Institution: University of Northumbria at Newcastle

Unit of Assessment: UoA 12 Engineering

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

1.1. Overview

The unit is composed of 125 staff (121.41 full-time equivalent (FTE)) from the departments of **Mechanical and Construction Engineering** (68 staff), **Mathematics, Physics and Electrical Engineering** (50) and **Applied Sciences** (7). This represents more than a fivefold increase in the number of staff members returned to the engineering unit of assessment in REF2014 (23 FTE), and it builds directly on the foundations of the University Strategy set up in 2013 (REF5a, section 2).

Our long-term vision for achieving research excellence in engineering has been to transform ourselves from an academic community of exceptional teaching and islands of research excellence into a unit renowned for its distinctive, pervasive and exceptional research. In order to achieve this, we have employed a strategy centred on (i) growing the extent (in both size and capacity) and the diversity of the research staff base, developing existing strengths in renewable energy, smart materials and communications, and driving new research agendas in civil and construction engineering (sections 1.2 and 2); (ii) creating complementary and connected research facilities through structured capital investment in our research infrastructure (section 3); and (iii) developing new, tailored processes and financial systems to grow, foster and sustain an ambitious, vibrant and engaged research community (sections 2, 3 and 4). Particularly noteworthy evidence for the success of the unit's strategy is shown below.

Evidence

- Our leadership in setting research agendas is exemplified in the award of an EPSRC Centre for Doctoral Training in Renewable Energy Northeast Universities (CDT in ReNU) as a lead institution (£5.5M), involving 36 partners.
- The impact of our research excellence in building information modelling (BIM) was recognised by the *Times Higher Education*, receiving the title of the 'most innovative contribution to business–university collaboration 2017' for our spin-out BIM Academy Enterprises Ltd.
- Research innovation and working in partnership within the Unit are evidenced in a new Hub for Biotechnology in the Built Environment (HBBE), one of only thirteen such hubs, nationally awarded under the Research England Expanding Excellence initiative (£8M).
- Our growth in research quality is reflected in an increase in the number of outputs published in journals with benchmark refereeing standards such as *Nature* stable journals, *Science* and *PNAS* (2 in REF2014, 27 in REF2021).
- The relevance of our research to UKRI and other funders has resulted in awards in excess of £28M, by comparison with £5.3M during REF2014.
- Our cohort of junior academics has secured 9 EPRSC First Grant and New Investigator Award schemes, by comparison with 1 during REF2014.
- Our investment and prioritisation in developing future research leaders has led to a rise in PhD completion, which has grown to 145 from 33 during REF2014.

To support our growth, we have developed aspects previously highlighted by the REF2014 panel as 'world-leading', namely 'advanced materials and manufacturing' and 'communications', reconfigured our estate, and introduced exciting new interdisciplinary communities.

1.2. Unit structure and achievements

The unit is organised as shown in **Fig. 1**. In order to develop progressive, productive and engaging research communities with both identity and freedom to innovate and adapt, we have enlarged the number of our interdisciplinary research groups from three to five since REF2014. The research groups **Renewable Energy Technologies and Materials** and **Photonics, Communications and Nonlinear Systems** remain, while a new **Civil and Construction** group has emerged from close collaborations between construction project management and civil engineering teams. The former group **Advanced Materials and Manufacturing** has increased and branched out into two distinctive research entities: **Smart Materials and Surfaces** and **Manufacturing and Engineering Materials**.

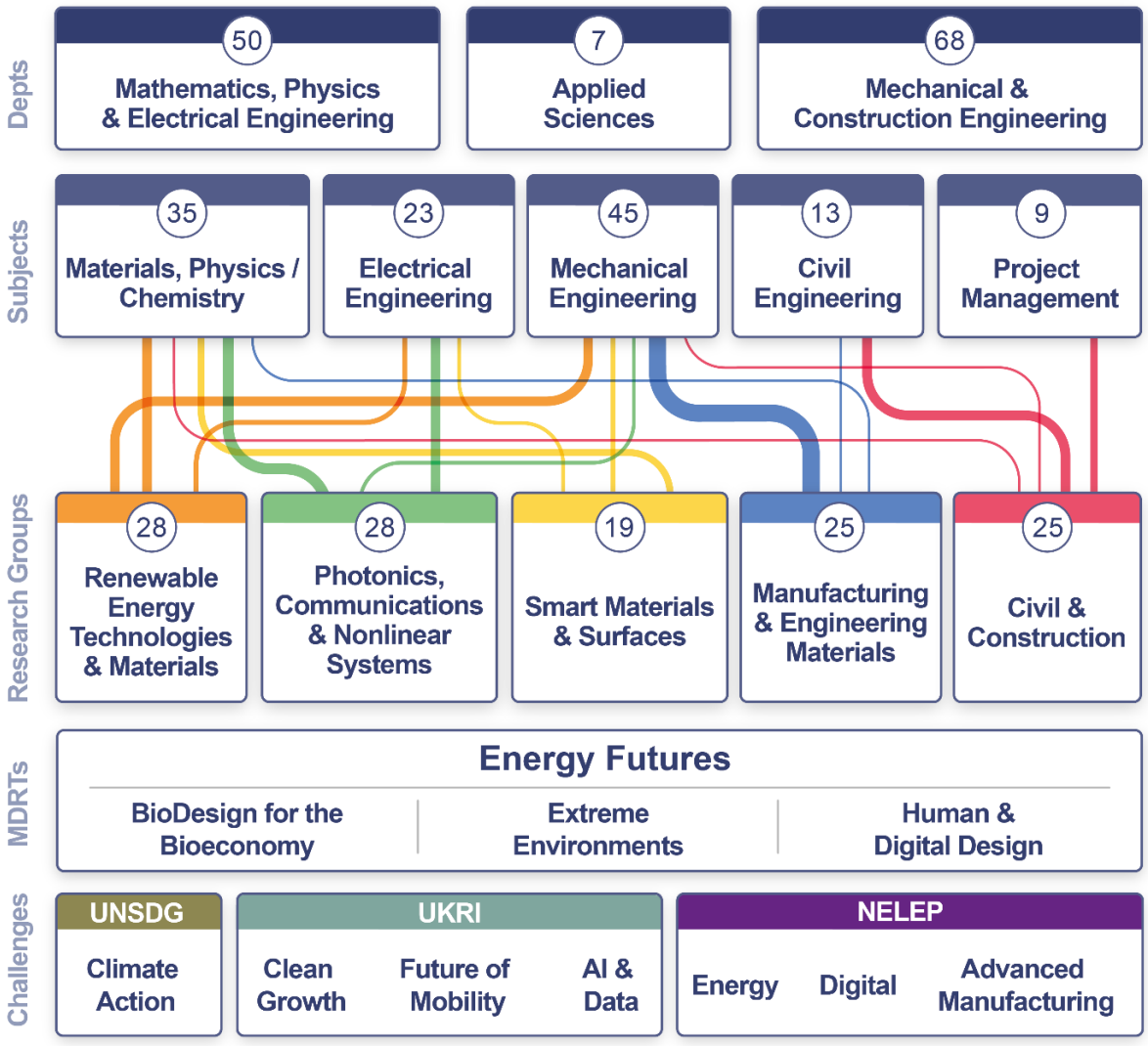

***Figure 1**: Unit organisation and alignment to university structure and global challenges (see REF5a, Fig. 1). The numbers designate the number of staff members. 'Challenges' are aligned to the North East Local Enterprise Partnership (NELEP) areas of strategic importance, the UKRI Industrial Strategy Grand Challenges and the United Nations Sustainable Development Goals (UNSDG).*

Growth was enabled through strategic university-wide investment in multidisciplinary research themes (MDRTs; REF5a, section 2.2) designed to address key regional, national and global societal challenges (see **Fig. 1**). Our MDRTs specifically aim to enhance the interdisciplinarity of our research while strengthening our core research groups through the development and strategic recruitment of staff. We underpin and lead the MDRT **Energy Futures** and actively contribute to the MDRTs **Human & Digital Design**, **Extreme Environments** and **BioDesign for the Bioeconomy** (section 1.3 and 4.3.3).

Our research groups foster inclusive and engaging collaborations and have registered major achievements, a far-reaching influence and sustained growth across the unit, as exemplified in the following subsections.

1.2.1. Renewable Energy Technologies and Materials

The group focuses on renewable and sustainable solutions to meet energy demands. Areas of excellence include developing new photovoltaics and photocatalytic materials (#1); phase change materials and thermal energy storage and systems (#2); and power and control systems (#3).

#1: Our innovations and leadership in energy materials have been enhanced through EPSRC core funding designed to advance research in photovoltaics and in fuel cells and through our role on national programmes such as NECEM (North East Centre for Energy Materials, EP/R021503/1) and PVTEAM (Photovoltaic Technology based on Earth Abundant Materials, EP/L017792/1). We lead Northumbria's first EPSRC CDT (EP/S023836/1), which offers a pioneering training programme encompassing small-scale renewable and sustainable distributed energy, and we co-deliver the first international renewable energy postgraduate training programme in China (see section 4.2).

#2: We have developed new phase change materials for latent heat storage systems for domestic heating via organic Rankine cycle turbines, which use accumulated thermal solar energy. Our expertise in concentrated solar thermal plant and storage for combined heat and power systems has produced a prototype in Spain (H2020 Innova MicroSolar €4.0M) and new product lines at the Aavid Thermal Division of Boyd Corporation for high temperature heat pipes and thermal storage and at Strategie SRL for a new control system.

#3: Our power and control systems researchers have developed sector-leading models and solutions for the transition to net zero carbon emissions. These include how to (i) best integrate renewable energy, electric transport and electricity grids; (ii) develop smart chargers for electric vehicles (KTP009331 with Sevcon); and (iii) develop optimal controllers for sustainable energy management in order to achieve an efficient and stable operation for future microgrids. These projects define the route to future green and sustainable energy and transport systems.

Examples of funding successes and partnerships

- EP/N024389/1 (*Zoppi*), EP/T005491/1 and EP/R014884/1 (*Beattie*) for photovoltaic materials; EP/S032886/1 (*Liu*) for fuel cells;
- EU ENTAS 622883 (*Mahkamov*) and THERMOSTALL 705944 (*Costa*, *Mahkamov*) for phase change materials;
- The Royal Society ICA\R1\191201 and GCRF 414707599 (*Mahkamov*) for solar storage;
- SEEV4-City EU Interreg (*Putrus*) and British Council IND/CONT/GA/18-19/22 (*Putrus*, *Marzband*) for energy systems and management.

1.2.2. Photonics, Communications and Nonlinear Systems

We have strengthened our research excellence in the area of communications and made exciting new developments in the areas of nonlinear and complex systems and photonics. Exemplified areas of success include optical wireless communications (OWC) (#1); nonlinear waves and photonics (#2); and complex and random systems (#3).

