succession planning for **Hinduja**.

Bioengineering

- To expand Bioengineering capability (REF2014) with leadership in biomanufacturing, **Bartolo** was appointed Professor, alongside ECRs **Domingo** and **Weightman**. Biomimcry

was established with Research Fellow **Parry**, Lecturer **Nabawy**, and PDRA-to-Lecturer **Parslew**.

- Continuing to build capacity and research quality (REF2014), **Biomaterials** gained two Research Fellows, **Jones** and **Parry,** and two Lecturers, **Blaker** and **Tsigkou**, after Merry left for Readership at Nottingham. Biomechanics was strengthened with recruitment of Lecturer **Cooper**.
- To give future research direction in Industrial Biotechnology (REF2014), **Dickson** transferred as Professor from the Faculty of Life Sciences and **Anastasiou** was appointed Lecturer, mitigating the retirement of **Mavituna** and **Webb**, and departures of **Campbell** and **Westerhoff** to Chair positions at Bradford and Amsterdam.
- To strengthen crystallization research and plan succession for the retirement of **Davey**, **Vetter** was appointed RAEng Industrial Fellow and **Cabeza** RS Industry Fellow.

Energy

- To reinforce our leading position and develop new areas in power systems, **Jarman** was appointed as Professor, **Iacchetti**, **Parisio**, **L. Chen**, **C. Zhang**, and **Ponocko** as Lecturers, and **Martínez Ceseña** as Research Fellow. **Z. Wang** left to become Pro-Vice-Chancellor and Executive Dean, Exeter University, **B. Wen** moved to Virginia Tech, USA, and **Todd** died in service.
- International collaborations were furthered (REF2014) through **Mancarella** and **Ochoa**'s professorial appointments joint with Melbourne.
- To consolidate and develop research in nuclear engineering (REF2014), six ECRs were appointed, **Turner**, **Vaseliou**, **Harrison**, **Leay**, **Theodosiou** and **Atas**. Expertise in thermal hydraulics was expanded with **Cioncolini** as Senior Lecturer. **Taylor** was appointed Professor in Nuclear Energy Systems to lead on engineering and social science aspects of nuclear energy.
- To expand offshore renewable energy research (REF2014), **Draycott** was appointed as Dame Kathleen Ollerenshaw Fellow.
- To respond to priorities of a low-carbon economy, **Parkes** was appointed Ekpe Fellow in climate impacts, **Hoolohan** Presidential Fellow and **Sharmina** Lecturer in Tyndall Manchester.
- To create a critical mass in catalysis, **Hardacre** was appointed Professor, **Parlett** as Research Fellow, and **Spallina**, **Fan**, and **Perez-Page** as Lecturers.

Environment

- In Environmental Engineering, research in geotechnical and water engineering (REF2014) was reinvigorated with appointment of Professor **Harou,** Presidential Fellow **Ma**, and two Lecturers **Bottacin-Busolin** and **T. Foster**. In geoenvironmental engineering three ECRs were appointed, **Lombardi**, **Sedighi**, and **Syed**, and in geological sequestration **Hadi-Mosleh** as Lecturer.
- To establish leadership in Circular Economy, including in Royce, **Shaver** was appointed Professor in polymers following retirement of Lovell. **Cuellar-Franca** and **Stamford** were appointed Lecturers in life-cycle analysis and **Gallego-Schmid** as Lecturer in Tyndall Manchester. To develop capacity in infrastructure materials, **Su** and **A. Foster** were appointed as Lecturers, following departure of **Gillie** for a Chair at Warwick, and as succession planning for **Bell**.

Integrated Systems

- To consolidate and advance research in aerospace (REF2014), **Bojdo** and **Quinn** (formerly PDRAs) were appointed to new Lectureships and **Roberts** to a Lectureship in space technologies.
- **Z.-G. Ding** was appointed to a Chair to provide new leadership in communications and 5G systems, replacing **Brown** and **Rezazadeh** on retirement and **Sloan** who became CEO Microwave Inspection Technologies. **Wright** and **O'Toole** joined as Lecturers replacing **Armitage** on retirement and **Duff** who joined Semtech.
- Responding to advances and an increased focus in robotics, **Herrmann** was appointed as Professor and **Arvin** and **Watson** as Lecturers, following retirement of **Gray** and **Oakley** and departure of **McCormick** for BAE Systems.
- **Kiss** was recruited as Professor to provide leadership in process integration, as **R. Smith** approached retirement, and **J. Li** as Lecturer. **L. Zhang** was appointed Lecturer to strengthen control systems, replacing **H. Wang** who became Senior Distinguished R&D Staff, Oak Ridge National Laboratory, USA.

Computational Modelling

- To improve engineering analysis through large scale computational modelling (REF2014), **Borodin** was appointed Research Fellow in solid mechanics, **Lazarov** as Senior Lecturer, who after departure was replaced by **Darvizeh** as Lecturer in solid mechanics. **Lind** and **Fourtakas** were appointed as Lecturers in SPH, and **De Rosis** and **Keshmiri** as Lecturers in complex flows and biofluids engineering.
- **Sarkisov** was appointed as Professor to enhance multiscale modelling.

From Lecturer level onwards, all our category A research-related staff are on open-ended contracts. Most of our research fellows will move, or have moved, onto open-ended contracts at the end of their fellowship.

PDRAs. Within period 678 PDRAs were recruited to the Unit, with 252 in place at period end. In 2018, University policy and process were adapted to allow all research staff with four years' continuous service to transfer to open-ended contracts. Fixed-term contracts are still used for research staff with less than four years' continuous service. We have no zero-hours contracts.

Supporting positions. Researchers' teaching responsibilities were lightened by the recruitment of 15 teaching-focused posts, and support for impact included the appointment of **C. Jones** as a Knowledge Exchange Fellow in Tyndall Manchester.

2a.2 Staff development

We follow UoM policy in staff development (REF5a §3.1). Training and development opportunities for academics, ECRs, and PDRAs are provided through Faculty central professional services and the Library, with courses including Career Management, Wellbeing, and Leadership & Strategy. In 2017-18, 120 staff from the Unit participated in these courses.

Annual Performance and Development Reviews (P&DRs) with trained reviewers are encouraged and offered to all staff, but complying with local Union agreement, are not compulsory. The P&DR covers routes to promotion, training opportunities, and development objectives. The effectiveness of the P&DR is evidenced in the 2019 CAPITA University Staff Survey, with 398 academics and researchers from the Unit participating: 95% of participants reported that the process had given them clear objectives and 82% engaged in work-related training in the previous year.

Staff are encouraged to have a mentor in addition to their line manager, and for academic probationers a mentor is mandatory. The Manchester Gold Mentoring Programme links staff to more experienced colleagues.

New academics and research fellows. The New Academics Programme (NAP) delivers training on teaching, research, social responsibility, and professional development. The NAP includes research structures, strategy, data management, funding, and research proposals, managing a group, supporting postgraduate researchers, EDIA, export controls, knowledge transfer, IP, generating impact, and publication strategies (within UoM's commitment to DORA, journal-based metrics are used to inform researchers, but not determine, where to publish for maximum impact). In the period, 142 staff from the Unit completed the NAP.

Newly appointed staff are set challenging probationary objectives for their probation period by line managers including completion of the NAP, with fairness of objectives across Departments ensured by a NAP Senior Mentor and HoD. Performance against the objectives, including approving the completion of probation, is reviewed at an annual Personnel Committee meeting. In the rare cases where insufficient progress is made, further training and mentoring is immediately put in place.

Mid-career academics. Mentoring and support is provided to help staff lead large collaborative grant proposals and to apply for prestigious grants and fellowships. Staff are encouraged to take research leadership positions (e.g. PGR Director) to broaden experience for future promotion. Our strong mentoring of staff is highlighted by REF2014 ECRs being appointed to professorships in this period, e.g. **Haigh** in characterization, **Kinloch** in nanomaterials, **Nair** in materials physics, and **Engelberg** in corrosion.

Senior Staff. UoM's leadership programme Inspiring Leaders (launched in 2019) blends acquisition of knowledge with the opportunity to collaborate with peers to improve leadership skills. The programme leads to an ILM Level 5 Award in Middle Management. In the Unit, 55 staff participated in 2019-20.

Wellbeing framework. In addition to UoM-level provision (REF5a §3.1), multipurpose wellbeing rooms have been established to support breast-feeding and those who need to manage health conditions or need a quiet space. Coffee mornings have been organized to encourage interaction across Departments and social gatherings, including walking lunches and casual and sporting events, to promote a healthy work-life balance. Local bespoke wellbeing days have been held yearly for staff. Dedicated wellbeing courses included Imposter Syndrome, Resilience, Wellbeing through Change, and Working Remotely. A range of options is available for flexible working, leave, and return from leave (§2c).

COVID-19. Along with the support described in the Institutional COVID Annex, affected probationers were given an extra probationary year. To help maintain the Departmental social fabric, Zoom coffee mornings and Friday 4 pm social events were introduced.

2a.3 Support for ECRs

We build on UoM policy (REF5a §3.3.2) with actions measured against UoM's Concordat Action Plan, Staff Survey Action Plan for research staff, and Research Staff Culture Surveys, modelled on the Welcome Survey and the CEDARS survey from Vitae®. UoM held its European Commission HR Excellence in Research Award throughout the REF period (renewed 2020). Staff awareness of the Concordat is developed online, through local presentations to staff and PGRs.

ECR fellowships

UoM invests in three early career fellowship schemes to support outstanding ECRs, including PDRAs, to build an academic career:

- **Presidential Fellowships** attract the best ECRs with a growing research reputation, regardless of discipline, who move into permanent academic positions after five years. The Unit was awarded five: **Mingo**, **Hoolohan**, **Hunt**, **Ma**, and **Iles-Smith**.
- **Dame Kathleen Ollerenshaw Fellowships (DKOFs)**, established in the Faculty to support diversity, attract creative and ambitious candidates who also move into permanent academic positions after five years. Through the scheme we have refined our recruitment processes to ensure a diverse application pool. Since 2018, eligibility is no longer restricted by years of post-doctoral experience or whether the applicant already holds a permanent academic position. The Unit was awarded three DKOFs: **Jones**, **Ouro**, and **Draycott**.
- **Dame Kathleen Lonsdale Fellowships (DKLFs)** attract exceptional candidates who would benefit from flexible development opportunities. DKLFs last five-years and are supported by bp-ICAM, providing salaries, research expenses, and £25k flexible funding (e.g. sabbaticals, secondments, funds for childcare or caregiving when attending conferences, and special support in managing disability or health issues). The Unit was awarded two female DKLFs: **Parry** and **Joss**.

Other 5-year research fellowships have been used to advance strategic areas:

- **UoM at Harwell (UoMaH) Research Fellows** provide an interface between researchers at UoM and the national facilities at Harwell, such as DLS. UoM fully funds **Hunt**, **Mirihanage** and **Yan**; **Eastwood** and **Parlett** are co-funded by DLS and **Khan** is co-funded by STFC.
- Department-funded research fellowships supporting RAEng Research Chairs are held by **Chen**, **Shanthraj**, and **Vallés**.

All ECR fellows are given support in writing applications and interview preparation. Some fellowships require an internal selection process where applicants receive feedback before submission.

Other externally funded ECR fellowship successes in the period include these:

- RSURF (**Eggeman**, transferred from Cambridge, **Nair**, **Race**),
- EPSRC ECRF (**Jivkov**, **Saiani**)
- Leverhulme Trust ECRF (**O'Toole**)
- NERC Fellowship (**Ma**)
- UKRI Future Leaders Fellowship (**Boland**)
- ETI-EPSRC David Clarke Fellowship (**Williams**)
- Royal Commission of 1851 Research Fellowship (**Iles-Smith**, transferred from Sheffield)

New academic appointees. New Lecturers typically receive a £10-20k start-up fund to cover consumables, travel to conferences, and establishing collaborations. A DTA PhD studentship or equivalent is provided to help support their independent research. Shared academic group laboratories allow access to well-found resources and a chance to interact. Appointees to lectureships have a reduced teaching load during their probationary period. All new academics have an academic mentor as well as a line manager (§2a.2).

PDRAs. PDRAs are given the same opportunities as academics with PD&Rs and training, with a recommendation of 10 days/year spent on professional development in the courses mentioned in

§2a.2. PDRAs are encouraged to participate in supervising taught students, training PGRs, and co-chairing research meetings.