#1: Our research in the fields of OWC technologies for ultra-fast and secure communication systems includes both indoor and outdoor environments as part of the 5G/6G wireless networks. We have developed (i) OWC systems for smart environments; (ii) novel polymer light-emitting diodes in OWC for both illumination and data communications; (iii) a higher data rate OWC link for delivering high-speed internet for rail passengers, in collaboration with the Network Rail Infrastructure Ltd and Tethir Ltd; (iv) a high-speed OWC link for the 'last mile access' network with ISOCOM Ltd; and (v) a simulator for future extraterrestrial free-space optical links with the European Space Agency.

#2: We have developed specific research, which targets advancing dispersive hydrodynamics and its applications to optical and water wave systems. Our applications in nonlinear photonics have resulted in significant breakthroughs in both extreme compression of light pulses in fibre lasers (in partnership with LumOptica Ltd) and in the control of optical rogue waves in telecommunication systems for defence and security. We have recruited talented early-career researchers (ECRs) to form an exciting new photonics strand, with a focus on nano-, quantum and molecular optics: *Sathian* (co-inventor of the room temperature maser, *Nature* 2018); *Ho* and *Zhu* (optical vortex, micro optics and nanomanipulation techniques, e.g. *Nature Photonics* 2014); and *Etherington* (organic display, e.g. *Nature Communications* 2016).

#3: Our research into modelling complex and random systems has led to (i) the introduction of novel paradigms for the use of complex networks in machine learning and artificial intelligence and (ii) the study of non-equilibrium and nonlinear magnetic phenomena aimed at the development of advanced data storage systems (*Nature Nanotechnology* 2016, *Nature Physics* 2017).

Examples of funding successes and partnerships

- H2020-MSCA-ITN VISION 764461, EU COST Action IC1101 and 19111 (*Ghassemlooy*) and EP/P006299/1 (*Ghassemlooy*, *Le Minh*) for OWC;
- Innovate UK 6926 and EU ERDF (*Ghassemlooy*) for high-speed internet;
- EP/R00515X/2 (*El*) and Royal Society IES\R2\170116 (*Moro*) for hydrodynamics and water wave systems;
- DSTLX1000116851 (*El*) for nonlinear photonics in telecommunication systems;
- Leverhulme Trust Grant RPG-2017-228 (*Moro*) for complex networks.

1.2.3. Smart Materials and Surfaces

The group develops functional-structural materials and fabrication strategies, including the directed assembly of complex, micro-constructed soft materials systems and their nanocomposites. We study how micro-structured surfaces can shape liquids and create super liquid-repellent, super slurp and super slippery surfaces (#1); how to manipulate droplets or liquid films (#2); and the production of sensing or actuating structures and micro-devices (#3).

#1: We have elucidated the process of dewetting (*Science Advances* 2016) and are applying this principle to liquid–liquid systems activated by electric fields. Our research has improved the flow of liquids in pipes and textured surfaces; and the subsequent development of slippery liquid-infused porous surfaces is being used to develop medical diagnostic applications, in partnership with QuantuMDx (KTP10797 and patent WO2019072940).

#2: The discovery of the 'Leidenfrost engine' (*Nature Communications* 2015), which was both a mechanical engine achieving rotation and the first ever demonstration of a sublimation-based heat engine, offers new ways of controlling and creating Leidenfrost turbine surfaces. This research focuses on exploiting extreme environmental conditions, such as found in deep drilling and outer space, for the purpose of harnessing the vaporisation of liquids and ice at high-temperature differences. Achieving droplet control during evaporation has application in a broad range of fields (printing, heat transfer, cleaning), and we are investigating new mechanisms for controlling droplet motion during evaporation on the basis of hygrotaxis (*Nature Communications* 2018).

#3: We use microfluidic channels to develop microgel systems (patent US20150294805) and surface acoustic waves to develop bio- and wearable sensors. The technology is further being developed through two KTPs – one with Epigem Ltd, rated as 'outstanding' by Innovate UK, and used for the diagnosis of infectious disease, the other with Hart Biological Ltd, used for the monitoring of patient drug levels (patent GB2577073A). By exploring soft matter mechanics, we have also developed a new optical sensing technology (*Nature Communications* 2020).

Examples of funding successes and partnerships

- EP/R036837/1 (*Ledesma*, *McHale*, *Wells*) and EP/L026899/1 (*Xu*) for dewetting and flow on texture surfaces;
- EP/P026613/1 (*Wells*) and EP/S036857/1 (*Semprebon*) for slippery liquid infused porous surfaces;
- EP/P005896/1 (*Ledesma*, *McHale*, *Wells*) and EP/N007921/1 (*Xu*) for Leidenfrost turbines and microfluidic systems;
- EP/P024408/1 (*Ledesma*) and Royal Society RG150470 (*Ledesma*, *Wells*) for droplet motion;
- EP/P018998/1 (*Fu*) and 3D-MIPS Attract-EU (777222) (*Torun*) for sensing.

1.2.4. Manufacturing and Engineering Materials

The group focuses on (i) developing the next generation of cutting-edge manufacturing technologies and processes; on (ii) improving manufacturing systems, organisation and sustainability; and on (iii) advanced materials such as nanocomposites, lightweight or functional materials. Areas of excellence include composite and polymer materials (#1), additive manufacturing (#2) and coatings (#3).

#1: Our research on composite materials focuses on delivering new solutions for the automotive and aerospace sectors. This is evidenced by our leading position in research into composites for structural applications within the EU's Graphene Flagship. Our research combines novel 'concept' materials with the latest safety design approaches and aims to reduce the environmental impact of future structures through advanced, ultra-light graphene-based polymer materials, efficient fabrication and manufacturing processes, and life-cycle analysis.

#2: Rapid prototyping research via sand casting and additive manufacturing allows the production of prototypes at a fraction of the time and cost required by established methods. This research has led to new [text removed for publication].

#3: We have developed new bulk and thin-film coatings (i) for medical applications such as joint replacement; (ii) for [text removed for publication]; and (iii) for both subsea applications and shape memory alloys for microactuators used in hydraulic and pneumatic systems. Our research impact has opened multiple new product lines, factories and jobs (see section 4.1).

Examples of funding successes and partnerships

- EU Graphene Flagship (604391, 696656 and 649953) (*Elmarakbi*) for new composites research;
- KTPs with Lear Corporation Ltd (11215) (*Hackney, Unthank*), Platinum Electrical Engineering Ltd (11021) (*Hackney*) and Cheaperwaste Ltd (12061) (*Dai*, *Hackney*) to increase manufacturing output via rapid prototyping;
- Leverhulme Trust Grant RPG-2018-344 and EU-HePULSE (885534) (*Birkett*) for thin films;
- EP/P019889/1 (*Gonzalez Sanchez*) for shape memory alloys.

1.2.5. Civil and Construction

This group supports a strong interdisciplinary team, which spans researchers in civil engineering, project management, construction, building information modelling and bioengineering. Areas of excellence are advanced structures and materials (#1), civil and geotechnical engineering challenges (#2); and digital environment informatics (#3).

#1: A new research hub – the Hub for Biotechnology for the Built Environment (£8M; Research England), underpinned by EPSRC funding into computational colloids and 'thinking soils' – is producing buildings constructed from living engineered materials and responsive to their environment. Our research into microbe-based self-healing concrete supports a European test standard for RILEM. We lead the international working groups on cold-formed aluminium structures and off-site construction that led to policy development for Eurocodes 3 (steel) and 9 (aluminium) and to four successful KTPs.

#2 Our research into visualisation approaches has resulted in new live streaming sensor networks, processed through artificial intelligence and funded through collaborations with national agencies (Transport Scotland; Highways England), local authorities (South Tyneside Council), industry (Avametrix; Costain Group; Global Digital Systems Instruments) and utilities providers (Northumbria Water, subsequently solicited as a government research case study). In addition, our NERC-funded work, namely seven projects awarded since 2016, has underpinned decision-making on natural hazard threats to people and infrastructure (see section 4.3.3).

#3 Our research into the digital environment has redefined digital transformation policies in national construction sectors (e.g. Brazil, Ireland, Mexico, Canada, Hong Kong) and has been central to major high-profile developments [text removed for publication]. We have developed a new building informatics digital toolkit, xBIM (extensible building information modelling), which has seen industry-wide uptake (21,486 users, as of November 2020), and our research successes have resulted in a multi-award-winning spin-out company: BIM Academy Enterprises Ltd.

Examples of funding successes and partnerships

- EP/N005791/1 and EP/R003777/1 (*Zhang*) for thinking soils;
- KTPs on steel structures with Intelligent Steel Solutions (11533) (*Hackney*, *Nagaratnam*, *Poologanathan*); Extraspace Solutions Ltd (123771) (*Khaliq*, *Nagaratnam*, *Poologanathan*), Redbrookes Ltd (12399) (*Nagaratnam*) and Project Advisors International (10761) (*Benghi*, *Greenwood*);
- NE/T005653/1 (*Lim*, *Martin*, *Torun*); NE/P000010/1 (*Lim*); Scottish Road Research Board: Science and Innovation fund (2017; 2019) (*Lim*) for decision-making on natural hazards;
- EU H2020 RINNO (892071) (*Kassem*) and Innovate UK (105882 and 105438) (*Kassem*, *Greenwood*) for digital building informatics.

1.3. Impact strategy and interdisciplinary research

Within the overarching approach of research power with quality (REF5a, section 2.1), the unit's strategy for research impact is to stimulate significant beneficial changes that endure and grow, and to do so through meaningful, effective working relationships with research beneficiaries and by developing a specifically interdisciplinary focus. Building lasting collaborations with our external partners, research users and stakeholders has been a central feature of our pathway to an impact strategy (examples are given in section 4). This feature has been sustained through structured strategic investment in impact – which involves people, processes and funding streams – by tailoring and targeting support across four themes:

(i) deriving direct industrial benefits from scientific advances as a result of product development or improvement (e.g. impact case studies (ICSs) led by *Birkett*, *Hackney*, *Shyha*);

(ii) consolidating, developing and expanding partnerships with non-academic users and beneficiaries at international, national and local levels (e.g. ICSs led by *Kassem*, *Corradi*);

(iii) embedding greater interdisciplinarity, efficiency, resilience and sustainability into changing working and operational practice, then actively fostering these features (e.g. ICSs led by *Greenwood*, *Lim*);

(iv) targeted promotion of and investment in engaging with beneficiary communities in order to facilitate the uptake of research innovations (e.g. ICSs led by *Davenport*, *Mahkamov*).

Our impact strategy has been realised through (i) active research group communities that foster and develop coherent, ambitious and productive collaborations and research agendas; (ii) research-focused industrial advisory boards that refine and address business-critical and timely research problems; (iii) MDRTs that transcend conventional boundaries in order to achieve significant impacts beyond academia; and (iv) impact support infrastructures.