Monthly business-engagement lunch-hour sessions, where former PDRAs in industry and spin-outs discuss alternative career paths, were organized for PDRAs/PGRs by the Faculty (35 attendees per session). The Masood Entrepreneurship Centre (part of the UoM's Business School, REF5a §4.1) provided training in the period to 91 PDRAs/PGRs from the Unit with a focus on Innovation & Commercialization of Research. There were 221 participants in the Centre's extra-curricular programmes.

Departmental and Faculty PDRA forums enabled PDRAs to participate in University strategy, raise issues, and organize their own community meetings. PDRAs also had dedicated quarterly open meetings with Faculty leadership with typical attendance of 140.

With the COVID-19 pandemic, the Faculty Researcher Development Team provided >100 one-to-one sessions with PDRAs for career, CV, and interview advice in preparation for a potentially challenging post-COVID-19 job market.

2a.4 Sabbatical leave and fellowships

All academics can apply for leave to initiate or complete an ambitious programme of research or impact activities (REF5a §3.3.1). Sabbaticals are awarded in response to an application detailing a research plan, including international visits and funding sources, its strategic benefit, and capacity to cover other responsibilities. In the period, ~40 members of the Unit took academic leave for 6-12 months e.g. **L. Li** to consolidate Laser Processing research, **Rogers** to develop research on Smooth Particle Hydrodynamics, **Anderson** to focus on Climate Change, **Davey** to take visiting positions at Jülich and Uppsala, and **Winterburn** to start the spin-out Holiferm**. Anderson**'s work had multiple impacts, including an invited one-to-one meeting with EC President's Climate Advisor Vandenberghe, advice to UK MPs and Scottish Government, and carbon budget projects for other nations (§4a).

Academic staff are encouraged and mentored to apply for fellowships and grants with significant dedicated research time, with successes including **Boland** (Future Leaders Fellowship), EPSRC Established Fellowship for **Saunders**, and ERC Starter Grants for **Haigh** and **Nair**.

2a.5 Exchanges between academia and business

Our strategic commitment to external collaborations for impact is supported through several channels. In addition to sabbaticals, academics can divide their time between the University and their spin-outs (e.g. **Miller** for BIOGEL). **Cotton** served on the Technical Advisory Board for the NG Deeside Innovation Centre and was seconded to the company for 12 months to provide specialist engineering support. Aided by ESRC IAA support, **Mander** was seconded to a BEIS Select Committee. Funded by an NWO Fellowship (Dutch Research Council), **van Silfhout** was seconded to ESRF (Grenoble, France) to lead 12 researchers and technicians in research with DUBBLE@ESRF small-angle X-ray scattering and spectroscopy facilities. **Carrasco**'s sabbatical was at the Robotics Applications in Challenging Environments group at UKAEA. **Cabeza** was awarded a Royal Society Industry Fellowship with AstraZeneca, allowing long-term collaborative links to be built during the 4-year placement, and **Vetter** was awarded an RAEng Industrial Fellowship.

KTPs (§1e.1) enable researchers to split their time between the University and a company. Our 42 KTPs included B&M, Cobra Biologics, Extronics, Pilot Group, P&G, Superglass, and Cygnet-Texkimp.

Industry has also embedded researchers directly in the Unit (e.g. Sony, FEI Colloids), enabling collaboration and transfer of technology. **Burnett** was originally an FEI employee developing tomography equipment on campus before joining UoM as a Lecturer, then Director of the Henry Moseley X-ray Imaging Facility.

Split-site PhDs have enabled company employees to work towards their doctorate in both the Unit and company research laboratories (Morgan Advanced Materials, Petronas, Solvay). Students can study either full or part time and have both Unit and company supervisors.

Staff exchanges occur beyond industry. **Vijayaraghavan** was awarded a British Science Association Media Fellowship in 2017 and **George** presented television programmes, four for BBC Four, two for BBC Two, and one for BBC One North West (§4a.5).

2a.6 Recognition and reward for research and impact

Departments review staff each year and consider whether to encourage them to apply for promotion. Departmental promotion committees hold informal reviews of all cases and provide feedback through line managers to refine submissions before formal review.

UoM's promotion criteria explicitly include Academic Enterprise & Knowledge Transfer with equal parity with Research. They consider career breaks, parental and carer leave, and part-time working (§2a.2), and from 2021 factors related to COVID-19. In the period, there were 193 promotions within the Unit, with an increase in applicants' success rate from 39% to 70%, attributed to improved mentoring and guidance.

UoM contracts allow staff to earn royalties from IP licensees and shares in spin-outs, incentivizing impact (§1e). Along with sabbatical leave (§2a.4) and opportunities for exchanges and secondments, in our work-allocation model up to 15% academic time and up to six months PDRA funding is given to academics to help develop impact.

2b. Postgraduate research students

The Unit had 2,823 PGR students during the period and 1,460 graduations. The PGR training and recruitment strategy is guided by the Departmental Director of PGR and the Faculty Research College under the Associate Dean for Postgraduate and ECR Development**.** Students' experience is monitored mainly through the normally biennial Postgraduate Research Experience Survey (PRES). From the Unit, 736 students responded to the 2019 PRES. Each Department also reviews its PGR activity annually and takes action to improve student experience.

2b.1 Recruitment

Research students are recruited through external advertising (e.g. FindAPhD.com), annual University (and some Departmental) PGR Open Days, and by reaching out to our own taught students. Advertisements are designed to be attractive to all potential candidates, including those with protected characteristics. Advertisements are almost always on free-to-access platforms to ensure global visibility (as evidenced by 1,150 international applications/year). All advertisements state that we welcome applicants from all sections of the community and appointments are made on merit.

All PGR interviewers complete EDI and unconscious-bias training (REF5a §3.4). The Disability Advisory Support Service (DASS) assesses and provides support for students upon arrival, including specialist software, furniture, and equipment. To increase EDIA support, Advanced Biomaterials and Advanced Metallic Systems CDTs have been trialling a new structured interview

process, including giving questions to candidates beforehand to help preparation and demonstrate freedom from bias. In 2020, UoM established a PGR Widening Participation group.

2b.2 Studentships

High EPSRC income to the Unit resulted in 165 DTP studentships within period, supplemented by 11 BBSRC studentships. We led or participated in 13 CDTs including renewals, resulting in 263 studentships:

- Advanced Biomaterials CDT (lead Unit and Sheffield)
- Advanced Metallics CDT (lead Sheffield)
- Aerosol Science CDT (lead Bristol with Bath, Cambridge, Hertfordshire, Imperial and Leeds)
- Future Innovation in Non-Destructive Evaluation (FIND) CDT (lead Bristol with Imperial, Nottingham, Strathclyde and Warwick)
- Integrated Catalysis (iCAT) CDT (co-director in Unit)
- M4DE (Materials for Demanding Environments) CDT (lead Unit)
- Graphene NoWNano (lead UoM and Lancaster)
- Next Generation Nuclear CDT (lead Unit with Lancaster, Leeds, Liverpool and Sheffield) which was renewed as GREEN CDT (Growing Skills for Reliable Economic Energy from Nuclear).
- Power Networks CDT (lead Unit)
- Industrial Doctorate Centre in Quantitative Non-destructive Evaluation (NDE) (lead Bristol, with Imperial, Nottingham, Strathclyde, Warwick)
- EPSRC & MRC Regenerative Medicine CDT (lead Faculty of BMH)
- Science and Technology of Fusion CDT (lead York, joint with Durham, Liverpool and Oxford)

These CDTs leveraged additional funding with three of the CDTs requiring industry co-funding for every studentship. Our strong links with industrial partners provided further fully-funded and UKRI-industry-funded studentships (11 iCASE and 22 CASE top-up).

Our internationalization strategies, including academic teams visiting Chile, China, and Mexico, attracted 1,371 registered PGRs. The quality of our international students is highlighted by funded scholarships including CONICYT Chile, China Scholarship Council, CONACyT Mexico, Marie Curie, Commonwealth and national government (Ecuador, Iraq, Malaysia, Saudi Arabia, Thailand, and Turkey). We have 2+2 programmes with Singapore A*STAR (since 2013) and the University of Melbourne 2+2 (launched in 2020). The UoM-funded 73 President's and 23 Dean's Scholarships attract the best students worldwide.

The funding profile of 773 registered PGR students in summer 2020 across all year groups in terms of FTE was 235 self-funded/industry funded, 210 UKRI funded (including EPSRC 107 CDT, 75 DTP and 16 iCASE), and 130 University funded (including 73 by Schools, 11 by Faculty and 24 Presidential Scholarships).

2b.3 Supervision and monitoring progress

All students are assigned a main supervisor and one or more co-supervisors. The main supervisor is an experienced non-probationary academic, whereas the co-supervisor may be a new academic leading a research project (NAP provides supervisor training, §2a.2). All students also have an academic advisor outside the supervisory team for advice and pastoral support. The Departmental

Head of PGR also provides support and addresses issues of progress and supervision. Departmental Student Welfare Officers deal with students' wellbeing, including help to access mitigating circumstances procedures, and counselling services and DASS provided by the Faculty (§2a). Some Departments have used a PGR Buddy Scheme which pairs incoming PGRs with senior-year PGRs, who give personal help and advice, e.g. on relocation, GP registration, and local transport.

UoM's electronic progression system (eProg) is used to record and track key PGR progression milestones, including a student's attendance, engagement, training, progress, and annual assessment. The first-year progress report determines whether PGRs who are unlikely to complete should withdraw at an early stage. These actions led to PGR completions within 5 years increasing from 71% for 2010 entries, to 79% for 2014 entries, and an average completion rate of 76% for 2010-14 entrants.

2b.4 Training and support

PGRs are fully integrated with other research staff and attend and present at group and theme seminars. Annual Departmental PGR conferences are held which all Department research staff attend. Typically research talks are given by First- and Third-Year PGRs and posters by Second-Year PGRs with prizes for best presentations. At the annual University Postgraduate Summer Research Showcase, students from all Faculties present posters and participate in a 3-minute thesis talk competition. Some CDTs hold joint conferences with their partner Universities or synergistic CDTs (e.g NoWNANO with Cambridge's Graphene Technology CDT.)

Departmental, Faculty, and CDT funding ensures that all students can attend at least one and usually several international conferences during their PhD, with external funding enabling more.

An induction session for new PGRs includes talks on the structure of the PGR programme, expectations of PGRs, rules of progression and examination, health and safety, library information and computing resources, and opportunities for graduate teaching. PGRs have the same Faculty-run training opportunities as other ECRs including IP support (§2a.2), with additional courses in Academic Writing, Graduate Teaching Assistant Training, Writing up Your Thesis, and Viva Survivor (576 students participated in 2017-18). To provide a continuing guide for PGRs and ECRs, **D. Foster** authored the book *A Concise Guide to Communication in Science and Engineering* (OUP, 2017/18).

The knowledge and skills training needed by PGRs is agreed with supervisors and forms part of progression monitoring (§2b.3). To broaden their development, PGRs are encouraged to attend other PGT and UG lectures. Our CDTs offer further specialized training, reviewed externally by EPSRC.

Enterprise training is given by the Masood Entrepreneurship Centre through e.g. the Graphene Hackathon, monthly lunchtime meetings, UMIF guidance, and prizes (e.g. Eli Harari Innovation Awards).

PGRs also gain experience in wider research communication by participating in our outreach activities (§4a).

2c Equality, Diversity, Inclusion, and Accessibility (EDIA)

UoM was one of the first Universities to establish Social Responsibility as a core goal. It is committed to Equality, Diversity, and Inclusion (REF5a, §3.2) and our Dignity at Work policy for staff and students emphasizes the right of everyone to be treated with respect. Social responsibility resonates strongly in the Unit and in the recruitment and progression of our academic, research,

technical, and administrative staff. We follow UoM guidance on EDI in all training activities (§2a.2, REF5a §3.2).

The Faculty has dedicated EDIA leadership positions at Vice Dean, Associate Dean, and School levels. EDIA postholders serve on leadership teams and chair EDIA committees addressing EDIA characteristics, as well as developing our EDIA objectives and Athena SWAN actions and progress. In the Unit, the Departments CEAS and Materials held Athena Swan Silver within the period (Silver and Bronze in REF2014), and MACE and EEE held Athena Swan Bronze. With the restructure, both the Schools of Engineering and of Natural Sciences will apply for Athena Swan Silver in November 2021.