Our ICSs reflect our achievements in transformative research-led change. For example, our continued advances in manufacturing technologies and new materials have led to the creation of 19 jobs and new multimillion-pound production lines (ICSs led by *Birkett* and *Hackney*). New international and regional policies, along with the training of professionals, have arisen from our advances in research with digital data (ICS led by *Kassem*). Our leading research into new retrofitting methods has generated both new methods, which have been implemented internationally, in 8,650 restoration projects, alongside 75 new jobs (ICS led by *Corradi*). Our long-standing excellence in digital built environments has provided new open-source tools, which have contributed to dramatic increases in sector-wide productivity and in the accessibility of digital technologies (ICS led by *Greenwood*); more effective and potentially life-saving tools have been

introduced to reduce the threats of geotechnical instabilities (ICS led by *Lim*). Our pioneering concept development in the Theory of Change for science, technology, engineering and mathematics (STEM) education has impacted over 90,000 children from non-affluent areas and our resources and approaches have been widely adopted, for example by organisations from across North East England and in primary schools in Nigeria (ICS led by *Davenport*).

This approach to impact has also been supported by the university's investment in people (i.e. by the impact support team; see REF5a, section 2.3), and in processes (i.e. by the inclusion of impact activities as part of both the annual personal development objective setting and the promotion criteria, with their associated evidence base). We have created a unit academic impact lead (*Lim*), who works closely with colleagues and have a dedicated impact development fund. The lead delivers both regular training and tailored support, in impact and related activities, for members of staff at all career stages (e.g. when accounting for the needs of diverse and protected staff groups), fostering proactive and continuous engagement in the impact agenda. This engagement is reinforced for all staff members at appraisal (section 2).

Example of developing impact through strategic support for staff

Lim received support from the unit in the form of a high-specification processing machine designed to stimulate a new area of research in geohazard analysis. This led to a transformational advance in processing large datasets for wide-scale 3D monitoring surveys. The direct results were four consecutive years of UKRI funding, award-winning international collaborations, multiple high-impact publications in collaboration with indigenous Arctic communities, and [text removed for publication].

Our impact strategy guarantees sustained support for and focus on (i) continuing and developing current successes and (ii) creating new areas of impact after REF2021. Maturing research areas are setting current impact agendas and addressing key national and international challenges. Examples include *Le Minh* in optical wireless data communications, *Fu* in cattle disease diagnostics, and *Poologanathan* in fire-resistant building materials.

Interdisciplinary research has been integral to the unit's successes and will be the cornerstone of future research growth. Interdisciplinary research is specifically supported by departmental directors of Research & Knowledge Exchange (*Xu*, *Zoppi*), and further enhanced by our drive to address global challenges such as climate change, clean growth, large-scale natural hazards and sustainability of resources and buildings. Such goals drive our involvement and investment in the MDRTs and are core to our leadership principles within the Energy Futures MDRT (led by *Beattie*).

While our organisational structures and unit leadership provide strategic frameworks, targeted workshops and seed-corn funding to facilitate cohesive research, it is the drive and vibrancy of the unit's staff that have defined the successful functioning, growth and empowerment of MDRTs (see further examples in section 4.3.3).

1.4. Research integrity, open research and open data

The unit builds on institutional policies (REF5a, section 2.5) to enhance the reach and significance of selected outputs. Financial support is provided for gold open-access article processing charges, resourced through both university- and unit-level funding.

Data and analytical codes are now routinely made available as part of outputs using discipline-relevant Distributed Active Archive Centres (e.g. the UKRI Centre for Environmental Data

Analysis). In addition, free to access data repositories such as 'figshare' (institutional license) and code-sharing platforms such as GitHub are actively promoted and widely used within our research groups. Providing access to our published data and analytical codes has enhanced the reproducibility, robustness and impact of our research outputs.

No research project can be undertaken in the unit without an ethical audit having been conducted and approved. Our approach of intentionally incorporating open and inclusive ethical evaluations into formal training, research group discussions, mentoring and supervision processes firmly embeds good practice, with all its associated benefits, into the unit's identity and effective operation.

Evidence

- An exemplar of code sharing is *Warren*'s gprMax, an open-source software released on GitHub that stimulated new user communities with a recent free training event attended by 44 countries. The code has been used by Google Fiber, DSTL and the US Army Engineer Research and Development Center and implemented in the NASA Radar Imager for Mars.
- All CDT supervisors are registered practitioners in Responsible Research & Innovation (RRI, a framework accredited by ORBIT-RRI) and subsequently train postgraduate researchers (PGRs) and colleagues, embedding RRI within the unit. This model has been presented as good practice to all UK CDT directors (September 2020, *Beattie*).

1.5. Summary of transformation since REF2014

After REF2014, our strategy has been to grow high-quality research. This has produced an orchestrated step change in the capability and capacity of the unit. The successes related to our strategic objectives (marked here in italics), as stated during REF2014, for the 2014–2021 period are as follows:

(i) *Increase our research capacity and academic base through the appointment of high-quality staff*. Our academic staff base has grown from 73 in 2013 to 133 in 2020, and there has been a >5-fold increase in submitted staff, from 23 in REF2014 to 125 in REF2021 (details in section 2).

(ii) *Increase our research capability through capital investment in state-of-the-art equipment and laboratories*. We have more than doubled our investment in research-focused capital projects by doubling our engineering laboratory space and developing new specialist laboratories (details in section 3).

(iv) *Increase the number of research students with timely completion*. Postgraduate researchers (PGR) completions have increased from 33 during REF2014 to 145 during the REF2021. The new figure includes 47 collaborative partner-funded PhDs that span industry (e.g. JC Consulting) and national authorities (e.g. Transport Scotland).

(v) *Expand our international collaborative network*. The proportion of journal articles with international co-authors has increased from 54% in 2014 to 79% in 2020 – a percentage spread across 45 countries (data from SciVal October 2020).

1.6. Future strategic aims and sustainability (2021–2028)

Building on our current trajectory of expansion and enhancement of the staff base, sustained investment in state-of-the-art facilities, and innovative supporting processes, the unit aims to consolidate its advances and drive excellence by setting ambitious yet achievable goals, thus

realising the university's wider strategic vision for 2030 (REF5a, section 1.2). We anticipate that global and national challenges such as responding to climate change, achieving net zero emissions and sustainable and efficient buildings, or exploring manufacturing and quantum technologies will dominate our research agenda. Our objectives for the next REF period are:

(i) to enable and diversify impact by engaging with industry and stakeholders in identifying engineering challenges and solving them to the benefit of society. We plan to drive growth around the themes of Manufacturing the Future, Energy and Healthcare Technologies;

(ii) to empower our research groups so that they achieve self-sustaining research quality. We will also develop a nascent group in quantum and molecular photonics through further appointments, designed to support our recent intake of exciting ECRs, to enhance cohesion in the team and to secure dedicated laboratories and equipment for a new area of research excellence;

(iii) to use our recent investments of both intellectual and infrastructure capital (section 3) in transport and aerodynamics to design multiscale engineering materials and systems for resilient applications in extreme environments;

(iv) to nurture our large pool of ECRs so that they transition into research leaders, and to provide mentoring for our more junior staff members, helping them to gain recognition through (associate) professorships;

(v) to continue to promote the theme Women in Engineering and ensure an appropriately diverse contribution to the future directions of the research agenda within the unit (see section 2). We will upgrade our Athena SWAN award to Gold (the first submission is due in late 2021) and continue our pioneering work with Northumbria University STEM (NUSTEM) towards inspiring the next generation of engineers.

(vi) to further develop our excellence in digital construction through initiatives such as the proposed International Centre for Connected Construction (IC3), a £44M partnership with UKRI and North East Local Enterprise Partnership to maximise the impact of digital technology for safer, higher quality and better performing built assets.

2. People

2.1. Academic staff strategy and development

To achieve the unit's aim of ambitious but sustainable and structured growth in both research capacity and research capability, our staffing strategy relies on (1) creating conditions of inclusive development for our staff and PGR community; and (2) pursuing the rigorous and targeted recruitment of both internationally excellent research leaders and dynamic and exciting ECRs in emerging research areas.

Our academic staff base has increased from 73 in 2013 to 133. Even more significantly, 93% are now independent researchers – academics with a significant responsibility for research, as defined in our code of practice (see REF5a, section 3.1.5) – by comparison with 34% in the last REF period (**Fig. 2a**). This increase includes 19 staff members not submitted to REF2014 who are now independent researchers. A strength of our strategy has been to exploit flexibly the diverse research expertise within the unit. Where possible, we work together to develop exciting and productive new collaborations within a supportive and inclusive research environment.

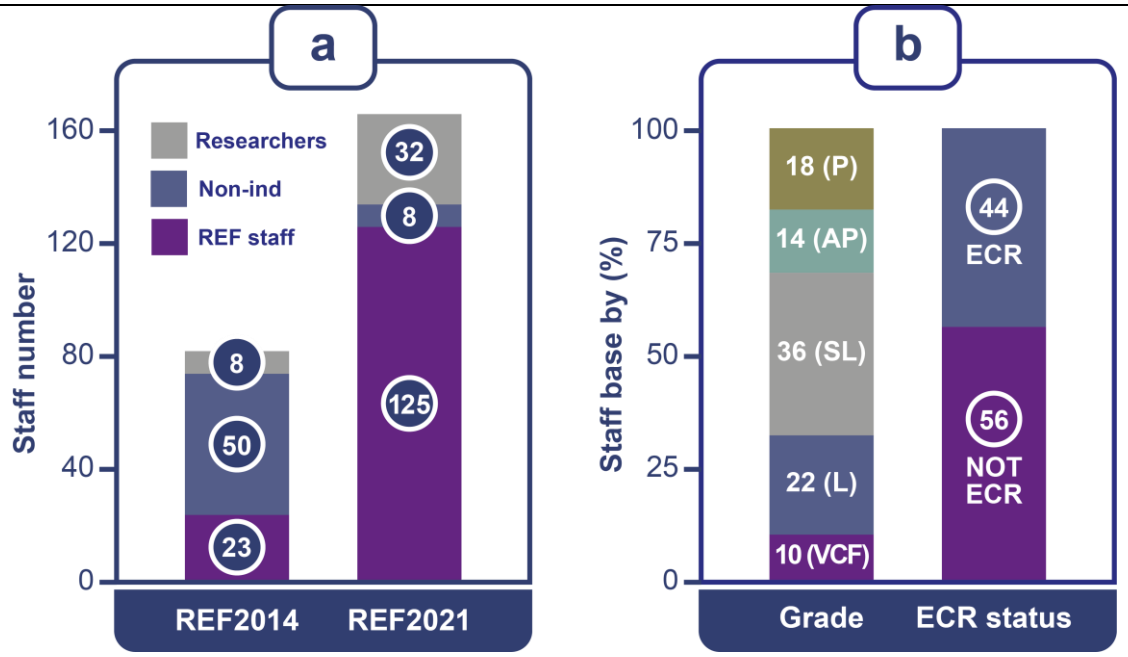

***Figure 2**: (a) Step change in our staff base. 'Non-ind.' designates academic staff without significant responsibility for research; 'researchers' designates postdoctoral researchers and KTP associates who are not independent. (b) Staff base in engineering, by grade and by REF ECR status of the 125 submitted staff. P stands for professor, AP for associate professor, SL for senior lecturer, L for lecturer and VCF for vice-chancellor's fellow.*

Fig. 2b gives an overview of our staff base, organised according to academic title and career stage. Since 2014 we have expanded and revitalised the academic staff base through the appointment of 83 research leaders and ECRs with an intentionally interdisciplinary perspective on research excellence, who recognise both its academic and its practice-based forms. The introduction of video conferencing screening interviews has enabled a truly diverse worldwide recruitment catchment, 22 out of the 83 new members being drawn from outside the UK. Fifteen professors and associate professors have been recruited over the period, providing an agenda-setting culture of research leadership.