Multiple mechanisms help provide a supportive and inclusive research culture, e.g. targeted mentoring in fellowship and funding applications to under-represented groups. In the 2019 CAPITA University Staff Survey, 92% of participants considered UoM to be a good place to work, 84% felt it was committed to equal opportunities, 89% felt it acted fairly in recruitment, and 87% were aware of their responsibilities within UoM's Dignity at Work and Study Policy on bullying, harassment, and discrimination.

2c.1 Recruitment and promotion

Our recruitment strategies have addressed the need to improve diversity across gender, Black, Asian, Minority Ethnic, disabled, and other minatory groups. We have monitored progress, initiated new recruitment, selection, shortlisting and interview processes, and improved systems of support and mentorship. New actions included highlighting flexible working options in advertisements and gender decoding of advertisements to ensure inclusive language.

All staff in recruitment panels attend regular mandatory courses on Unconscious Bias, Diversity in the Workplace, and Recruiting Staff at Manchester. At interview, standard proformas are employed to ensure fairness and consistency of process. We have endeavoured to increase the diversity of interview panels with female and BAME representation and to avoid overburdening individuals, we have extended female and BAME representation to senior researchers or another submitted Unit.

We review career paths from PhD to professor to ensure sustainability in recruitment and career progression, and, in each research area, a suitable senior-junior ratio and EDIA balance. To help address gaps in research while improving protected characteristic representation, we have targeted ECRs using DKO and DKL Fellowships (§2a.3). Large programme grants (e.g. MIDAS, LightForm) have increasingly introduced EDIA Committees with an EDIA charter, including policies on enhanced payments to PhD students for extended parental leave, childcare funding to help conference attendance, and care-friendly scheduling of meetings.

Our gender balance across returned staff improved from 14% to 18% female between REF2014 and REF2021, and the percentage of BAME staff increased 26% to 28%.

Taken together these actions led to a 25% and 10% increase in the number of female and BAME applicants for vacancies over 2016-19. The Unit increased the absolute number of female PGR entrants by 8% between 2014/15 and 2019/20. The proportion of BAME PGRs has been greater than 50% consistently during the period, and as a proportion of all PGR entrants has increased from 59% in 2014/15 to 64% in 2019/20.

2c.2 Flexible working

All Departments support flexible working (REF5a §3.1), which can be written explicitly into staff contracts, e.g. reduced hours to accommodate childcare arrangements (73 of the Unit's research

staff are part-time with the number of PDRAs/Research Fellows increasing from 13 in 2016 to 27 in 2020). Most meetings are organized between 10 a.m. and 4 p.m. and the dates of large meetings, such as School Boards, published at the start of the academic year. Our Special Leave Policy accommodates serious family illness and allows temporary reduction in working hours.

UoM's package for parental leave provides six months at full pay, three months at statutory level, and three months unpaid leave. Shared parental leave was introduced in 2015. Cover is provided by a fixed-term appointment. For PDRAs whose grant does not include parental leave, Departments underwrite the salary if a grant extension is possible or appoint a research associate for the period.

Keeping-in-Touch days enable staff to maintain contact with the Department while on parental leave, and staff can choose to continue receiving Department emails and newsletters.

Part-time staff are treated the same as full-time equivalents for promotion and career-progression opportunities.

2c.3 Returning from periods of leave

We provide support for staff and research students returning from periods of leave. Staff recovering from illness are assessed by the Occupational Health Service and a return-to-work plan agreed. In consultation with their line-manager, staff may choose to phase their return. They may be relieved from teaching and given a reduced administrative load for up to six months to focus on research. They can also draw on UoM's Peer Support Group and several Health and Wellbeing services and facilities.

2c.4 Support for disabled staff

UoM's Disability Advisory Support Service (DASS) supports students and staff with a disability. DASS assists individuals in applying for RCUK Disabled Student Allowance (DSA) and Access to Work (AtW) to fund specific equipment or reasonable adjustments to conduct research. Departments address individual cases where routine adjustments do not suffice.

Staff who identify as disabled receive extra support to enable their participation in meetings or Departmental events (e.g. use of a palantypist). Where extra costs associated with disability arise for conference travel, UoM's DASS can provide funds not covered by the DSA or AtW schemes.

2c.5 Equality and diversity issues in constructing REF submission

Training of assessors of REF submissions complies with UoM's Ensuring E&D in REF2021. At Departmental level, assessments of contributions, especially outputs, were mediated by panels with the maximum possible diversity, typically in gender, ethnicity, and career stage.

The final selection of outputs was by algorithm to eliminate selection bias at this stage. To test for overall bias, the numbers of outputs submitted by minority groups were compared with those expected from the corresponding proportions of staff in the Unit. None of the differences between submitted and expected numbers were statistically significant.

ICSs named all contributing researchers independent of career stage. Professional Services supported all shortlisted ICSs to avoid staff being disadvantaged by other commitments. Selection bias was analysed at institutional level rather than by UoA and results are summarized in REF5a (§3.4). In this Unit, 38% of ICS lead authors and 18% of contributors identified as female, the latter matching our gender balance.

3. Income, infrastructure and facilities

3a. Research funding and strategies for generation

Over the REF period, the average research income per FTE increased by 47%, with 59 awards of £1m or more. The Unit's market share of research income rose from 4.4% to 6.3%.

Our research funding strategy was established within the framework of Faculty, School, and Departmental structures (§1b), guided by Departmental Senior Leadership Teams, Research Committees, and External Advisory Groups. It is summarized here in the following §3a.1-§3a.4

3a.1 General strategies for income generation

Individuals and Research Groups have a range of strategies available for securing research income:

- Exploit expertise and facilities within UoM's Research Institutes bp-ICAM, DNI, NGI, PSI, and others (§1f.1) to promote cross-disciplinary proposals, e.g. Prosperity Partnerships and EPSRC Strategic Equipment.
- Initiate larger research proposals in emerging areas with experienced researchers who identify opportunities and facilitate consortia, e.g. the EPSRC project Home Offshore, which brought together researchers in renewable power, robotics, and artificial intelligence (£1.8m to UoM, lead **Barnes**).
- Capitalize on international research links to access overseas and UK funding for international collaboration, e.g. DISCOVERER. Over the period EU funding (§3a.2) grew by 66%.
- Manage and develop major long-term industrial relationships (§1c, §1e), e.g. Rolls-Royce (£6.3m to Unit), including the UTC, which was a significant contributor to the E Fan X programme in which high-voltage technologies are used in new-concept aircraft. Our work led to technology being adopted in new programmes on hydrogen-fuelled aerospace. Other examples beyond the Prosperity Partnerships (§3a.3) include (with total direct funding to Unit within period): NG (£6.4m), Petronas (£1.4m), EDF (£1.3m), and Airbus (£1.1m), and growing relationships, e.g. Rapiscan Systems (Personal Screening Systems, £0.6m).
- Prepare Research Groups for future trends through timely appointments (e.g. **Liu** for Future Substations) and by rapidly assembling multidisciplinary teams aided by project managers (§3a.1). Workload models and sabbaticals (§2a) ensure staff can concentrate on large bids. Departmental funds and DTP awards support novel research proposals and larger bids.
- Draw on dedicated professional support (PS) staff (REF5a §4.1) to identify opportunities and provide administrative support over the project lifecycle. Research Support Managers work with Strategic Funding and Business Engagement teams to understand future priorities and assist large-scale bids. The Faculty's Research Strategy Coordinator Group facilitates responses to short-deadline calls, e.g. for the successful RE3 and National Nuclear User Facility (NNUF) bids. It also implements Faculty review of e.g. EPSRC Strategic Equipment applications.
- Provide proposal-writing workshops, mock-interview panels for individual researchers, and internal peer review by Review Champions (those with outstanding success with research funding).

3a.2 Major research consortia

We have led and participated in research consortia through a strategy of identifying leaders and then building teams aided by PS staff. Examples follow with Unit award value and, where appropriate, total award in parentheses:

Unit-led with external partners

- Royce, £215m, the UK national institute for advanced materials research and innovation, research hub at UoM (**Withers**) supported by spokes at Sheffield, Leeds, Liverpool, Cambridge, Oxford, Imperial College London.
- RAIN (Robotics and Artificial Intelligence for Nuclear), £4.1m (UoM £0.6m), lead **Lennox** with 10 UoM CoIs and EURATOM, Sheffield, Liverpool, Oxford, Nottingham, Lancaster, Bristol, Oxford, and 37 project partners including Sellafield, NDA, NNL, EDF Energy, Rolls-Royce.
- UK Catalysis Hub - 'Science': 2 Catalysis at the Water-Energy Nexus, £3.9m, lead **Hardacre** with 3 UoM CoIs, 6 other universities.
- Home Offshore (Holistic Operation and Maintenance for Energy for Offshore Wind Farms), £1.8m, lead **Barnes** with 8 UoM CoIs and Cranfield, Warwick, Durham, Herriot-Watt, and project partners Offshore Renewable Energy Catapult, Siemens Wind Power.
- MY_STORE (SUPERGEN Energy Storage Challenge), £1.3m, lead **Mancarella** with 8 UoM CoIs and 9 project partners including Ove Arup, AE Technology, Electricity NW, Hitachi Europe.
- LightForm (Embedding Materials Engineering in Manufacturing with Light Alloys), £3.5m, lead **Prangnell** with 6 CoIs and Cambridge, Imperial and 28 project partners including Airbus, BAE Systems, Rolls-Royce, DSTL.
- Transformer Research Consortium Phase 4, £1.6m, lead **Z. Wang** with 2 UoM CoIs and 10 Project Partners including NG, M&I Materials, Shell Research.
- GEMS (Geometric Mechanics of Solids: New analysis of modern engineering materials), £1.3m, lead **Jivkov** with 2 UoM CoIs and project partners EDF Energy, NAFEMS, Amec Foster Wheeler, Simpleware, Playgen.
- PACIFIC (Providing a Nuclear Fuel Cycle in the UK for Implementing Carbon Reductions), £1.2m, lead **Abram** with 5 UoM CoIs and 10 other universities.
- HEXMAT (Heterogenoeous mechanics in hexagonal alloys across length and time scales), £1.1m, lead **Preuss** with 2 UoM CoIs and Imperial, Oxford.
- MIDAS (Mechanistic understanding of Irradiation Damage in fuel Assemblies), £3.8m, lead lead **Preuss** with 5 UoM CoIs and Imperial, UKAEA, Oxford and 17 project partners including EURATOM, Rolls-Royce, NNL, EDF.
- TORONE (TOtal characterization for Remote Observation in Nuclear Environments), £0.9m, lead **Martin** with 2 UoM CoIs and Lancaster and project partners Japan Atomic Energy Agency (JAEA), NDA, University of Florida.
- Robotics for Nuclear Environments, £2.0m, lead **Lennox**, with Birmingham, UWE.
- CoatIN (Intelligent engineering coatings for in-manufacture and in-service monitoring of critical safety products), £0.9m (total £2.6m), lead **Matthews** with Belfast, London South Bank University, Swansea, SRUC, Sheffield and 8 project partners including Qioptiq, AWE, GE Power, Manufacturing Technology Centre UK.
- NNUF Molten Salts in Nuclear Technology Laboratory, £1.8m, lead **Sharrad** with UCL, Edinburgh, Sheffield.

EU projects and external partners

- CROSSBOW (CROSS BOrder management of variable renewable energies and storage units enabling a transnational Wholesale market), H2020 RIA £1.1m, lead **Milanovic** with 3 UoM CoIs and 12 other EU countries.
- DISCOVERER (DISruptive teChnOlogies for VERy low Earth oRbit platforms), H2020 FET £2.0m, lead **Roberts** with 4 UoM CoIs and Denmark, France, Germany, Spain, USA.
- Graphene Flagship, H2020 FET £4.0m, 14 UoM CoIs including **Bissett**, **Kinloch**, **Nair** and **Young**.
- CORREL-CT (Correlative tomography), H2020 ERC Advanced, £2.0m, lead **Withers** with 2 UoM CoIs.