We have strategically developed staff capacity on the basis of current and emerging engineering challenges: we aimed for a critical mass that can achieve global recognition but is also sustainable, being matched with state-of-the-art facilities (section 3), and cohesive across multifaceted cross-disciplinary research groups. The development of the research environment has been further driven by structured research support (e.g. financial enabling funds of circa £50k per annum for the unit and internal output/proposal review panels).

These initiatives are open to all, but particularly targeted at ECRs and staff members with less developed research profiles, as they aim to ensure inclusivity and access to resources for all staff. Examples include travel, collaboration-focused funds and specialist training, for example EPSRC mock panel events and internal review panels. This approach has been particularly successful in supporting new staff or ECRs to achieve a step change in the significance and reach of their work (see section 2.1.2).

The allocation of financial support is considered by a mixed-gender, multi-career-stage panel that considers (i) the diversity and spread of funding across the unit, (ii) the applicant's engagement with the wider support structures in place (research mentors, research development manager and

research groups), and (iii) significance and potential rewards – which range from initiating a first research activity to leading large collaborative international funding proposals or networks.

2.1.1. Recruitment, probation, mentoring and promotion

All new appointees to the unit follow a standardised selection and interview process (REF5a, section 2.2) and a probation period is mandatory for all new starters, although the timing and delivery methods are flexible enough to allow for equality and fairness and to accommodate different expectations. A probation plan is agreed between the new starter and the head of department that links appropriate research objectives and career progression with support mechanisms (funding, mentoring and guidance) for achieving them. Progress against the plan is reviewed and supported thereafter by the research mentor on a monthly basis.

Probation panels have independent representation from other units; this ensures parity and transparency. Individual circumstances such as extended periods of leave, or evolving situations such as cover for other staff, or change of roles, may dictate when various research objectives are assessed. Examples include supporting [text removed for publication] throughout a career break, and [text removed for publication] was given extra time to meet probation objectives after taking a leading role in developing the new Geotechnics laboratory.

All members of staff are given (i) a research mentor focused on research output quality enhancement and research plan development, either progressively or supportively (in the case of researchers returning from leave), and (ii) a Higher Education Academy (HEA) mentor focused on teaching practice development and on progress towards becoming an HEA fellow. A key role for our research mentors is to challenge mentees' level of ambition, so that they aim for the most prestigious outlets for their research and achieve the greatest international reach. Research mentors are also responsible for supporting researchers through probation, a long-term illness, or personal circumstances such as caring responsibilities.

Mentors are expected to help staff members map themselves against the promotion criteria and create a personalised route map for promotion (REF5a, section 3.4). During the REF period, the unit achieved 7 promotions to professorship, and 20 senior lecturers were promoted to associate professorships. The unit has used this rigorous and supportive process to balance internal progression with the recruitment of exceptional external scholars.

2.1.2. ECRs

In REF2014 we submitted 10 staff members who met the REF2014 ECR definition. Since then the unit has invested significantly in the development of this cohort of researchers, not least by appointing 54 new ECRs.

Example of ECR support and career development

Liu joined the unit in 2015 as a lecturer, receiving tailored support in grant preparation from the unit. He was mentored through the process by *Xu* and his underpinning research was enabled through unit funds (equipment, consumables and travels). As a direct result of this investment, guidance and support, *Liu* has successfully achieved several grants, including an EPSRC New Investigator Award in 2019 (EP/S032886/1). He received due recognition through the title of associate professor in 2020.

The appointment of ECRs via the VCFs scheme (REF 5a, section 2.2.3) has been essential to the development of exciting research areas that are emerging. Examples include *Sathian*, *Ho*, *Zhu* and *Etherington* in photonics and *Longo*, *Walley*, *Tiwari*, and *Hutter* in energy materials.

ECRs have benefited from targeted infrastructure and equipment funding and from larger group investment. Alongside all new staff, they are supported with a PhD studentship if they are in a position to capitalise on this support) and a flexible budget on arrival that helps them to establish research directions, develop collaborations and integrate fully into the unit's research culture.

Example of supporting VCFs to become established academic staff

Zabiegaj joined the unit in 2017 as a VCF and was awarded £30k to purchase a tensiometer for the characterisation of absorbing foam and nanoparticles in order to reduce pollution from transport. Her research is now expanding into pulmonary surfactants via a unit-sponsored PhD student in 2018. She successfully transitioned to senior lecturer in 2020.

ECRs receive collegiate support in the form of highly restricted administrative duties and lighter teaching loads; VCFs start with 10 teaching credits in their first year, building up to 30 by the third. This gives them the time they need for intellectual development and the physical resources, infrastructure and guidance for building a strong research profile. Several VCFs have already transitioned to senior lecturer during the REF period after successfully completing their probation (e.g. *Kirillov, Semprebon* and *Warren*).

The university runs an ECR Forum, and the ECRs' voice is influential through both Research & Knowledge Exchange committees and the implementation of feedback from the Careers in Research Online Survey. Representatives of the unit's self-organised ECR network, which is led by *Zabiegaj* and *Iacocca*, attend (i) departmental management groups, to ensure that inclusive perspectives and ideas are considered in the running of individual departments, and (ii) MDRT steering groups, where they contribute to defining wider research directions at an institutional level. ECR events supported by central research services have included, for example, a 'world café'-style event devoted to improving our research culture, and researcher resilience events facilitated by external consultants.

2.1.3. PDA and sabbaticals

A biannual performance and development appraisal (PDA) system is used for formulating and reflecting on an individual's 'research and innovation plan'. Researchers are encouraged to specify stretching but achievable objectives related to publication, research grant applications, impact, enterprise or knowledge exchange, and public engagement. Set alongside teaching and administrative objectives, this plan is facilitated through engagement with our clearly defined support structures to continually raise grant application and output quality.

The unit runs a research sabbatical scheme. Sabbaticals for one semester are allocated through a competitive application process, informed by a track record of high-quality publications and external funding, along with plans for external engagement and impact and for the strategic and inclusive development of the unit. All staff members are encouraged to apply every seventh semester, regardless of their FTE hours. Incoming colleagues, so long as they have navigated probation, can access the scheme more quickly, and sabbatical opportunities are especially promoted for staff members on return from career breaks or other periods of leave. Examples of the diverse work that has been achieved across all career stages through sabbaticals include the development of successful proposals such as a responsive flagship CDT call (*Zoppi*); starting

grants (*Ledesma*) and a new research fellowship followed by a period of research at leading European institutions (*Gao*); focused research time devoted to underpinning impact development (*Benghi*, *Fu*, *Shyha*; *Hackney*); and personal and mentored development towards research independence (*Li*; *Osborne*).

2.1.4. Postdoctoral researchers (PDRAs)

The unit upholds the principles set out in the Concordat to Support the Career Development of Researchers (REF5a, section 3.4). On the date of the census, it has 32 PDRAs, in comparison to 8 in 2013. We deliver independence mentoring to PDRAs and allocate project time for work towards achieving personal research outcomes. We introduced mandatory training for principal investigators to support an appropriate developmental culture for PDRAs. PDRAs are also part of the developmental PDA system and have access to the same training portfolio as our academics.

Our policy is to actively invest in fixed-term members of staff, assisting them in their applications for permanent contracts. For example, *Agrawal*, *Benassi* and *Congy* transitioned from PDRAs to lecturers after competitive recruitment processes.

2.2. Postgraduate researchers (PGRs)

We have 117 postgraduate students registered for a doctorate degree in engineering in 2019/20; and 145 PhDs have been awarded since 2014 (see **Fig. 3** for distribution and postgraduate output contributions).

Funding for PGRs within the unit is divided between university-funded studentships (see strategy in REF5a, section 2.2), industry, the EPSRC CDT in ReNU, the European Regional Development Fund (ERDF), the NERC-funded One Planet Doctoral Training Partnership (DTP), Marie Skłodowska-Curie Innovative Training Networks (ITN Kestcells and Vision), the Defence Science and Technology Laboratory in the Ministry of Defence (DSTL/MoD), overseas governmental organisations, and self-funded students. During the REF period, 52% of our PGRs received external funding to cover their fees and stipend. Additionally, we provide doctoral studentships as part of match funding for large grant applications, integrating postgraduate students into strong, agenda-setting programmes and networks. We have supported five staff members – *Harrington*, *Edmondson*, *Ponton*, *Tindall*, *Weirs* – to undertake a PhD, enabling skills enhancement and the expansion of high-quality research within the unit.

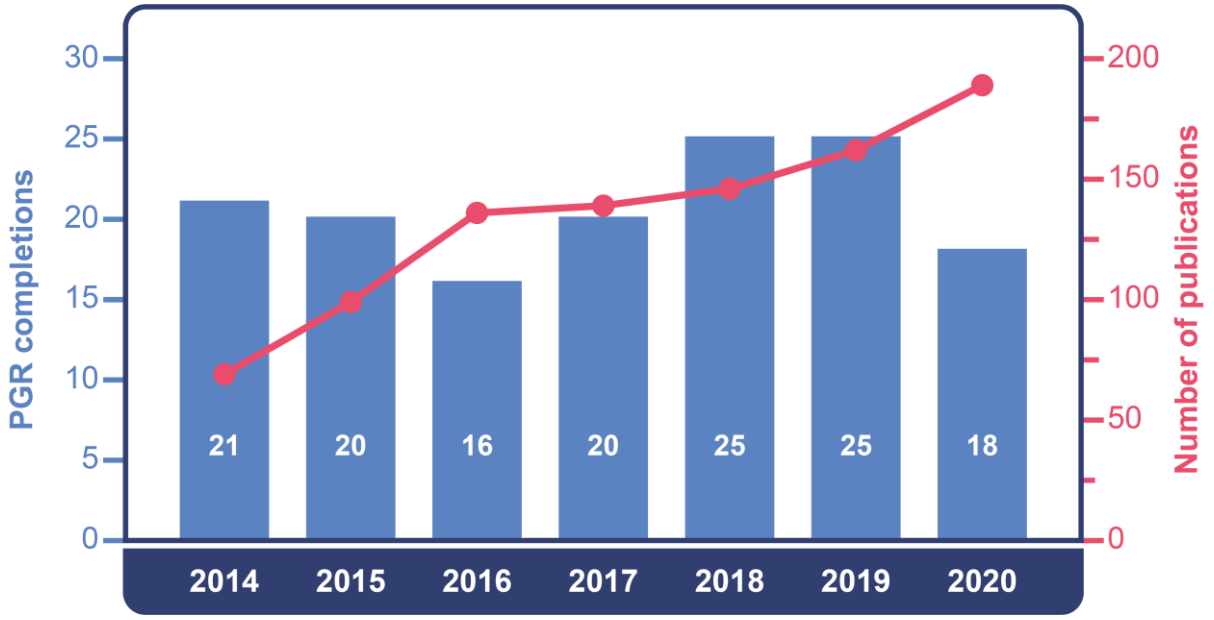

***Figure 3**: Number of PGR completions by year (columns with numbered totals) and postgraduate output generation (red line). Source: Web of Science.*

2.2.1. Student progression

Each student meets regularly, at least monthly, with his or her principal supervisor and has at least one other internal academic supervisor. Monthly meetings are documented and record progress and objectives with our online e:Vision tool, which also allows for the monitoring of student engagement and progression. The process is overseen by the Graduate School (REF5a, section 3.5) and assessed at an initial project approval stage in month 4, then two progression reviews follow for full-time students, in months 11 and 23. Milestones include a written report and a viva with an internal examiner, both designed to formally review progress, set the objectives and identify training and resource needs. We aim to foster the highest quality level in our graduates' work through research group support and through inclusion in the development of research projects (e.g. *Qu, Xu, Ruiz-Gutierrez*, *Orme* and *Campbell* were successfully appointed to PDRA positions).

Challenges faced by students throughout the COVID-19 pandemic have been acknowledged and responded to with increased flexibility in the adaptation of research plans, extension of deadlines for internal reporting, and provision of a suite of mental health and well-being support measures including counselling.

2.2.2. Student training and support

All PGRs enrol on the university's Professional Development and Researcher Training Programme, which is mapped onto the four Vitae domains: intellectual abilities, personal effectiveness, research governance, and engagement. Training involves unit-specific sessions, often delivered through research group workshops or presentations and online interactive courses. Students who are part of CDTs, DTPs or ITNs access additional advanced training, which is built into programmes designed to equip future research leaders in their field; some of this training is open to all PGRs.

All PGRs can attend a three-day course on introduction to teaching that enables them to get involved in academic activities with undergraduates, equipping them for careers beyond the successful completion of the thesis.

2.2.3. Postgraduate environment and engagement

PGRs in the unit are based in research suites located adjacently to staff offices that allow access to common spaces shared between students and staff. Postgraduate offices offer individual workstations with further hot-desking facilities within laboratories. Since 2018 our students are also able to access (i) dedicated areas within the new Research Commons in the City Library; (ii) collaborative and networking space for digital and open scholarship, with bookable rooms for reading, meetings and consultation; and (iii) expert face-to-face support across the research spectrum.

Examples of PGR development

- *Aggarwal* (Northumbria's IEEE Student Branch lead) received the Region 8 Regional Exemplary Student Branch Award in 2019. *Aggarwal* also chaired the Women in Engineering Affinity Group 2015–2018 and in 2017 organised the first Women in Research event, which was followed by an International Women's Day.
- *Angelis* received specific IT support to set up a Google group for ground-penetrating radar (GPR) modelling that now assists 275 researchers worldwide; and he co-led the organisation of an online workshop on GPR processing funded by the unit.
- *Ranaweera* joined the Brilliant Club's Scholars Programme and tutored in school and sixth form colleges to help pupils from underrepresented backgrounds to access university.
- *Hayes* was supported in an application to the European Network INTERACT for equipment funds and travel to Arctic Canada, where he hosted a Reddit 'Ask Me Anything' session on his research on the impacts of permafrost degradation on communities, under climate change, and attracted *c*.37,000 views and 200 questions in 24 hours.

All PGRs have access to a budget designed to cover their research expenses and travel (the amounts depend on the funder). Students are also encouraged to be proactive and organise their own specialist conferences and training events. Additionally, it was a collective and coordinated request from the postgraduate community within the Civil and Construction research group that led to our institutional membership of the Construction Industry Research and Information Association. Supervisory teams give advice on how to access external research funding from EPSRC networks, the Royal Academy of Engineering, the Royal Society of Chemistry or the Institute of Physics; the applications of *Amirkhalili*, *Campbell*, *Nwankwo*, *Qu*, and *X.Xu* have been successful. PGRs in the unit are supported by our staff to become actively involved with professional bodies in the Institution of Engineering and Technology (IET), the Institute of Electrical and Electronics Engineers (IEEE), the Institution of Civil Engineers (ICE), the Chartered Institution of Building Services Engineers (CIBSE) and the Institution of Mechanical Engineers (IMechE) – and their local branches (section 2.3).

Attendance at relevant research group meetings and seminars is mandatory for all PGRs in engineering, as it embeds them into the unit's research practices. Students are also required to present their research at a dedicated annual postgraduate conference, to provide a supportive and inclusive research culture, and to foster cross-disciplinarity. Student conferences are organised by a postgraduate student planning committee, under the guidance of the unit's

postgraduate leads (*Jovanovic* and *Rahmati*) and postgraduate director (*Shyha*), who secure inclusive representation and additional development opportunities for PGRs.

2.3. Equality, diversity and inclusion (EDI)

The unit recognises that diversity, addressing inequality and creating vibrant and inclusive research environments is fundamental to our success and sustainability. We are strongly committed to an equality and diversity agenda that fosters mutual respect and an inclusive and empowering culture for all. Athena SWAN departmental self-assessment teams led by *Gao* and *Burluka* are actively working towards award submissions in 2021, while *Penlington* is co-leading a Northern Power Inclusion Matters initiative (EP/S012206/1) that aims to shape an actively inclusive culture in the Engineering and Physical Sciences community. This initiative sustains greater equality for all, including people of different genders, ethnicities, sexual orientations and (dis)abilities.

A pervasive strategy throughout the unit's growth and development has been to diversify engagement within the discipline, both directly, through the growth of our own staff base (**Fig. 4**), and indirectly, through focused initiatives. This strategy is reflected in a threefold approach: (i) a continued investment of efforts and resources into redressing, through our NUSTEM initiative (section 4.2), the imbalance that affects young people from Black, Asian and minority ethnic (BAME) and disadvantaged socioeconomic backgrounds who choose engineering as a career; (ii) a consciously flexible and inclusive strategy for recruitment and working practices that is overseen by Athena SWAN departmental committees; and (iii) compulsory and accessible professional training for all staff, designed to raise awareness and reduce the occurrence of unconscious bias (REF5a, section 3.6).

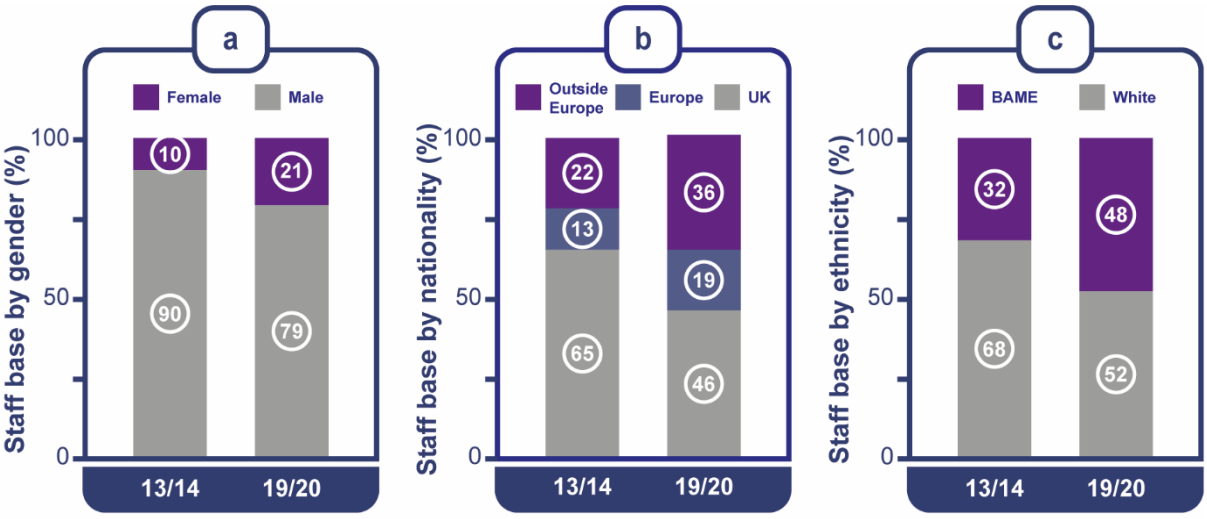

***Figure 4**: (a) Gender, (b) nationality and (c) ethnicity diversification in the unit during the REF period. Our REF2 attribution profile of outputs closely aligns to this diversification.*

In our recruitment process we take appropriate positive action, wherever possible, to address the under-representation of women in the unit. We look to advertise posts across a wide range of recruitment websites, and we promote options around flexible working arrangements and benefits in order to increase our appeal to a broader pool of candidates. All adverts for staff and postgraduate positions are checked for gender-coding words (http://gender-decoder.katmatfield.com); all interviews are conducted by mixed-gender panels whose members – of diverse backgrounds, wherever possible – have completed a fair selection and unconscious bias training. Whenever possible, research seminars and committees are scheduled during core

hours (10 a.m. to 4 p.m.), to facilitate the attendance of staff with caring responsibilities, and out-of-hours emails are discouraged. Where institutional timetabling protocols allow, we aim to keep one day per week free of teaching for each member of staff – and more than one where timetable constraints allow.

The unit supports university-wide engagement with the Race Equality Charter and its BAME staff network (REF5a, section 3.6) and has taken a proactive approach to the theme Women in Engineering by reducing gender inequality and showcasing the contributions of female engineers. In 2014 we did not submit any female academics as part of our submission to General Engineering. For REF2021, by contrast, a fifth of our submission is composed of female staff. Unit funds and resources have supported new initiatives to increase diversity in engineering and in STEM professions more broadly. Our rich diversity and our ability to make recruitments with a truly global reach are reflected in the fact that more than half of our staff consists of members who hold non-UK citizenship (**Fig. 4b**) and contribute to our multicultural environment.

Examples of leading EDI initiatives

- *Edmondson* organised and led an ICE200 event involving a series of workshops in order to explore the challenges and strengths of diversity. It culminated in the launch of a longitudinal research project designed to track the progression of 200 female and 200 male engineers at 3-year intervals, which provided unique insights by identifying both barriers to career advancement and ways to address them.
- *Costa* and *Zabiegaj* are working with IMechE, leading and delivering keynote addresses at the International Women in Engineering Day, which has been hosted and organised by our unit for the past three years.
- *Combrinck* was supported by the unit to train in the Cross-Institutional Action Learning for Women programme, which focuses on career enhancement and networking opportunities and has since been nominated by the IMechE for the 2020 Karen Burt Memorial Award.
- *Ponton* was supported to establish a mentoring scheme for Women in Construction, linking the unit's staff and students with industry, so as to provide female leadership, mentoring and help retention in the sector.

The unit recognises that good physical and mental well-being is fundamental to our vitality and delivering sustainable research. A well-being hub provides a range of supporting materials, including access to a Health Advantage app that supplies proactive well-being tools, and additional guidance for navigating the challenges of the COVID-19 pandemic (e.g. guides to remote working). Mental health is supported through training programmes and guided sessions and a well-being calendar of all relevant events, and the Employee Assistance Programme provides guidance and tools for achieving work-life balance (see REF5a, section 3.6), as well as 24 hour counselling service and tailored support and networks for new staff arrivals.