Led by other UoM units or institutions

- Future Manufacturing Research Hub in Compound Semi-conductors, £1.7m, **Missous** with lead **Cardiff**, **UCL**, **Sheffield** and 23 partners including **Lockheed Martin**, **NPL**, **Toshiba**.
- Large Area Metal Additive LAMA, £1.0m, **Prangnell** with lead **Cranfield**, **Coventry**, **Strathclyde** and 10 project partners including **DSTL**, **BAE Systems**, **Schlumberger**.
- NNUF Hot Robotics Facility, £0.9m, **Lennox** with **Bristol** (lead), NNL, and UKAEA.
- FutureDAMS (Design and assessment of resilient and sustainable interventions in water-energy-food-environment Mega-Systems), £2m (total to UoM £4.6m), **Harou** and seven other CoIs, 30 collaborators including Southampton, UCL, Newcastle, Cambridge, Yangon (Myanmar), Ghana Energy Commission, and six project partners including Nature Conservancy, International Union for Conservation of Nature, and the World Bank, USA.
- EPSRC Graphene Engineering with Graphene-based membranes**,** £1.3m (total to UoM £2.8m, 2013-18), **Holmes**, **Siperstein**, **Haigh**, **Kinloch**, and others with Leeds, Calgary, and nine project partners including AkzoNobel, DSTL, ITM Power and Electrochemical Energy Storage with Graphene-Enabled Materials, £1m (total UoM £1.9m, 2013-18), **Todd**, **Forsyth**, **Kinloch** and others with Liverpool and eight project partners including Qinietiq, Technical Fibre Products, Johnson Matthey, Rolls-Royce.

3a.3 Prosperity partnerships

UoM holds four Prosperity Partnerships, the joint highest within period. The Unit leads three:

- CAFE4DM (Centre in Advanced Fluid Engineering for Digital Manufacturing), EPSRC £2.3m, Unilever £4.5m, lead **Hardacre** with STFC, Essex and project partner Unilever.
- SusCoRD (Sustainable Coatings by Rational Design), EPSRC £3.0m, AkzoNobel £3.0m, lead **Lyon** with seven UoM CoIs and Sheffield and long-term strategic project partner Azko Nobel, with collaboration from end-users Tata Steel, Airbus, Crown Packaging.
- Preventing Surface Degradation in Demanding Environments, EPSRC £1.7m, BP £1.7m, lead **Withers** with six UoM CoIs and Cambridge, Imperial, Edinburgh, Leeds and project partner BP International.

Several academics are also directly involved or lead multiple framework agreements with strategic partners including **M. Smith**, **Iacovides** with EDF, **Abram** with NNL, and **Jones** with ONR.

3a.4 Major non-consortium research awards

In addition to support from research consortia and partnerships, the following major awards were made:

- Four RAEng Research Chairs **Xiao**, **Prangnell**, **Kinloch**, **Lennox**, 2 Royal Society University Research Fellows **Race**, **Nair**, UKRI Future Leadership Fellowship **Boland**, EPSRC Established Fellowship **Saunders**.
- ERC Starting Grants **Haigh**, **Nair**, ERC Advanced Grants **Withers**, **Matthews**, total support £4.8m.
- EPSRC SIMFUEL and Alpha-Active Material Manufacturing and Characterization Facility, £5.5m, **Abram**.
- EPSRC-UKCRIC National Centre for Infrastructure Materials: Extreme Loading Facilities, £3.0m, **Y Wang**.
- EPSRC GEMS (Geometric Mechanics of Solids), £1.3m, **Jivkov**.
- ERC MATTERDESIGN (New Science and Technology of Artificial Layered Structures and Devices), £1.0m, **Nair**.
- UK Charity To Find a Better Way SEMIS (Scanning Electromagnetic Inspection Systems), £1.6m, **Peyton**.

3a.5 Links between funding and high-quality output or impact

The following are highlights from across Themes (see also §1c.3):

- EU Graphene Flagship (including renewals in period) led to at least eight review and research papers in the Scopus top 1% field-weighted percentile.
- EPSRC LightForm Programme led to seven papers from the Unit in the Scopus top 5% field-weighted percentile and >35 papers with co-authors outside the UoM.
- EPSRC RESNET (2011-16) on electrical power systems resilience to extreme weather led to three papers in the Scopus top 1% field-weighted percentile and further EPSRC funding with researchers in Chile, culminating in the Chilean adoption of the project's planning tool and a 2018 Newton Prize for **Panteli** and **Mancarella** (§4a.1).
- The bp-ICAM grant led to understanding the mechanism of metal-based lubricant additives, such as molybdenum sulphide and ZDDP, with an almost a fourfold reduction in wear. The grant also improved understanding of causes of the failures due to environmental stress crack corrosion, with potential value to BP of $1m-$10m due to reduced maintenance and replacement.
- Electricity North West (ENWL) funding through Ofgem's Low Carbon Networks Fund Tier 1 Project led to a paper in the Scopus top 5% field-weighted percentile and contributed to the formulation of ENWL's Smart Street project on voltage control techniques (total £11.5m, www.enwl.co.uk/smartstreet).
- NG funding for research on new markers for ageing transformer insulation contributed to CIGRE technical brochure 779 and an IEC international standard adopted by NG for ~1,000 power transformers. In separate NG-funded research, a benign alternative was identified for the potent greenhouse gas SF_6 used as high-voltage equipment insulation.
- The EPSRC award Graphene-based Membranes (2013-18) was the starting point of an influential body of work by **Nair** that led to increased funding (Royal Society, EPSRC, Innovate UK, EC, Leverhulme; see §2a, §3a.2) and prizes (Institute of Physics, Institute of Metal Research Chinese Academy of Sciences, see §4b.4), and two Clarivate Highly Cited Researcher awards.

3b. Organizational infrastructure, facilities, and expertise supporting research and their impact

3b.1 Platforms and facilities and their impact

The Unit's world-leading facilities form the technology platforms underpinning outputs and impact. They are accessible to researchers, external academics, and industrial collaborators. The creation of Royce (§1f.1, REF5a §4.2) led to further investment in sustainably operated equipment and estate and gives focus for national engagement across UoM's platforms and those of partner universities. Highlights of the investment and their impact follow:

World-class laboratories (£545m). The MECD estate project began in 2018 and will provide 18,940 m^2 of modern laboratories by 2021 (£425m), including dedicated space for other platforms. The Royce Hub (§1f.1, £105m EPSRC) adds 5,618 m^2 of space with facilities for nuclear materials, bioengineering, and sustainable polymers. ~£15m was spent refurbishing laboratories as a temporary location for Advanced Materials research during the MECD construction.

2D Materials Platforms. The **National Graphene Institute** (£62m, EPSRC and ERDF) was commissioned in 2015 and operational from 2016 with additional ~£4m investment (UoM, EPSRC, EU) in laboratories (2016-19). The NGI has 7,000 m^2 of floorspace including 1,500 m^2 of clean rooms. It has the world-first integrated UHV dry transfer and characterization system (patented by UoM under Royce funding). Other platforms include graphene and 2D materials ink formulation and functionalization facilities, CVD growth, 2D/3D printing laboratory, scanning microscopy facility, optical characterization facilities (Raman, low-T photoluminescence), adaptive optical materials laboratory (IR/THz), electrical magneto-transport facilities (10 miliKelvin 14Tesla Oxford Instruments Titan), thermoelectrics laboratory, membrane laboratory, energy laboratory and nanocomposites laboratory (fabrication and testing). The **GEIC** (£50m, HEFCE RPIF, Masdar UAE, Innovate UK) was commissioned in 2016 and opened in 2018. It contains £10m (ERDF, Greater Manchester Combined Authority) of pilot scale facilities including spark plasma sintering, graphitization furnace, thermoplastic processing, thermoset composite processing, first roll-to-roll CVD machine from Aixtron, MOCVD machine, custom membrane pilot line, dry room with battery assembly line and printing laboratory. **Contribution to impact**: the **NGI** and **GEIC** together give the capacity to take work from fundamental concept (TRL1) to pilot-scale demonstrators (TRL5) through academic-industrial collaboration on the University campus. NGI provides the laboratory platform for joint academic-company projects, e.g. Petronas, Morgan, Sony, Lockheed Martin, Alpha Metals, Lifesaver, and Colloids have all embedded their researchers in the NGI. Licences from company collaborations include Inov8 (**Vijayaraghavan**), First Graphene (**Kinloch**) and Lifesave (**Nair**). GEIC Tier 1 industrial members (e.g. First Graphene, Gerdau, Haydale) have dedicated laboratory space in the building and ~100 days of equipment access per year and Tier 2 members (e.g. Highways England, QinetiQ) have 30 days of equipment access per year. These Tier members have to date used 700 days of access time (~£4m value). The NGI/GEIC also hosts 20 University spin-outs including Graphene Industries, SmartIR, LowDee, Molymem, Bespoke Crystals, Grafine, and Atomic Mechanics.

Photon Science Platform. The PSI houses 18 Unit staff among its 33 academics and has photonic, electronic, magnetic, surface science and materials structural characterization capabilities with a >£20m investment, including X-ray to THz ultrafast laser sources, Raman spectroscopy, world's first tool for single-ion doping of materials for quantum technologies and cryogenic, ultrafast, scattering-type THz-probe optical pump microscopy (EPSRC Equipment CUSTOM, £0.8m) facility for imaging single ion dopants, plasmonic modes, and Dirac surface states in topological insulators. The **Optical Sensing Lab** has facilities for combustion diagnostics

and gas sensing, including gas handling, fume extraction, high-pressure and turbulent burners, lasers for sensing and imaging of key gas species and particulates. **Contribution to impact**: The systems for CO_2 imaging on jet exhaust analysis are installed at the Instituto Nacional de Técnica Aeroespacial (INTA), Madrid, and the systems for analysing non-volatile particulate emission from jet-engine are under development with Rolls-Royce.

Cross-Scale Imaging. The **Electron Microscopy Platform** is one of the UK's largest with 5 TEMs, 13 SEMs and 5 focused ion beam (FIB) instruments (£11.6m in period). The **Henry Moseley X-Ray Imaging Centre** (**MXIF**) expanded into new laboratory space in 2014 aided by £17m RPIF and £4.2m EPSRC capital grant. (§3c.3). The MXIF has seven microCT scanners (MCT), including the UK's fastest (Rapiscan RTT110), versatile custom bays, and the highest-resolution laboratory-based MCT (Zeiss Xradia 810 Ultra) (§1f.1). In 2020, the Unit led the successful National Research Facility for Laboratory X-Ray CT bid with UoM as a hub (UoM, £6m) and Southampton, Warwick and UCL as spokes (£4m). **Contribution to impact**: Electron microscopy supports >450 internal users from 12 different university departments and the MXIF has supported >3,000 total users. Overall external access is reported within the Royce access (§3b.4)

Bioengineering Platform. The platform has invested in equipment to improve make, characterize and test capability, delivering greater resolution, throughput, and reproducibility (£7.5m in period). It hosts bioadditive manufacture and printing platforms, fibre-spinning facilities, and advanced imaging facilities. The biomechanical testing and evaluation suite (~£1m, Royce) can test multiple samples in biologically relevant conditions. **Contribution to impact**: Manchester BIOGEL spin-out's hydrogels are undergoing animal trials for nerve repair and anal fistula regeneration, and the imaging facilities are used by the Manchester University NHS Foundation Trust.

Metal Processing Platform. The platform hosts £6m of thermomechanical processing facilities (including instrumented sheet-forming press, cold rolling mill, quenching dilatometer, Gleeble simulator, and Zwick test frames) and advanced joining and cladding facilities (a micro-electron-beam welder, as well as robots and instrumented welding equipment for large-scale material addition). Combined with Royce Advanced Metals Processing at Sheffield, the platform offers unique UK capability. **Contribution to impact**: The equipment has been heavily used by internal and external researchers and by industry, e.g. nearly 900 hours on the dilatometer over six months in 2019-20, with ~20% from industry, of which half was for SMEs. The platform's Materials Testing and Analysis unit specializes in determining residual stress by X-ray diffraction and is an approved supplier to Rolls-Royce for this technique. More than 130 other companies have also used this service (e.g. for the measurement of retained austenite in the rolling bearing industry).

Nuclear Platform. The platform underpins UoM's role as a leading UK institution in nuclear engineering, with 80 academics in UoM, 30 in the Unit. It has four sub-platforms:

- **Nuclear Fuels**, founded in 2013, supports the academic branch of the UK Nuclear Fuel Centre of Excellence (NFCE), enabling unsealed samples of alpha-active nuclear materials to be safely manufactured, characterized, and tested. The facility includes a suite of atmosphere-controlled glove-boxes for radioactive powders, and manufacturing equipment for preparing nuclear fuels and waste-immobilization materials representing commercial products. It received £3.1m funding in period to research accident-tolerant fuels (£1m from DECC in 2015, £2.1m from BEIS, through NNL in 2017) and £1.9m for molten salts in nuclear technologies (NNUF, **Sharrad**). **Contribution to impact**: The NFCE facilities attracted funding for key research activities. BEIS, through NNL, provided £1.1m in 2017 and an extra £1m to support research into advanced materials for accident-tolerant fuels.