Examples

- [text removed for publication], a scientist specialising in computational materials and defects in them, was offered additional office space in order to create a physically separate research environment. This has prompted us to reconsider the needs of our unit's computational specialists more widely.
- After a career break, [text removed for publication] was mentored by *Beattie* and subsequently awarded a Daphne Jackson Fellowship (2014–16), and she is now pursuing an academic career.

The construction of our REF submission was compliant with all the EDI principles and practices set out in our Code of Practice. Research outputs were judged on the basis of quality, regardless of an author's protected characteristics. The best outputs from each staff member were identified through a combination of personal and double internal and external peer assessment. All staff members were invited to take part in internal peer review and calibration exercises, the unit lead (*Zoppi*) acting as a moderator. While eligible outputs of former staff were considered, those of current staff were prioritised for submission when peer reviews were of equal quality. All available EDI data were taken into account to ensure that the selected outputs were representative of the submitted staff pool and research topics.

3. Income, infrastructure and facilities

3.1. Research income and organisational strategies

The unit's strategy of developing communities of high-quality researchers, who work at the forefront of global challenges, has resulted in a substantial increase in awards and expenditure. During the REF period we have successfully secured over 170 research grants and contracts exceeding £28M.

Evidence

Income: We have increased the quantity and diversity of awards and the overall size of research income (RGCI) from £2.9M in REF2014 to £10.2M for REF2021 (yearly trajectory shown in **Fig. 5**).

Knowledge exchange: Our dedicated team of business development managers has helped colleagues to achieve a 100% success rate in knowledge transfer partnership applications, securing 16 KTPs (and another 5 since the census date) during the period, in comparison to 4 during REF2014.

Highlight projects from the unit's research income include:

- EPSRC CDT in ReNU (£5.5M, *Barrioz*, *Beattie*, *Zoppi*) as a lead institution, with Durham and Newcastle Universities and 35 supporting partners;
- Hub for Biotechnology in the Built Environment (Research England, £8M total, £3.7M to Northumbria, *Zhang*). Driving major growth, further supported via the BioDesign for the Bioeconomy MDRT;
- EU H2020 Innova-Microsolar (€4.0M, *Mahkamov* lead), designed to enhance the application of solar thermal energy in domestic and small business sectors for power and heat production;

- EU H2020 ITN Vision (€3.8M, £455k to Northumbria, *Ghassemlooy, Le Minh*) a training programme for visible light communication research for smart cities and homes, transportation, and medical applications;
- EPSRC Photovoltaic Technology based on Earth Abundant Materials – PVTEAM (£2.0M, £478k to Northumbria, *Forbes*), which aims to develop resilience and sustainability in energy materials;
- EU H2020 RINNO (€4.8M, £265k to Northumbria, *Kassem*), designed to increase building energy efficiency for renovation projects;
- EU Interreg North Sea Region SEEV4-City (€5.0M, £270k for Northumbria, *Putrus*), that aims to develop the uptake of electric vehicles by integrating renewable energy sources;
- Leverhulme Trust Research Project Grant (£225k, *Birkett*), which developed superhard biocompatible coatings.

Improvements in grant success rates within the unit are underpinned by our research structures and culture. Processes of grant application development and grant management are coordinated by the university's Research and Innovation Services (RIS) office. Funding calls, tailored newsletters summarising current opportunities, and UKRI and UKRO funding-related news are disseminated via email, call briefing events and workshops, social media, and dedicated intranet pages accessible to all staff. Additional resources are available to all members on the intranet and include funder information packs, templates for letters of support, bite-size guides and examples of previous successful grants on a range of funding topics and sources.

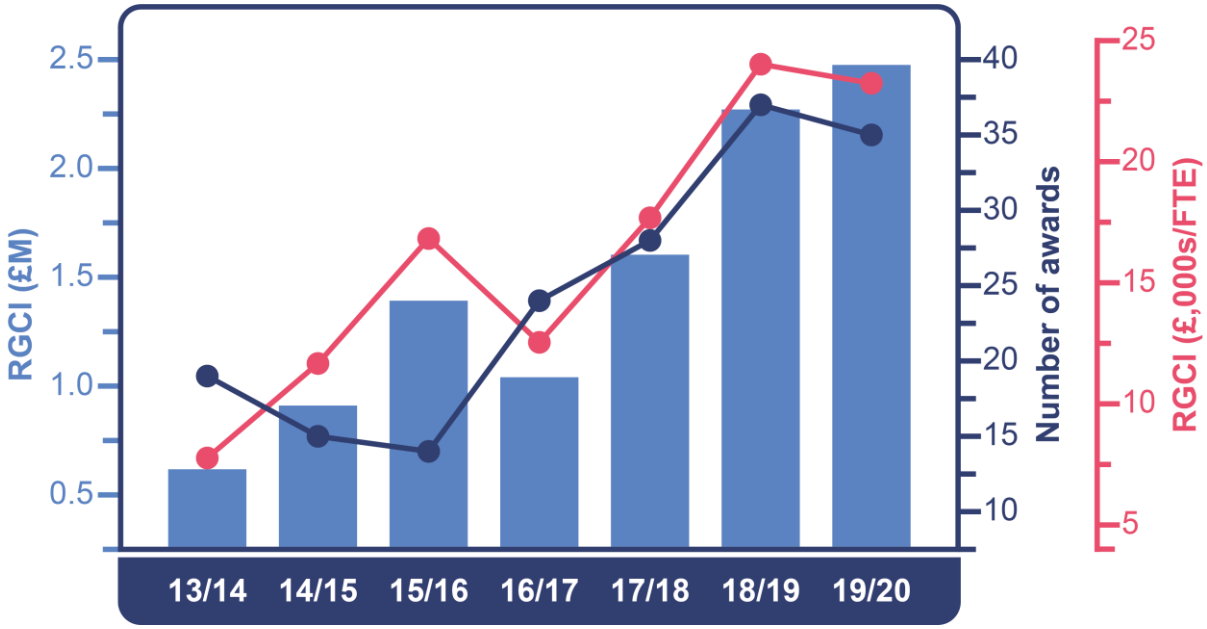

***Figure 5**: Transformation of grant success culture in our engineering unit. Evolution in the number of awards (blue line), as well as growth in RGCI (columns) and RGCI per FTE (red line).*

To enhance success rates for funding applications, departmental directors of research, supported by MDRT and research group leaders, are alerted once prospective applications are uploaded to our Agresso management systems, so that internal peer review by an appropriate subject expert can be arranged. Our emphasis on personal, career stage-appropriate support recognises the

diversity of our staff base and ensures equitable access to support for funding applications. The results of our income strategy can be seen in **Fig. 5**.

The unit's experience and proven practice, shared through research groups, has been a vital element in the increase of our RGCI across the staff base. We also acknowledge that many of our ECRs have yet to fully contribute to the growth of RGCI (given the lags between recruitment, awards and RGCI), and therefore provide a strong platform for further growth. Recent successes from our ECRs post-census date confirms this trend and sustainable strategy, e.g. *Tiwari* (£607k, EP/V008692/1), *Ho* (£373k, EP/V040030/1), *Khaliq* (£223k, Innovate UK), *Qu* and *Rasul* (£236k and £50k, respectively from British Council), and *Sathian* (awards from Research England and the Royal Society).

Examples of support for the development of winning grant applications

- ECR Writing Retreats allow dedicated space and time for continued formative feedback on proposals in development.
- The 'impact in funding bids' initiative supports principal investigators (PIs) in developing frameworks for pervasive impact throughout the proposal.
- 'Fellowship Ready' sessions support ECRs and the Next Generation of Large Award Holders programme helps researchers who have already won small to medium-sized grants to transition to larger-scale applications.
- Our research development managers in RIS work closely with researchers, providing bespoke support to PIs through pre-award and post-award officers, and our business development managers work alongside researchers to build and foster relationships with non-academic partners (section 4.1).

In 2014 the unit also revised its internal finance models in order to invest quality-related funding directly in postgraduate activities aligned with research quality enhancement, and developed a new overhead-sharing financial model (Research & Enterprise Rewards Scheme) designed to incentivise, reward and sustain new areas of impact, success and growth.

Examples of benefits from the Research & Enterprise Rewards Scheme

- *Xu* used the scheme to hire *Wang* after thesis submission in order to explore a new phenomenon that arose from the PhD research. This led to a high-impact publication in Advanced Functional Materials and a third place at the EPSRC photo competition in 2017.
- *Beattie* commissioned high-quality renderings for a successful Advanced Manufacturing interview panel (EP/T005491/1).

All staff members can apply for unit-managed funds to support networking, data collection, presentations of significant esteem, or the hosting of workshops. The outcomes from this outward-looking resource are tracked by the unit lead (*Zoppi*) and applied reflexively and responsively, in order to continually raise the unit's profile, embed our researchers in world-leading networks, and ultimately support high-quality impact and income generation. Sabbatical leave plays a key role here by providing the time for staff to write grants (see section 2.1.3).

Evidence

Our ECR support via unit funds, research development managers and probation objectives has resulted in a 1 to 9 increase in the number of ECR awards since REF2014, all coming from EPSRC First Grant and New Investigator Award schemes.

3.1.1. Technical research support

In parallel with increasing the numbers and the potential of its academic staff, the unit has restructured its technical team, which has 22 permanent technicians supported by 2 technical managers and by PhD qualified experimental officers. The technical team oversees health and safety in the laboratories and provides researchers and PGRs with training on specialised equipment. The experimental officers manage capital-intensive specialist hardware and complex apparatus, so as to ensure maximum utilisation, efficient productivity, and high quality of data. For example, *Maiello* is responsible for our materials characterisation suite, overseeing all electron microscopy, ion beam and X-ray work. Our experimental officers contribute to the generation and analysis of research data and actively (co-)author research outputs. They are complemented by an IT team of seven that provides dedicated support to staff and PGRs.

3.2. Infrastructure and facilities

The engineering unit is located in two adjacent buildings on the university city campus; all laboratories are within the Ellison building, totalling approximately 1,500 m^2. During the REF period we have invested over £11M in our estates and facilities (more than twice as much as during REF2014); this figure includes a £3.2M contribution from HEFCE. Expenditure was split between equipment (55%) and estates (45%). This investment has been used to renew and update essential equipment, extend the capacity and equipment base of existing research groups, and support exciting new research activities, opportunities and progressive developments. We have refurbished over 90% of our engineering laboratory space and have nearly doubled the physical footprint of our laboratories. A few notable investments are described below.

The Smart Materials and Surfaces Laboratory (SMSL), setup in 2013/2014, has now doubled in size, to accommodate the rapid growth of the Smart Materials and Surfaces group. It is a state-of-the-art laboratory, fully equipped with dark space, fume hoods and high-specification equipment such as contact angle goniometers, tensiometers and fluorescence microscopes used to understand and exploit the fundamental physics and engineering of liquid–solid interactions. We have also created an adjacent specialist lithography room for the design and manufacture of surfaces (£460k).

Evidence

The capital investment in the SMSL has supported eight EPSRC grants (a total of £2.2M) during this period and directly led to collaborative KTPs with QuantuMDx and Hart Biologicals.