Rolls-Royce has used the facility (through several PGRs) to research nuclear fuel materials.

- **Graphite** has specialist storage, fume-hoods and furnaces with associated gas characterization for active materials and impact excitation for dynamic Young's modulus measurements. **Contribution to impact**: Experimental measurements have enabled the Office for Nuclear Regulation to robustly challenge licensees operating Advanced Gas-cooled Reactors (AGRs) for up to a further 10 years, reducing potential CO_2 emissions (ICS **Jones**).
- **Thermal Hydraulics** has rigs for investigating rotating flow water, liquid injection into a vapour chamber and fluid structure interactions. It also has a high-flow internal air flow facility and large differentially heated cavity for the investigation of natural convection flows. Heat and fluid flow diagnostic techniques include Particle Image Velocimetry, Laser Doppler Anemometry, Phase Doppler Anemometry, and thermo-chromic liquid crystals. These facilities were established through investment from EDF-Energy, Rolls-Royce Nuclear, Magnox, EPSRC, and the North West Development Agency. **Contribution to impact**: Information on pressure losses in AGR fuel passages has been used by EDF-energy to validate their CFD codes. Quantification of heat transfer across AGR thermal insulation packs has been used by EDF-Energy (Barnwood) to develop their safety case for the AGR hot-box dome. Research on flow-induced vibrations of PWR fuel rods led to an invitation to join the VIKING consortium (EDF-France, Framatome, NRG, Vattenfall, and others). Work on characterization of water jet injection in PWR pressurisers is in progress and will be used by Rolls-Royce Nuclear.
- **Robotics for Extreme Environments Lab (REEL), Cumbria** has 300 m^2 of laboratories housing £2m of state-of-the-art robotics equipment including ABB and Kuka manipulators, mobile vehicles (aquatic, ground-based and aerial), sensory systems such as LiDAR, 3D cameras, and vision-based positioning systems for use in submerged and ground-based environments. There are large-scale mock-ups of nuclear challenges, including a storage pond and special nuclear material store. There is permanent accommodation for eight UoM research staff, and for seconded engineers from Sellafield (£0.9m NNUF equipment grant). **Contribution to impact**: Work has led to 10 deployments of robots into active facilities, four subsystems bought to market, and two spin-outs.

Pilot Plant Platform. The Unit has one of the largest university pilot-plant facilities in Europe with its own mechanical and electrical workshops and essential infrastructure (e.g. steam lines, optical-fibre connections) to facilitate large-scale, industrially relevant research. It is fully controlled with state-of-the-art Siemens software (PCS) and maintains strong links with Siemens. It underpinned the Centre in Advanced Fluid Engineering for Digital Manufacturing, CAFE4DM (£3m EPSRC, 2017, §3a.3) with pilot food-processing and ice-cream plants. **Contribution to impact**: Research is being deployed by Unilever in a digital twin to design a completely new facility for product personalization. Additionally, NIR, FTIR, and Raman spectroscopy are being evaluated at Unilever for shampoo-viscosity measurements for suitability in a factory environment.

Electrical Systems Platforms. These platforms span research from vehicle to national-grid scale simulation and test facilities. The **National Grid High Voltage Lab** is the UK's largest university HV laboratory and the only facility capable of operating at the voltage levels required for the UK 400kV power system. New equipment (EPSRC £1.9m) includes 800kV AC and 600kV DC test sets complementing the 2MV impulse generator. The laboratory supports research ranging from understanding fundamental high-voltage issues to applications in the field. The **Rolls-Royce Intelligent Electrical Power Networks Evaluation Facility** has a state-of-the-art 100 kW, 540 V

DC aircraft electrical systems demonstrator that supports fundamental and applications research. The **Grid-Scale Energy Storage Facility** is a 250 kW, 180 kWh, campus-based, grid-linked battery storage system with flexible control and high-power cell-testing systems. Our **Hardware-in-the-Loop Grid Emulator** is one of the UK's largest university facilities of its type, enabling the development of power system digitization and smart-grid technologies, e.g. with NG and Scottish Power to investigate digital sub-station technologies. **Contribution to impact**: This facility underpinned an ICS (**H. Li**). A research fellow has provided flexible support for short-term industrial projects, which delivered a range of impacts into the collaborating organizations, including Siemens, SSE, Carillion, NG, and Western Power Distribution. Rolls-Royce staff tested a prototype 140 kW starter-generator for small regional gas turbines.

Computational Platform. The Computational Shared Facility (CSF) provides a stepping-stone to regional, national, and international supercomputing facilities in the Unit's research. Staff influence the future provision of computing infrastructure through leadership roles in the UK and Europe, in organizations such as STFC, UKACM, and PRACE (https://prace-ri.eu), also N8-CIR (https://n8cir.org.uk/). **Contribution to impact**: Investment in the CSF has enabled a portfolio of >30 funded engineering projects that use, develop, or extend algorithms and computer software for virtual engineering, including two Prosperity Partnerships (CAFE4DM and SuSCoRD, §3a.3). The CSF was acknowledged in >100 of the Unit's publications.

Internal investment in well-found laboratories and midscale platforms. UoM invested £2.8m internally on small-scale (<£50k) items and >£4m on mid-scale (>£50k) equipment in the Unit through internal bidding.

Benefits in kind. Contributions provided by partners for platforms include the following:

- FEI Company (subsequently Thermo Fisher) embedded their staff (**Burnett**, §2a.5) to work on the combination of 3D imaging using X-ray CT and FIB-SEM serial sectioning at Manchester, and adopted in their commercial software from 2012 to 2015. FEI donated a Heliscan CT (£1m, 2015) machine to the UoM imaging centre.
- Morgan Advanced Materials loaned a pilot-scale reactor to the NGI to collaborate on scaling-up graphene production (§3b.1).
- The Unilever research laboratory in the Pilot Plant focuses on the rheology of the Unilever products and has a range of high-volume, high-pressure mixing equipment donated by Unilever.

3b.2 Technical support

Our technical staff are essential to supporting and extending the capabilities of our platforms and training users. In July 2020, we had 20 senior experimental officers (SEOs), 55 experimental officers (EOs), and 64 technicians with research-related duties. Specialist support includes EM (4 SEOs, 3 EOs), X-ray Computer Tomography (2 SEOs, 2 EOs), high-temperature processing (2 technicians), mechanical testing (1 SEO,1 technician), composite and polymer manufacturer (2 EOs, 2 technicians), High Voltage and Current Laboratories (2 EOs), and the MBE platform (1 SEO, 2 EOs). There are also 30 technicians in the Unit's electrical and mechanical workshops. The NGI is supported by 14 EO/Technicians and the GEIC is supported by 5 Application Managers, 6 Application Specialists, and 3 Technicians.

Technical support is increasingly sustained by adapting our platforms to a facility model for sustainable operation and cost recovery (§4a.3).

3b.3 Ensuring EDIA in facilities

Two of the four leadership roles in facilities are held by women (ADR for Facilities and Head of the EM Centre). Women accounted for a third of interviewees at the Unit's four successful bids to the EPSRC Strategic Equipment bids since 2017. ECRs are given priority in Core Equipment funds over the last three years to enable platforms to reflect future research demands. In 2016, 10% of the investigators on our EPSRC grants were female, increasing to 19% in 2019.

Physical access to facilities is considered through UoM's planning and operational processes. All are fully wheelchair-accessible and all our buildings have disabled toilet facilities, wide door access, and accessible light switches and swipe pads.

3b.4 Cross-HEI shared use of research infrastructure, including major research facilities in UK and overseas

Royce. To increase cross-HEI and industrial usage, Royce has developed seamless access to all partner Royce facilities with a unified equipment list for each theme independent of location. Total external and industrial access to UoM platforms through Royce (2018-20) was 8,900 hours and 5,400 hours (62 unique companies) respectively in period. Access was sustained by one-third recurrent funding (£8m to UoM) and sustainable pricing to enable world-leading support and access.

University of Manchester at Harwell. UoMaH is a portal to DLS, ISIS neutron source, Central Laser Facility (CLF), and the Scientific Computing Department (SCD) at Harwell. UoM has invested £1.3m annually (since 2018) and embedded a technical team of seven at Harwell with eight Fellows split-site to provide access for academic and industry users and to advance new techniques. UoMaH offers materials expertise and storage capability, radioactive-sample handling, and manufactures specialist containment cells for toxic materials for DLS, CLF and ISIS. Its partnership with 3Dmagination provided courses in reconstruction and analytical techniques to users of the National Laboratories. Collaborations are in place with HSE, UKAEA, Culham, Johnson Matthey, US National facilities, Cranfield University, BAE, AWE, and UKSA. Access to Harwell facilities is also a significant component of the research of the UK Catalysis Hub. **Haigh** and **Burke** contribute to management and external review of facilities at Harwell. **Haigh** is a member of the User Steering Group for the proposed I05 upgrade and new nanoARPES beam. **Burnett** is a member of the Working Group for Dual Imaging and Diffraction (DIAD) beamline at DLS.

SuperSTEM. This aberration-corrected scanning transmission electron microscopy (STEM) facility at the STFC's Daresbury campus is run by a consortium of Universities (Manchester, Leeds, Liverpool, Oxford, Glasgow, and York). A £7m investment was secured in 2017 for a third STEM instrument and complementary sample-preparation capabilities. During 2012-17, SuperSTEM assisted 190 distinct users (from 17 different countries) on 245 projects, resulting in >206 publications.

High-Supersonic Tunnel. HSST is the only operational blowdown wind tunnel in the UK offering long duration at high Mach numbers (4, 5 or 6 continuously for ~8 seconds). Since 2015, UoM has invested £70k to replace several of its ageing components and upgrade its flow measurement instrumentation. It was included in the National Wind Tunnel Facilities Initiatives in its second phase in 2019. Development of flow-diagnostic techniques for industrial-scale experiments, including PSP measurements with miniature cameras and background Schlieren, has led to collaborative wind-tunnel campaigns at the transonic wind tunnel at ARA and other European facilities (e.g. H2K wind tunnel at DLR Cologne).

Computing Resources. Time on the UK National Supercomputing Service ARCHER is provided through the UK High End Computing (HEC) Consortia, UK Turbulence Consortium, the UK Consortium for Mesoscale Engineering Science, and through direct Research Allocation Panel applications. The combined average given to researchers in the Unit is 75 MAU/year (equivalent notional cost of £45k/year), enabling them to generate publications and reference data to validate software and methods. Tier 2 HPC facilities such as CIRRUS, as well as the Hartree supercomputer, are heavily used for industrial projects, mainly with Unilever. A successful bid to use JADE, the Tier 2 facility running state-of-the-art GPU hardware, enabled us to test our research on fluid-structure interaction. Successful demonstration of our methods led to grants from Jaguar Land Rover (JLR), BAE Systems, Solomon Commercials, and others amounting to ~£450k. There has also been significant use of N8 HPC 2014-18, subsequently replaced by N8 Bede.

UK Facilities. Thirty-two Unit staff have led 136 projects (£6.9m of beamtime) at DLS. Other facilities accessed include ISIS (195 days), Warwick Centre for Ultrafast Spectroscopy (15 days), Laser at Didcot (15 days), and EPSRC National Ion Beam (20 days).

European synchrotron sources. Staff accessed ~240 days at non-UK facilities (e.g. ESRF, Petra-3, Elettra, ILL, SNS, APS, Astrid and MAX IV).

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

4a. Research collaborations, networks and partnerships

We strengthened our support for and expanded our collaborations, networks, and partnerships over the REF period, nationally and internationally.

4a.1 Collaborations with academic colleagues

The Unit's individual collaborations are world-wide. As an indication of reach, our researchers co-authored >650 papers with colleagues from the world's top 20 universities (THE World University Rankings), including Caltech, Columbia, Cornell, Harvard, Johns Hopkins, MIT, Princeton, Stanford, Berkeley, UCLA, Universities of Chicago and Pennsylvania. The award of 101 Marie Skłodowska-Curie ITNs, IFs, and RISEs helped develop training networks, fund mobility programmes, and promote staff exchanges. Since 2017, the Unit had 71 awards associated with other UK HEIs totaling £57.6m. Examples of formalized academic collaborations follow:

- Institutional research partnerships with the Universities of Melbourne and Toronto (§4a.1) led to eight joint engineering PhD students with Melbourne and six projects in engineering with Toronto.
- Institutional research partnerships established with the Universities of Tokyo, Tsinghua, Tianjin, and Jilin in porous materials and catalysis led to a H2020 Marie Curie RISE project (ZEOBIOCHEM, **Fan**).
- Joint professorial staff appointments were made with the University of Melbourne (**Mancarella**, **Ochoa**) and with the University of Chile. Collaborative research has resulted, supported by two Newton Projects, and involving the University of Chile, on disaster management and resilience in electric power systems (**Mancarella**). The first Newton project led to adoption of the project's resilience planning tool by the Chilean electricity coordinator, and in turn to investments against earthquakes of over $50m and award of a 2018 Newton Prize to the Universities of Manchester and Chile (§3a.5). The second project was extended to include Chile and Costa Rica.
- A partnership with two leading universities in Zambia (University of Zambia and Copperbelt University) was underpinned by a five-year MoU between the Universities of Zambia and Manchester (**Mutale**) to improve engineering research and education in the country's development. More than US$4m was raised including construction of a 66/11 kV demonstration substation featuring the latest ABB digital control to benefit >500 students and staff.
- A collaboration with Xiamen University, China and Technical University of Malaysia was established on resilient and sustainable electrification through the GCRF scheme (TERSE, **Mancarella**). Emerging impact includes the Ministry of Utility in Sarawak increasing energy to remote, off-grid households.

4a.2 Collaborations with research users

- Interaction has been facilitated with KTPs and IAAs (§1e.1). For example, five KTPs focused on the properties of elastomers for vibration and isolation systems for Ferrat (**Oyadiji**), a new measurement tool for the Aircraft Research Association (**Quinn**), a new condition-monitoring technology in turbine blades as well as early-stage detection in the main turbine governor valves for EDF Energy (**Sinha**), and capability for a sludge-removal system for the Fukushima decommissioning site (**Weightman**).

- Examples of relationship-building include work with the Defence Science and Technology Laboratory on environmental protection for gas-turbine engines (**Bojdo**) and with Maplebird on industrial applications of flapping-wing robots (**Nabawy**).
- Proof-of-concept projects with users include visualizing trade-offs for Thames Water (**Harou**), investigating reactor pressure vessel microcracks for AMEC (**Jivkov**), and examining the role of Cobotics (UK) in improving manufacturing with Procter & Gamble (**Weightman**).
- Engagement has been secured through secondments (§2a.5), e.g. with EDF (**Sinha** and **Rogers**), Unilever (**Prosser**), Siemens and JLR (**Revell**), Anglian Water (**Harou**), TATA steel (**Y. Wang**), the NHS (**Keshmiri**). Others in §2a.4, §2a.5.
- Collaborations with Rapiscan and Safeline Systems led to the companies funding lecturers (respectively **O'Toole**, 2019-24, **W. Yin**, 2012-15) and contributed to the Queen's Award for Enterprise in the Innovation Category (2016). Other collaborations included EDF Energy in monitoring the graphite core of the UK's AGRs and with Primetals Technologies and Tata Steel in licencing the EMspec technology for non-destructive characterization of steel microstructures.
- Collaborations with Sellafield Ltd have continued to develop the AVEXIS, MIRRAX and CARMA robots for radioactive environments (see §3b.1), with the company funding £400k and £2m in kind. Collaboration with Dounreay Site Remediation (DSRL) and the Atomic Weapons Establishment led to the first robot to be deployed into the active waste storage facility at Dounreay. Work with the Jožef Stefan Institute in Slovenia resulted in the first aquatic and ground based robotic surveys of an operational nuclear reactor.
- Collaborations with NNL, Forth Engineering, Atomic Weapons Establishment, EDF, GE, Braendler Engineering, and Nuvia were instrumental in securing the Robotics for Nuclear Engineering Programme Grant (£4.6m EPSRC) and the RAIN programme (£12.2m UKRI) with 37 project partners (§3a.2) led by **Lennox**.
- Interactions have been advanced through framework agreements (§1e.2, §3a.3), e.g. with NG for composite insulators, with Rolls-Royce UTC in Electrical Systems (£400k/year direct funding), and several EU projects (SuSTAINABLE, NOBEL GRID, MIGRATE, CROSSBOW), all involving transmission and distribution companies from Europe and the UK including TSO from UK, Germany, France, Spain, Estonia, Bosnia and Herzegovina, Montengro, Croatia, Serbia, North Macedonia, Greece, Romania, Bulgaria, Italy, Portugal. Examples of impact include a load-forecasting tool applied by EDP Portugal (SuSTAINABLE), a demand-disaggregation tool for distribution networks in Spain and Greece (NOBEL GRID), and a Network Reliability Asset Replacement Decision Support Tool applied by NG.

4a.3 Collaboration through Research Centres and Institutes

We collaborated on projects through multiple interdisciplinary Research Centres and Institutes (infrastructure and impact in §3b):

- **bp-ICAM** (§1f.1) supports Unit-led research through its EPSRC Prosperity Partnership (§3a.3) with Cambridge, Imperial College, Sheffield, Leeds, and Edinburgh.
- **National Graphene Institute** (§1f.1, §3b.1) acts in a hub-and-spoke model with UK Universities Bath, Cambridge, Exeter, Imperial, Lancaster, Nottingham, Oxford, Sheffield, Southampton, UCL, Warwick, and cooperating with academic institutions overseas, Chalmers University, CNR (Italy), CNRS (France), Columbia University, ETH Zurich, Geneva University, Harvard, Italian Institute of Technology, National University of

Singapore, NIST (Japan), Yale, and engaging with businesses Alpha Metals, Graphene Industries, Haydale, Petronas, Rolls-Royce, Sony. Studies have been scaled-up with Morgan Advanced Materials and Petronas and licenced to First Graphene.

- **Photon Science Institute** (§1f.1 and §3b.1) underpins national collaboration with UK academia and industry through Royce with TRAC-costed access to its expertise and facilities (§3b.2). Internationally the PSI has strategic collaborations with the Universities of Melbourne and Toronto (§4a.1), and with Harvard, Ghent and the BP Koirala Institute of Health Science (Nepal), supported by a UK GCRF award. Advances in detection technologies have been translated to CERN, supporting collaborative research in exotic atoms at the limits of nuclear existence. With Ionoptika, **Curry** led the development of the P-NAME system and its prototype SIMPLE (EPSRC, £3m, sited at the National Ion Implantation Centre, University of Surrey), which was subsequently launched as a commercial tool (Q-One).
- **Dalton Nuclear Institute** (§1f.1) supports a wide academic and industrial community. Its academic partners include Surrey, Huddersfield, Imperial, Lancaster, Leeds, Liverpool and Sheffield and non-academic partners NDA, Sellafield Ltd, Radioactive Waste Management, AWE, Rolls-Royce, EdF Energy, Jacobs, NNL, BEIS, MoD, UKAEA, Office of Nuclear Regulation, CEA and IAEA.
- **Thomas Ashton Institute** (§1f.1) is a partnership with the Health and Safety Executive (HSE) with networking activities that include the Oil and Gas Technology Centre, Offshore Renewable Energy, Food Environment Research Agency, Yorkshire Water, OFGEM, Global Offshore Wind, Lafarge Nigeria, the NHS, and the HSE's Safety and Reliability Society, Science Hubs, Futures Team, and Shared Research Programme. It has built external stakeholder networks, engaging with 58 companies from 15 different sectors including academia, construction, energy, engineering, government, transport, and manufacturing. The Institute has been supporting the national effort to combat COVID-19, and continues to deliver The Health and Occupation Research Network (THOR) funded by HSE and inform HSE guidance with funding by the Lloyds Register Foundation.
- **Rolls-Royce University Technology Centre** (§3a.1) has worked with mainly EU and US companies including Liebherr, Liebherr Aerospace, Nexans, IRT, Tyco Electronics, Microsemi, Knowles Capacitors, Technalia, Deep Concept, Applied Superconductors, Hyper Tech Research and Columbus Superconductors. The collaboration with Hyper Tech Research in the US led to further collaboration with the US Air Force through the US/UK Windows on Science program.
- **Northwest Composites Centre**, which is part of the Polymers, Composites and Textile subtheme, has collaborated with partners from the USA, Japan, Singapore, China, India, Italy, France, Portugal, and Brazil. Industrial collaborations led to an ICS (**Potluri**) developed with Cygnet-Texkimp and projects including with major prime companies (Airbus, BAE Systems), Tier 1 suppliers (GE Aviation, Collins Aerospace, GKN) and Tier 2 suppliers (Axon Automotive, Sigmatex) (£3.5m within period).
- **Tyndall Manchester** (§1f.1) has partners within the UK and internationally (Latin America, Southeast and East Asia, and Africa). Researchers have regularly worked with Government departments and Select Committees, multiple Local Authorities, the UN, large organizations e.g. Electricity North West and NG, also SMEs (e.g. DSposal, K Lowther & Co, and Alfred Enderby), NGOs (e.g. Friends of the Earth), and community groups. Our researchers took up visiting positions at Uppsala, Bergen, and the International Rice Research Institute (Philippines). Public engagement activities included collaborations with artists on

exhibitions and events such as the Climate Control Exhibition in the European City of Science programme 2016.

- **National Grid Power Systems Research Centre** (including National Grid High Voltage Laboratory, §3b.1) develops commercial solutions to electrical network challenges and has worked with Scottish Power Energy Networks, M&I Materials, Shell, Weidmann, EPRI, SGB-SMIT, UK Power Networks, TJH2B, Hyosung, SSE, Prysmian, EPRI, NPL, and EA Technology. Success is illustrated through two ICSs (**Z. Wang**, **Rowland**).
- **Henry Moseley X-Ray Imaging Centre** (§3b.1). External users in the last two years of the period came from Universities, Cardiff, Leeds, Bath, Birmingham, KCL, London, QUB (Ireland), Weizmann Institute (Israel), Nelson Mandela University (SA), and from industry, Sasol, BP, Nanoco, Oxford Instruments, UKAEA. The MXIF has supported >3,000 users within period.

4a.4 Contributions to economy and society

Contributions include environmental policy, improved manufacture, robotics, sports, and music production.

- Policy engagement by Tyndall Manchester influenced carbon target setting from local to global scales, e.g. through presentations (e.g. **Anderson** annually at the UN Conference of the Parties), workshops and formal evidence submissions involving stakeholders such as the International Maritime Organization (ICS, **Larkin**), and Greater Manchester Combined Authorities (ICS, **McLachlan**).
- **L. Li** collaborated with JLR to develop laser surface cleaning for laser welding of aluminium alloys. From 2014, this technology, which reduces joint failures, was deployed at JLR to produce Land Rover cars with lighter aluminium car bodies (https://www.lasersystemseurope.com/news/jaguar-land-rover-sees-weight-savings-thanks-laser).
- In 2014 **L. Li** and colleagues commercialized the first super-resolution microsphere amplifying lens (SMAL) through a spin-out LIG Nanowise. With >£2.5m private investment, the lens led to an optical microscope with 50-nm resolution, which has been sold worldwide since 2019 with an annual revenue of £106k (https://find-and-update.company-information.service.gov.uk/company/08835324/filing-history).
- **Hinduja** in collaboration with ELE Advanced Technologies developed a robotic electrical chemical machining (ECM) system tailored for turbine-blade manufacturing through a KTP project. The technology has been deployed by the company for manufacturing turbine blades for aero-engines.
- **Winterburn** and **Dolman**'s 2018 spin-out Holiferm demonstrated reduced production costs of biosurfactants at two commercial sites to pilot scale. A control system was established, a scaled-up model verified, and the technology shown to produce sophorolipids from waste oil and sugar streams, offering industrial applications at low cost and risk.
- **Miller** and **Saiani**'s work on a self-assembling oligo-peptide led to PetGelDesign (founded October 2013), which after private and VC investment was relaunched in 2018 as Manchester BIOGEL, to make its hydrogels readily available to researchers in 3D cell culture, 3D bioprinting, and medical devices, with a distribution network covering Europe, India, and China. It was awarded two Innovate grants, a KTP with Imperial College to apply its PeptiGel® product, and a Sustainable Innovation Fund award to integrate its product into workflows of UK companies Cellesce and Qkine.