We have fully refurbished and extended the Communication Laboratory, which now integrates both visible light and cellular network communication teams within a dedicated space (£410k). We have acquired new deposition systems to cope with the increased demand from our research groups for thin film and coating fabrication (£300k).

A new Material Characterisation Laboratory, housing our electron-, ion- and photon-based equipment, now provides cutting-edge facilities for all our research group activities. We have

invested in a new high-resolution scanning electron microscope and in a new powder X-ray diffractometer (£1.4M). The facilities are also used by industry, [text removed for publication].

We have extended our machining and prototyping facilities through the addition of 5-axis computer numerical control machining and a range of 3D printers, forming machines and laser cutters that total over 30 individual tools available to all staff and students (£970k). This inclusive approach fosters a research community that can benefit from access to cutting-edge equipment and from knowledge transfer and consultancy opportunities; it also ensures that sought-after specialist skills are developed from undergraduate through to postgraduate level, to produce high-skilled ECRs.

We have invested in new Geophysics, Hydrology, Structures, Geotechnics and Highways Engineering Laboratories and redesigned and expanded the Concrete Laboratory, equipping it with a new 3D concrete printer and a large-scale covered outdoor working space with a closed system designed to remove contaminants for safe disposal; this development underpins our collaborative research with Lynx Precast, MMC Engineer Ltd, and Extraspace Solutions Ltd. The unit's researchers now have access to the latest large-scale flumes and rainfall simulators for collaborative research with utilities companies, urban planners and dam construction projects. They use ground-penetrating radar systems, 3D vibrometers, seismic detection equipment, 3D laser scanners, drones and geomatics equipment to monitor natural hazards and to alert national and international agencies about their imminent threat; and they test and analyse new road materials in collaboration with [text removed for publication] (£1.3M).

We have refurbished all existing wet processing laboratories and created new ones, nearly doubling our capacity to support the unit's expansion into new areas such as nanomaterials and printed electronics. We have also created multiple flexible-space laboratories in order to allow the rapid deployment of experiments, develop prospective collaborations and facilitate multidisciplinary projects (£460k). We have undertaken an overhaul of our space for PhD students, with a view to creating a friendly and productive atmosphere, giving direct access to laboratories and promoting interactions between research groups that share common agendas (£210k).

To address an increasing demand, from our researchers, for large data processing, informatics, and sophisticated modelling, at the end of the last REF period we invested £460k in a high-performance computing (HPC) Oswald cluster. We have further upgraded the HPC (£360k), which now contains two clusters with 1,216 cores for processing, a graphics processing unit (GPU) node, dedicated visualisation nodes and 571 TB parallel storage and allows the unit to address increasingly computationally demanding research problems (e.g. *Whalley*, *Rasul*, *Tiwari*). Additional GPU and CPU power has been accessed at national facilities (e.g. *Warren*: EPSRC Jade Tier-2 HPC and HPC-Europa3).

3.2.1. External facility access and collaborations

To foster external networks and access to high-quality instrumentation and data sources not available internally, we proactively encourage and target collaborations and partnerships. We routinely access X-ray photoelectron spectroscopy at Newcastle NEXUS (formerly a national facility), as well as their ion beam facility (*Fu*, *Rasul*, *Liu*). *Zoppi* worked with Surrey's Ion Beam Centre for implantation and reference specimens and with the Horiba France SAS R&D centre in Saclay-Paris, France for mass spectroscopy (EP/N024389/1), while *Etherington* accessed the Diamond Light Source (RAL) for crystal structures.

A formal collaboration has been established with Nanyang Technological University, Singapore (EP/R014884/1 and CDT in ReNU), allowing access to *in situ* and *operando* electron microscopy

techniques (*Beattie*, *Qu*) that complement those available at the York JEOL Nanocentre and at Durham's GJ Russell Microscopy Facility (*Barrioz*, *Hutter*, *Qu*, *Zoppi*).

We have routinely used (i) the Fraunhofer Institute for Solar Energy Systems (*Beattie*) to perform concentrated sunlight measurements; (ii) clean room facilities at Durham University (*Agrawal*, *Woods*) and at ETH Zurich (*Torun* EU-COST-MP1407 and EU-ATTRACT_3D-MIPS-ID270); and (iii) radionuclide research facilities at the Institute of Energy and Climate Research at Forschungszentrum Julich, Germany (*Lewis* EP/P004873/1 and Royal Society of Chemistry Researcher Mobility Grant KE2466).

Example of impactful collaboration

Our collaborations with AkzoNobel (*Unthank*) yielded two industrially funded PhD students, two patents and the sharing of research facilities and equipment across the university and industrial sites, as well as the donation to the unit of thermal analysis equipment for polymer and materials studies.

3.3. Future estates plan

To drive research excellence and support our researchers, we will make further investments in our estates. Key priority items for the unit's five-year strategic plan to 2025 are a redevelopment of the thin-film fabrication laboratory (£1M, partly funded by the North East LEP's Energy for Growth fund); new wet laboratories for research on nanomaterials; and a new space for the International Centre for Connected Construction (IC3, see section 1.6).

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

The unit promotes both fundamental and applied research in order to advance the frontiers of engineering and offer effective solutions to partners and collaborators. We have achieved this through sustained investment in new international research networks; strategic developments to support research groups with specialist capital and spaces; and protected, research-focused time for our staff.

The unit's research has created new systems that aim to drive economic growth (section 4.1), educate and transfer knowledge, reduce inequalities, and prompt influential networks to engage with diverse communities and publics (section 4.2). Our interdisciplinarity is forging exciting new developments in engineering and achieving academic reach that is now demonstrably global (section 4.3).

Evidence

Across the unit we have achieved:

- industrial influence and impact – through new products that arose from contributions to 41 patent awards; 44 externally funded collaborations with industry; and leading roles in 15 professional body networks;
- new policy and process definitions – by having key roles in more than 20 international networks and by influencing national-level decision-making in more than 10 countries;
- academic significance – through 64 academic honours and awards; 98 memberships of industrial, governmental or international advisory boards; more than 152 invited presentations and keynotes; the organisation of 76 conferences; and 45 editorial positions secured.

4.1. Major industrial collaborations and economic stimulus

Contributing to and working with industry is core to research activities carried out within the unit, and hence to the support structures and processes designed to make collaborations flourish and endure (section 3.1). In recognition that effective relationships require time and concerted effort to grow and maintain, the unit typically invests 25% of its budget in supporting collaborative research across the full spectrum of partnerships. We enable targeted risk-taking ventures by establishing new embryonic relationships, priming them, developing them, or taking them in new directions.

The research group platforms (**Fig. 1**) and their strong links with industrial advisory boards have supported an inclusive progression and expansion of successful collaborations, using a networks of networks approach to enriching the research environment.

Our business development managers (section 3.1) have been instrumental in helping academics to work effectively with industry by proactively creating opportunities, mentoring, and even acting as mediators in early meetings, so as to focus the agenda on achieving productive new economic impacts. The unit's support structures have facilitated cross-cutting collaborations, which range from nurturing some emergent opportunity to realising the full potential of our engineering advances. We enabled a new collaboration with Technip FMC Plc to provide solutions for subsea umbilical systems for oil and gas platforms (*Gonzalez-Sanchez*), and this led to an industry-funded PhD partnership designed to generate new areas of research. *Shyha* developed [text removed for publication].

Supported by the unit's travel funds and then speculative investment in new 3D printing innovations, our research on additive manufacturing and sand-casting products led to new tooling processes [text removed for publication]. Our work with the automotive sector includes a collaboration with the Lear Corporation UK Ltd (*Unthank*, *Hackney,* KTP11215) in synthesising new polymers for foam seating products to reduce production time, operating costs and environmental impact; and, recently, a collaboration with [text removed for publication].

Example of growing new areas of industrial collaboration

Our strategic investment of resources and leadership in materials engineering and analysis have led to a partnership, unique in the UK, with Ansys Inc., a company that has sponsored a new computational fluid dynamics research laboratory in the unit (2019; the laboratory is led by *Penlington* and *Xu*). This collaboration and contribution to the research base is already revolutionising our capabilities, primarily in propulsion and turbines research. Wider benefits have also accrued to the structural researchers of the Civil and Construction group, who have secured three KTPs. Additionally, this themed support for materials analysis in civil engineering has led to a new formulation, independently recognised as 'leading' in Advances in Engineering Civil Engineering Significance Statement (*Richardson*), and has stimulated award-winning high-impact geotechnical monitoring research papers and collaborations with Global Digital Systems (GDS) Instruments (Materials and Structures Outstanding Paper 2018 Award, *Mendes*).

Enabling support from the unit is used strategically, to develop successful and sustainable relationships with research beneficiaries. The unit's workload provision for staff and match-funding of a collaborative PGR have been essential to the progress registered in the study of [text removed for publication].

4.2. Contributions to society, community and public engagement

The unit has sought to maximise societal impacts by generating vibrant and sustainable initiatives that reflect the diversity of wider society, by breaking down conventional boundaries and by achieving inclusivity, which is at the heart of our vision of external engagement. Our approach has made significant contributions throughout society, from inspiring primary school pupils to addressing global gaps in skills, improving equality and access through the transformation of international intellectual capital in renewable energy, and driving step changes in sustainability through digital construction and monitoring technologies.

Our NUSTEM initiative has reimagined STEM outreach to engage with diverse communities, working both nationally and internationally. The unit's dedicated team – supported by our wider research community, which delivers specialist sessions – works to address the gap in academic progression in physical and environmental sciences education for students with protected characteristics, specifically targeting the under-representation of females and the need to engage young people from disadvantaged areas. Our innovative Theory of Change approach has facilitated work directly dedicated to educating and empowering over 90,000 young adults and key influencers, demonstrating a nearly 30% rise in children's desire to pursue engineering careers (the rise was 80% in young girls). Our People Like Me approach has been adopted internationally. For example, 2,400 education kits have enabled critical early-stage exposure to STEM activities, learning resources and aspirational career paths for pupils across 45 schools in Nigeria. As part of the unit's response to COVID-19, the rapid translation of 'STEM at Home' activities has provided a vital and resilient engagement resource, now widely accessible to potentially vulnerable communities.

Evidence of societal uptake and reinvestment

In addition to attracting over £1M in external funding, NUSTEM has provided oversight, steering and guidance to organisations such as the Institute of Physics, the Reading Agency, and the UK Government STEM Strategy Team on how our Theory of Change approach can be used to generate quantifiable changes in various communities' engagement with STEM skills and applications. The £1.25M North of Tyne Combined Authority STEM and Digital Skills programme is based directly on our research.

Our efforts to embed inclusion and diversity in engineering through research-led initiatives are also making quantifiable differences to global skills shortages. For example, our long-standing research expertise in photovoltaics and energy conversion (*Forbes*, *Putrus*, *Beattie*) has been central to training over 560 postgraduate students at the Institute for Clean and Renewable Energy (ICARE) at the Huazhong University of Science and Technology, China. Originally established through EU-China funding (EuropeAid/128796/L/ACT/CN) and now supported mainly through workload provision and travel funds from the unit's resources, this institute is the first international multipartner training programme in renewable energy in China, addressing a gap in skills in a growing industry and providing access to specialised energy education and professional training for minority groups. The ICARE Initiative was praised by the Ministry of Education as 'a flagship project of Sino-foreign cooperation' and has catalysed new investments into photovoltaic infrastructure as a result of workforce upskilling and advancement of education–industry partnerships.

Our leadership in energy growth and development has developed regionally through *Beattie*, who sits on the North East Energy Catalyst – a group facilitated by the North East Local Enterprise Partnership for delivering the 'energy for growth' strategy in the region. We have also created a new international training platform for Nigerian engineers to develop transformative skills and knowledge in renewable energy, green materials, sustainable agriculture and waste-to-energy systems (*Azimov*; the platform is funded by the Royal Academy of Engineering). The initial pilot has equipped hundreds of local engineers to adopt environmentally conscious, effective, and sustainable practices and, once the process is complete, the unit's leadership will look to develop and exploit these successes still further.

Example of investing in and realising the impact of transformative practice

- Unit funds initially supported research on BIM and digital construction, which resulted in the establishment of BIM Academy Enterprise Ltd, a joint venture with Ryder Architecture. The unit subsequently supported the work of *Kassem* and colleagues with funds for a dedicated research assistant to provide policymakers with actionable road maps to BIM transformation; these have now been adopted into national policies on digital construction in Canada, Ireland, Mexico, and Latin America (among other places).
- The unit funded *Corradi*'s early development of innovative reinforcement techniques for historic masonry. These techniques have subsequently been adopted [text removed for publication]. The research has also informed RILEM and American Concrete Institute international guidelines.

In addition to supporting the reach and significance of existing areas of excellence such as our renewable energy technologies research, the unit has set up and fostered new research groups and focus areas. For example, unit funds were allocated to resource *Greenwood* and *Benghi*'s

creation of an open-source xBIM Toolkit (section 1.4) for the automated transfer of accurate and complete information throughout the design, construction, operation and maintenance phases of the building lifecycle. Additional business support from the unit then enabled engagement with over 100 international users, including new partnerships with Project Advisors International (UK) Ltd and major social housing provider Your Homes Newcastle (KTP10761, *Greenwood*) to use the xBIM toolkit to extract geometric and semantic data for performance monitoring of buildings. The significance of research on visualising the live sensor-based results from the toolkit on a dashboard has also been recognised through best paper awards at the 2018 Sustainable Ecological Engineering Design for Society Conference and in the 2019 BIM Show Live.

We now partner with Lucion Environmental Ltd (KTP10293, *Benghi*) to develop a new way of completing safety and risk management assessments in buildings using 3D BIM. The unit is actively working to develop this expertise in digital construction through the leadership of a consortium that brings together industry, academia and the public sector, championing the use of digital technologies to influence long-term productivity and safety improvements via our IC3 consortium (see section 1.6).

We have embedded bespoke public engagement in major funding applications in order to make engineering more relevant and accessible to the public, improve communication and promote the unit's research. We provide design and training clinics for our staff and for researchers who make presentations to the general public and to younger audiences. During the REF period we have led over 50 showcase events in non-scientific communities.

Examples of public engagement

- Our renewable energy team created exhibits and demonstrator products for events such as Street Scientist during 'Dippy on Tour' at the Great North Museum (2019), the Beamish Museum (2015) and the Big Bang Fair North East (2017).
- Our smart materials and surfaces team contributes to 'Nature's Raincoats', a public engagement collaboration between the universities of Edinburgh, Northumbria, Nottingham Trent and Oxford, and regularly performs at local and national events (e.g. Big Bang Fair 2018, 2019, Maker Faire 2018).
- We showcased our control and power engineering research at the regional Maker Faire throughout the period 2012–2018, during the Great Exhibition of the North (2018), the Beamish Museum's Wind in Your Sails (2016–2018) and the BBC micro:bit (2016).

4.3 Academic significance

4.3.1. International academic collaborations

Our research groups provide dedicated forums for the dissemination and development of collaborative ventures, optimising and expanding successful working relationships and exploiting emerging opportunities. International academic collaborations account for 13% of our funded research projects during the REF period.

Examples of leadership in multi-institution partnerships

- *Mahkamov* (i) leads Erasmus+ programmes in (a) renewable energy upskilling for undergraduate and postgraduate students from Latin America (http://www.thecruxproject.eu) and (b) PhD upskilling in clean thermal power systems (http://www.asiaxis.eu/index.html) and (ii) co-leads with *Azimov* a programme that focuses on engineering skills enhancement in South East Asia (http://www.skybelt.eu). All projects are valued at €1M each and involve 23 individual institution partners in Europe, America and Asia.
- Our work on visible light communications was part of the Centre of Excellence for Learning, Innovation, Networking and Knowledge (cLINK, EU Erasmus Mundus) (*Le-Minh* and *Ghassemlooy*), and *Ghassemlooy* was vice-chair of EU FP7 cost Action IC1101.

4.3.2. Contributions to the discipline

Our engineering unit has sought to enrich the discipline and advance its sustainability by contributing to new knowledge through high-quality papers and by establishing future directions through keynote addresses, industrial speaker events and involvement with selection panels for external funding. We have disseminated current advances through conferences, seminars and practitioner workshops and improved the quality and standards of research via our editorial and reviewer roles. We also prioritise discipline development through the leadership of professional and regulatory bodies (e.g. *Corradi* chairs the Northern Counties Committee of the Institution of Structural Engineers). The procedures (section 2) and research group communities (section 1) set up within the unit have helped to grow these metrics, but the embedded interdisciplinary focus has also transcended traditional boundaries, providing more reflexive and innovative approaches to making progress in the discipline.

Our researchers also support the essential work of funding bodies by both reviewing and selecting projects for funding. Among our colleagues in the unit, 11 are registered EPSRC Associate College members, while 8 serve as Full College members and 25 have reviewed proposals for EU Horizon 2020, UK research councils, charities and international funding agencies. *Beattie*, *El* and *Xu* have served as panel members for EPSRC and NERC, while *Torun* served as vice-chair for the H2020 FET OPEN Programme in 2015 and 2017. Our junior staff members also make important contributions to the discipline, for example *Shahzad* has received numerous awards for his work on solar desalination and air-conditioning including Energy Globe Saudi Arabia (2019 and 2020), the Global Water Award 2020 (Innovative Individual Award for Youth) and the MEED Sustainability Medal (2020).

The unit supports its staff in organising events and conferences; it does so both financially and through strategic optimisation and detailed content assistance. Our seminar series brings engineers and scientists from across the UK and beyond to promote research collaborations and widen cross-discipline perspectives. A high-profile example was the visit of *Dr Henk Jonkers*, world-leading expert on bio-based self-healing concrete. The visit involved a workshop with our biotechnology research hub and culminated in a public seminar, followed by an interview with the BBC that involved *Jonkers* and *Richardson* as Northumbria's lead.

Examples of international events organisation

- The 24th Annual Conference of the Chinese Society of Chemical Science and Technology in the UK and of the Society of Chemical Industry's Chinese UK Regional Group (*Xu, Li,* 2017, 240 participants);
- The ground-penetrating radar modelling workshop across the MDRTs of Energy Futures and Extreme Environments (*Warren*, 2020, 330 participants). The unit is now supporting the production of continuing professional development (CPD) resources to address community requests for additional training;
- *Azimov* led international workshops funded by the British Council on Future Low Carbon Propulsion (2018) and autonomous vehicles (delayed to 2021 at our partner institution, the Central Scientific Research Automobile and Automotive Engines Institute in Russia).

We also encourage our staff to improve data accessibility to all (section 1.4). *Etherington* is working with the Royal Society Archives to make publicly available, online, hundreds of transcriptions from Sir John Herschel, as part of the Epsilon project (https://epsilon.ac.uk); this is a virtual space allowing users to navigate the history of scientific discoveries through a repository of nineteenth century letters.

Further disciplinary and scholarly contributions have been made by those among our staff who act as (associate) editors for scientific publications such as the *Journal of Automotive Composites* and the *Journal of Vehicle Engineering* (*Elmarakbi* editor-in-chief), the *International Journal of Computer Application in Technology* (*Dala*), *Frontiers in Physics: Mathematical and Statistical Physics* (*Kirillov*), the *Journal of Intelligent Industrial Systems* (*Busawon*), *IEEE Transactions on Industrial Electronics* (*Gao*) and *Fluids MDPI* (*El*). Across the breadth of our research activities, our researchers are supporting and promoting the scholarship of others through peer reviewing for leading journals in the field.

4.3.3. Beyond disciplinary boundaries

The unit's interdisciplinary research practice has fostered strong themes that focus on our use of, interaction with, and threats posed by natural resources and phenomena. Our visible light communication team, led by *Ghassemlooy*, and thin-film photovoltaic team, led by *Beattie*, are working with Northumbria's Solar Physics group to develop SULIS (Solar cUbesats for Linked Imaging Spectropolarimetry) – not only the first UK-led space science mission, but one envisioned to provide unprecedented measurements of the magnetic field of the corona and answer fundamental questions that underpin the sources of space weather. SULIS was recently awarded £360k by the UK Space Agency for laser communications for CubeSats.

Field, recognised as a leader in interdisciplinary research (Royal Society APEX award), is working to understand and pre-emptively improve policymakers' and the public's reaction to the implementation of wastewater reuse for human consumption (a project supported within our Energy Futures and Human and Digital Design MDRTs). Our civil and electrical engineers (*Edmondson*, *Lim*, *Torun*) collaborate with computer information scientists and geomorphologists to address threats to arterial transport networks and city utilities posed by costly and complex natural hazards – namely to address them through the development and operationalisation of sophisticated new digital information alert systems (an initiative funded by NERC, NE/T005653/1, NE/P000010/1 and by Northumbrian Water; also advancing the Extreme Environments MDRT).

In addition to new research-led policies and processes (section 1.3), the unit provides technological solutions to the dramatic impacts of climate change on vulnerable Arctic

communities and vital infrastructure through funded collaborations with geochemists, geophysicists and national agencies that aim to develop new passive seismic sensors capable of monitoring permafrost thaw processes for the first time (this is funded by the NERC Arctic Office; Extreme Environment MDRT, *Lim, Martin, Warren*).

4.4. Summary

Our unit has driven a transformative change in research capacity and capabilities during the REF period. It has overseen the creation and evolution of productive and dynamic research group communities; new procedures, virtuous circles of support, and reward systems; and an ambitious and enabling expansion of facilities (more than £11M invested in space and equipment). These changes have afforded an exceptional growth in the strength and diversity of our staff base and its performance (increases larger than fivefold in submitted staff and research awards, larger than threefold in RGCI); and this growth is supported by targeted global recruitment, dedicated professional support teams and ambitious strategies designed to enhance the impact, inclusivity and accessibility of our work. We end the REF2021 period as a coherent and exciting unit, with interdisciplinary innovations and advances central to our vision of sustained research excellence and lasting impacts on the economy, society and the discipline.