- Robotics research by **Lennox** and **Watson** aided by EPSRC RAIN and RNE funding (§1c.3) led to 2018 spin-out ICE9 which sold ~100 low-cost robots in 2018-20 to universities in the UK, Europe, and Africa to support undergraduate teaching.
- Manchester Robotics, launched with £240k funding from UoM's Innovation Factory (§1e.3), produced an educational tool Puzzlebot by **Stancu** and **Soutis**. It has attracted funding from industry (BAE Systems, Airbus) and been adopted for Control Systems MSc teaching, UCAS visits, and since COVID-19 for remote home use, including by UCAS participants.
- Advanced Hall Sensors, launched in 2011 by **Missous**, has continued to provide a route to exploit research into compound semiconductor, quantum-well, and Hall sensors. It received an Institute of Physics Business Innovation award in 2020 for commercializing devices based on university technology.
- **Ejohwomu** led a team of researchers from Manchester, Coventry, and Brighton Universities to deliver the rapid assessment of inhalation resistance of 150,000 uncertified medical face masks for Manchester City Council for protection against COVID-19 in 2020.
- **Vijayaraghavan** and colleagues developed a graphene-reinforced rubber composite delivering high grip and durability, with IAA and KTP projects generating underpinning data. It was patented by Inov-8 and UoM in 2017 and was introduced into athletic footwear with a new product line featuring G-Grip™. The G-series flagship shoes launched in 2018 were the first sports shoes to incorporate graphene, and were followed by Roclite G-grip shoes, also in 2018, and the first hiking shoes and boots to incorporate graphene outsoles (https://www.inov-8.com/blog/product-insights).
- **Lyon's** research with Highways England identified the cause of early failure of bridge coatings, doubling time to first maintenance and saving ~£40 per square metre of structure.
- Research from CAFE4DM, lead **Hardacre**, resulted in Unilever designing a new facility for product personalization, with the STARM algorithm being scoped for the next generation of in-silico product-innovation tools.
- Signal Wizard Systems was spun out from signal-processing research by **Gaydecki** and sells music-effects devices to professional musicians worldwide. R&D partners include the manufacturer of bespoke violins, Johannsson Violins (Reykjavik, Iceland, http://www.hansjohannsson.com/). The flagship product vSound was launched in 2018.

4a.5 Engagement with diverse communities and publics

Our outreach programmes are designed to inform and enthuse the public and to encourage school children to consider engineering as a career (§4a.6). They are also an opportunity for our researchers, especially PGRs (§2b.4) and those funded by outreach activities on research grants, to gain experience and skills in communicating research to a general audience.

Media and public-engagement initiatives

The following highlights reflect initiatives by individuals and Research Groups.

- **George** delivered the three-part Royal Institution Christmas Lectures in 2014 televised by BBC Four (https://www.rigb.org/christmas-lectures/watch/2014/sparks-will-fly-how-to-hack-your-home). Across live TV and iPlayer views for the month after broadcast the Lectures had 2.2m views, and teaching material from the Lectures has continued to be used in UK schools. The material was developed by UoM's Science and Engineering Research Innovation Hub who went on to create content for the Christmas Lectures in 2015 and 2016. George also presented programmes on engineering for BBC Four, Two, and One

North West, including *Television's Opening Night: How the Box was Born* and *Rise of the Robots*.

- The Manchester Recycled Robot Orchestra was launched by **George** to raise the profile of robotics technology among school children and the wider public. Partly funded by the EPSRC, it performed at the 2016 Euroscience Open Forum, Manchester Science Festival and Science Museum, London. It toured the UK sponsored by the Royal Academy of Engineering in 2017 with attendees in Bristol, Edinburgh, and Manchester totalling ~1,000. Behind-the-Scenes footage appeared on BBC *Make it Digital*. The project legacy continues with electronic kits for building a robot orchestra. In total, ~100,000 children interacted directly with the Orchestra initiative.
- Tyndall Manchester's researchers delivered TV, radio, and other media presentations on climate change including **Larkin**'s (then **Bows-Larkin**) 2015 Ted Global talk on Climate Change from the Royal Institution, with 1.3m views (https://www.ted.com/talks/alice_bows_larkin_climate_change_is_happening_here_s_how_we_adapt?language=en), and **Anderson**, **Larkin**, and **McLachlan**'s talks at Glastonbury 2019 and Blue Dot Festivals 2017–19.
- **Archer** was voted a 2015 winner of the UK I'm an Engineer, Get Me Out of Here! (https://imanengineer.org.uk/) and **Blanford** a 2016 winner of the UK I'm a Scientist, Get Me Out of Here! (https://imascientist.org.uk/).

Large-scale Events

Teams from the Unit participate each year in large annual public outreach events, accessing audiences who would not typically engage with science or engineering. Some examples follow:

- At ScienceX, an annual science pop-up at the Trafford Centre, Manchester (https://www.mub.eps.manchester.ac.uk/sciencex/), colleagues and students showcased their research, with over public 25,000 interactions in 2019 and an estimated 51% of under 18 attendees being from BAME backgrounds. Contributions included the bioelectronics team (§1c.3) showcasing research on flexible electronic circuits.
- At UoM's Community Festival (http://www.socialresponsibility.manchester.ac.uk/strategic-priorities/engaging-our-communities/public-events/community-festival-2019/) in 2019, with 3,000 attendees, displays included the CAFE4DM team (§3a.3) demonstrating behaviour of non-Newtonian fluids.
- At Bluedot, the award-winning weekend of discovery at Jodrell Bank (https://www.jodrellbank.net/bluedot/), which attracted 25,000 people in 2019, concert-goers engaged with our research through talks and hands-on activities, including the Lego-based Mars rover.
- At the British Science Week Science Extravaganza in 2018, the campus hosted table-top activities, lectures, and workshops, welcoming ~1,000 students aged 11–13 years over four days. Aligned with our N8 Agri-Food research network, in one of our thematic activities What is your carbon FOODprint?, students picked items in a supermarket stall and calculated the carbon footprint at checkout.
- At the Manchester Science Festival, an activity exploring interactive fluid simulation using 3D cameras was developed into the Knead for Speed: Aero Challenge, aided by an RAEng Ingenious award (2016-17). School children in groups of 20-30 designed an aerodynamic car in clay before scanning it into a virtual simulation.
- At the 2019 Pint of Science festival, the Robotics Group engaged hundreds of visitors.

- At the 2017 Cheltenham Science Festival, the Sensing Technologies group, funded by Find A Better Way, presented their Sensing Danger exhibit. Over six days it attracted ~5,000 visitors, who used purpose-designed metal detectors to hunt for objects buried in sand while learning about landmine-detection technology.

4a.6 Contribution to the sustainability of the discipline

Future engineers and widening participation

We interact with 30–40 local schools/year in visit days in which student visitors are introduced to our staff and researchers and state-of-the-art facilities (e.g. electron microscopes). Since 2017, our Armourers Ambassadors (supported by the Armourer and Brasiers Company) have made up to 20 visits a year to local secondary schools delivering activities such as chocolate impact testing. Extended interactions have also been fostered through our CDTs. The NOWNANO and M4DE CDTs (§2b.2) each encourage public engagement activities, e.g. M4DE has run science projects over several weeks with student groups from four local schools and colleges. Each year, at least six students from disadvantaged backgrounds have been hosted on the Nuffield Research Placements scheme.

Our residential Materials Science Summer School, held yearly since 2015, hosts 20–40 Year-10 students, giving them a flavour of university life. Between 30% and 50% of attendees come from disadvantaged backgrounds and are helped by bursaries we provide to reduce attendance costs from £300 to £25. Over 80% of attendees rated the Summer School as good or excellent, with some schools in disadvantaged areas sending students year after year.

Internationally, the Unit's staff have been approached to assist e.g. with US high school projects. While small in scope due to their individual nature, we contributed to projects on 3D printing a students discovered our work through our Open Research activity (§1g).

Other examples of widening-participation activity follow:

- UKRI Future Leadership Fellow **Boland** ran the #signscience campaign providing sign language STEM outreach, with >10k views.
- Our Women of Science campaign was initiated by PGR **Archer** in 2016, using funds won through I'm an Engineer Get Me Out of Here (§4a.5). The campaign educates the public on issues concerning equality in STEM and was awarded the 2020 Robert Perrin medal from IOM3 for outstanding commitment to outreach activity.
- Since 2014, ~20 PhD students acted as Widening Participation Fellows, delivering over 1,000 hours of engagement activities with schools in disadvantaged areas.
- Since 2016, ~15 PGR students supervised research projects for the Manchester Access Programme (MAP), each year, a scheme supporting local students from low-participation neighbourhoods to apply to research intensive Universities.
- Since 2017, we have run the IET Faraday STEM activity challenge for 4-6 widening-participation schools (teams of 5–6) giving them experience of the University campus.
- Since 2018, PGR students provided workshops to support an IntoUniversity centre in North Manchester, part of a national initiative offering an after-school club for local widening-participation students. One PGR was nominated for a National Education Opportunities Network Award for their individual contribution (2018).
- To engage girls with engineering, our academics and researchers ran the Who Do You Want to BEE day in 2019 where 140 girls from Years 5 and 6 in targeted schools took part

in workshops, talks, and speed networking. This activity was paired with the Athena Swan team's support of female staff and students.

- In 2019 UoM secured a sponsorship of £10k from Whirlpool to expand the regional final of the IET First Lego League, a robotics competition for school children. Through the sponsorship the event doubled in size to 90 children and 20 teachers in widening-participation schools.

Committee membership of learned societies and professional organizations

Staff served on >70 committees of learned societies and professional organizations, including the following:

- **Ainsworth** Chair Welding Institute Engineering Research Committee
- **Barnes** CIGRE Working Group B4-57
- **Blanford** Faraday Division Council RSC; Vice-Chair, Joint Colloids Committee RSC
- **Bourne** Business & Community Engagement HSE
- **Burke** President Royal Microscopical Society
- **Carbone** IUPAC Polymer Terminology
- **Cartmell** EC COST Biomedicine and Molecular Biosciences Domain; Council Tissue Engineering and Regenerative Medicine International Society, EU Chapter; Secretary UK Tissue and Cell Engineering Society
- **Cernik** Vice-Chair European Powder Diffraction Committee
- **Cotton** CIGRE Working Group D1.63
- **Ding Z.-T.** Technical Committee (TC) Nonlinear Systems and Control, IEEE Control Systems Society; TC Adaptive and Learning Systems, International Federation of Automatic Control
- **Dudek** IEEE Neural Systems and Applications TC; Chair Sensory Systems TC IEEE Circuits and Systems
- **Edmondson** MACRO Group RSC
- **Fan** Committee British Zeolite Association
- **Filippone** Aerospace Technology Institute, Aerodynamics Strategic Committee
- **Freer** European Ceramic Society Trust
- **Gardner** President International Society Clinical Spectroscopy
- **George** Vice President IET
- **Gong** BSI TCI/024, Physical Testing of Textiles
- **Grieve** IET Standards Smart Agriculture
- **Gresil** Chair Structural Health Monitoring, British Institute of Non-Destructive Testing; American Society of Mechanical Engineers NDE Committee
- **Heath** IEEE Control Systems Society TC System Identification and Adaptive Control
- **Jarman** Chair International Electrotechnical Commission (IEC) TC14
- **Jivkov** Chair TC2 European Structural Integrity Society
- **Joekar-Niasar** Chair UK Chapter International Society of Porous Media
- **Katnam** IAG for NPL Composites, Adhesives and Polymers
- **Keshmiri** Council IMechE
- **Kopsidas** ECOFYS European Copper Institute
- **Lea-Langton** Combustion Institute Committee; UK Aerosol Society Committee; Society of Automotive Engineers Committees

- **Leay** Treasurer Miller Trust for Radiation Chemistry
- **Lennox** Vice-chair IChemE Process Management and Control SIG
- **Li L.** Vice President of Association of Industrial Laser Users
- **Li Y.** China National Textile Standard Technology Committee
- **Majewski** IoP Printing and Graphics Science Group Committee
- **Martin** Chair, Biochemical Engineering SIG, IChemE; Medals & Prizes Committee IChemE
- **Masters** Chair British Liquid Crystal Society
- **Matthews** UK Tribology Network Steering Committee (IMechE, IET, IOM3, IOP); IOM3 Engineering Division Board; Society of Vacuum Coaters Board
- **Moore** UK Surface Analysis Forum
- **Ozanyan** Vice-President for Publications IEEE Sensors Council; e-Books Editorial Advisory Board, IOP
- **Pereira Da Fonte** Fluid Mixing Processes SIG (IChemE)
- **Persaud** President International Society for Olfaction and Chemical Sensing; Institute for Bioengineering of Catalonia; Secretary and Treasurer, European Chemoreception Organization; Treasurer UK Semiochemistry Network
- **Peyton** Secretary, Founding Member, International Society for Industrial Process Tomography
- **Rogers** UK Fluids Network, Chair SPHERIC Steering Committee
- **Sampson** TAPPI International Research Management Committee
- **Sarkisov** Board of Directors International Adsorption Society
- **Shokri** Soil Physics and Hydrology Executive Committee, Soil Science Society of America
- **Thomas** Finance Committee IOP; DLS User Committee
- **Wilkinson** IOM3 Polymer Board
- **Wright** Hon Sec Instrument Science & Technology Group Committee IOP
- **Zhou** Light Metals Board IOM3

Support for and exemplars of interdisciplinary research

Interdisciplinarity is central to the Unit's Research Themes, infrastructure, and activity (§1b–§1f, §4a.3). The following are some individual examples of national and international collaborations supporting interdisciplinary research:

- The UK Catalysis Hub (§3a.2), resulting in new non-thermal plasma catalysis (https://www.nature.com/articles/s41929-018-0206-2).
- DISCOVERER (§3a.2), satellite materials tested externally on the International Space Station during 2020.
- Collaboration with Medicine and Chemistry at Leeds on drug-induced benefits of exercise (https://doi.org/10.1038/s41467-017-00429-3).
- Novel tendon attachment and repair strategy (MRC, device patented PCT/EP20/056104) trialled with Liverpool veterinarians.
- International collaboration on water-TiO2 interactions including ESRF and DLS and institutions from the UK, Spain, France, and Switzerland (https://doi.org/10.1038/nmat4793, https://doi.org/10.1021/acs.jpcc.9b04383).

Responsiveness to national and international priorities and initiatives

Members of the Unit provided national and international leadership in grand challenge areas:

- The national Advanced Materials agenda, through our leadership of Royce (§1f.1), and, in the EU, our key roles in the H2020 Graphene Flagship project (§3a.2).
- The Tyndall Centre for Climate Change Research (UEA, Manchester, Cardiff, Newcastle, Fudan), with leadership of Tyndall Manchester (§1f.1,§4a.3).
- The design and operation of dams to support sustainable development through our leadership of the FutureDAMS project, with 6 partners and 30 collaborators around the globe (§3a.2).
- Support for the Government's nuclear agenda, e.g. through our leadership in robotics for radioactive environments (RAIN, CARMA, §4a.2).

In addition, staff served as academic experts to >40 national and international government bodies and institutions, including the following:

- **Anderson** Scottish Climate Assembly and Welsh Assembly Government Climate Change Committee; Ministry for Foreign Affairs, The World Bank
- **Azapagic** Parliamentary Commission for Manufacturing
- **Burke** Irradiation of Structural Materials (OECD-NEA); Science Advisory Board Atomic Energy Canada
- **Crossley** Greater Manchester Energy Advisory Group
- **Gallego Schmid** UN Life Cycle Assessment Initiative
- **Gough** Climate Assembly UK
- **Harou** DEFRA Business & Community Engagement Panel
- **Iacovides** Nuclear Innovation and Research Advisory Board for BEIS
- **Jones** UK representative IAEA Decommissioning Network
- **Kopsidas** Hellenic Quality Assurance and Accreditation
- **Levi** Chief Executive Panel Electricity North West
- **McLachlan** UK Net Zero Transport Board; Chair Greater Manchester Environment Plan Implementation Forum; Climate Assembly UK
- **Ozanyan** Sensors and Instrumentation Leadership Committee, BEIS
- **Revell** European Commission, Research Executive Agency
- **Sharrad** Molten Salts Advisory Group to BEIS
- **Smith, A.** Advisory Electrical Working Technology Group, Rolls-Royce and MoD
- **Thornley** Chair UK Bioenergy Stakeholders DECC; UK-Canada Biochar Network; Chair Advisory Group, National Committee Climate Change
- **Vijayaraghavan** European Committee Standardization CEN/TC 352/WG 1
- **Watson** International Scientific Advisory Panel ORCA Hub UK
- **Yang** Panel Ministry of Science and Technology of China

4b. Indicators of wider influence

4b.1 Journal editorships and books

Along with routine peer review work for research journals, 95 staff served as Associate, Assistant, or Guest Editors of research journals, and 13 served as journal Editors-in-Chief:

- **Ainsworth** *International Journal of Pressure Vessels and Piping* (Elsevier)
- **Azapagic** *Sustainable Production and Consu*mption (IChemE)
- **Bartolo** *Biomanufacturing Reviews* (Springer)
- **Matthews** *Surface and Coatings Technology* (Elsevier)

- **Foster D.** *Vision Research* (Elsevier)
- **Ozanyan** *IEEE Sensors Journal*
- **Thornley** *Biomass & Bioenergy* (Elsevier)
- **Hayes** *Journal of Fashion Marketing and Management* (Emerald Group)
- **Lyon** *Corrosion Engineering Science and Technology* (Taylor & Francis)
- **Smith** *IET Research Journal on Electrical Systems in Transportation*
- **Terzija** *International Journal of Electrical Power & Energy Systems* (Elsevier)
- **Webb** *Biochemical Engineering Journal* (Elsevier)
- **Withers** *International Materials Reviews IOM3* (Taylor & Francis)

Staff authored or edited 21 technical volumes.

4b.2 Members of research councils and grants committees

Over 50 staff served as EPSRC Full College members, joining others reviewing for the BBSRC, ESRC, MRC, NERC, NC3Rs, UKRI, Innovate UK, Department of Health, Wellcome Trust, Royal Society, British Council, DLS, and internationally for the US Department of Energy, NSERC Canada, European Commission, European Research Council, also the American Chemical Society, Berlin Synchrotron facility, Chinese Academy of Sciences, CONACYT (Mexico), Czech Science Foundation, Danish Research Centre, Dutch Research Council, Flanders Research Foundation, Israel Science Foundation, MAX IV (Sweden), Ministry of Education and Science of Kazakhstan, National Science Centre (Poland), Research Council of Norway, Royal College of Surgeons in Ireland, Science Foundation Ireland, South Africa Science Foundation, Swedish Research Council, and others.

Several staff served in an advisory capacity:

- **Ainsworth** Royal Society Newton Advanced Fellowship Committee
- **Azapagic** Helmholtz Association International Advisory Panel
- **Carrasco Gomez** Ramon y Cajal Fellowship Panel (Spain)
- **Cruz Cabeza** Scientific Advisory Board, Cambridge Crystallographic Data Centre (CCDC)
- **Dickson** Scientific Advisory Board, National Institute for Bioprocessing Research and Training, Ireland
- **Gardner** DLS Scientific Advisory Committee
- **Gray** EPSRC Advisory Board, Innovative Manufacturing of Food
- **Grieve** UK Research Council Agriculture & Food Security Strategy and Policy Panel; UK STFC 21st Century Challenges Strategy Panel
- **Matthews** EPSRC Strategic Advisory Network; RAEng Membership Selection Panel
- **Preuss** Advisory Council ISIS; Beam-line Review Panel, DLS; Chair SAC, European Spallation Source; Advisory Board Australian Synchrotron
- **Wang H.** Chinese NSF Sub-committee Information Technology
- **Withers** EPSRC Scientific Advisory Team for Engineering; EPSRC Review Panel Culham Centre for Fusion Energy; Royal Society and RAEng University Research Fellowships
- **Young** Royal Society Membership Selection Committee; Royal Society and RAEng University Research Fellowships

4b.3 Fellows of learned societies and professional organizations

Over 80 of our academics have been recognized by election as Fellows of learned societies or professional organizations, including the Royal Academy of Engineering (16 in place in period including election of **Hinduja, Lennox, O'Brien,** and **Soutis**), the Royal Society (7 in place in period including election of **Withers**), and the Royal Irish Academy (**Hardacre**), also the IChemE, IET, IMA, InstMC, IoP, IMechE, IMMM, IAgrE, PhysSoc, RAeS, RSC, and in the USA, the IEEE, LIA, and OSA.

4b.4 Honours and prizes

Over 50 personal honours, medals, and prizes were awarded to staff.

Withers was awarded the inaugural Regis Chair in Materials, **O'Brien** CBE for services to science and engineering, **Azapagic** MBE for services to sustainability and carbon footprinting, and **George** MBE for services to engineering through public engagement.

Awards of medals and prizes included the following:

- **Boland** Jocelyn Bell Burnell Medal and Prize (Institute of Physics); Philip Leverhulme Prize (Leverhulme Trust); Isambard Kingdom Brunel Award (British Science Association)
- **Burke** Henry Clifton Sorby Award (International Metallographic Society); President's Award of the MIcroAnalysis Society
- **Foster D.** Verriest Medal (International Colour Vision Society)
- **Dickson** Peter Dunnill Award (BioIndustry Association)
- **George** Rooke Medal (RAEng); Harold Hartley Medal (Institute of Measurement & Control); Michael Faraday Medal (Royal Society)
- **Haigh** Rosenhain Medal (Institute of Materials, Minerals and Mining, IOM3)
- **Haigh** Royal Microscopy Society Medal for Innovation in Applied Microscopy for Engineering and Physical Sciences
- **Keshmiri** Frontiers of Engineering in Development Award (RAEng)
- **Kiss** Royal Society Wolfson Research Merit Award
- **Li L.** Donald Julius Groen Prize (Institution of Mechanical Engineers, IMechE); Arthur L. Schawlow Award (Laser Institute of America); Royal Society Wolfson Research Merit Award
- **Launder** Energy Systems Award (American Institute of Aeronautics and Astronautics); Nusselt-Reynolds Prize (World Conference on Heat Transfer, Fluid mechanics and Thermodynamics)
- **Lyon** Guy Bengough Award (IOM3); European Corrosion Medal (European Federation of Corrosion)
- **Mancarella** Newton Prize (British Council)
- **Matthews** Tom Bell Surface Engineering Medal (IOM3)
- **McDonald** George Stephenson Gold Medal (IMechE)
- **Miller** Philip Leverhulme Prize (Leverhulme Trust)
- **Missous** Brian Mercer award (Royal Society)
- **Nair** Moseley Medal and Prize (Institute of Physics); Philip Leverhulme Prize (Leverhulme Trust); Prince Sultan Bin Abdulaziz International Creativity Prize for Water
- **O'Brien** Longstaff Prize (RSC)
- **Panteli** Newton Prize (British Council)

- **Pickering** Frank Fitzgerald Medal (IOM3)
- **Preuss** Grunfeld Memorial Award and Medal (IOM3); William J Kroll Zirconium Medal (American Society for Testing and Materials)
- **Alonso Rasgado** Ohtli award (Mexican Ministry of Foreign Affairs)
- **Robson** Hume Rothery Award (IOM3)
- **Saiani** Philip Leverhulme Prize (Leverhulme Trust)
- **Santoro** Carl Wagner Medal of Excellence in Electrochemical Engineering (European Federation of Chemical Engineering); Tajima Prize (International Society of Electrochemistry)
- **Smith R.** Sargent Medal of the Institution of Chemical Engineers (IChemE)
- **Su** AJF Gold Medal Prize (World Intellectual Property Organization)
- **Szekely** IAAM Scientist Medal (International Association of Advanced Materials)
- **Webb** Council Medal (IChemE); Donald Medal (IChemE)
- **Withers** George Stephenson Gold Medal (IMechE); Platinum Medal (IOM3)
- **Yin H**.Turing Fellow (Alan Turing Institute)
- **Young** Platinum Medal (IOM3)

Over 50 prizes were awarded to staff for conference and journal papers.

4b.5 Invited keynote lectures and conference chairs

Academic staff gave over 1,600 oral conference presentations, including 680 invited keynote or plenary lectures at conferences in Australia, Austria, Belgium, Brazil, Chile, China, Columbia, Cuba, Cyprus, Czech Republic, France, Germany, Ghana, Greece, Hungary, India, Ireland, Italy, Japan, Malaysia, Netherlands, Poland, Portugal, Russian Federation, Switzerland, Taiwan, Turkey, Singapore, Spain, UK, USA.

Staff chaired or organized over 175 national conferences and 198 international conferences in Australia, Austria, Canada, China, Costa Rica, Czech Republic, Denmark, France, Germany, Greece, India, Italy, Japan, Malaysia, Nigeria, Norway, Poland, Portugal, Spain, Taiwan, Tanzania, Turkey, UK, USA, and Zambia.

4b.6 Co-operation and collaborative arrangements for PGR training

The Unit partnered 14 different universities across 10 CDTs (§2b.2). The Unit also participated in 2+2 PhD schemes with Singapore A*STAR and Melbourne University (§2b.2).