Institution: Joint Submission by the University of Edinburgh and Heriot Watt University as the Edinburgh Research Partnership in Engineering (ERPE)
Unit of Assessment: 12 Engineering

1. Unit context and structure, research and impact strategy

1.1. ERPE context and structure

As one of the largest and fastest growing intra-urban academic collaborations in the UK, our Vision is *to be a world-leading partnership which delivers research, innovation and training that underpins clean growth, healthier living and sustainable development in the era of climate emergency and an increasing and ageing population*. Our Mission to achieve this vision is *to develop and exploit advances in: artificial intelligence & robotics; data & communications technologies; materials & processes and numerical & physical modelling that address the major challenges facing global society and the environment that has lasting positive impact.*

The Edinburgh Research Partnership in Engineering (ERPE https://www.erpe.ac.uk/) was founded in 2004 with a joint investment of £22M from the University of Edinburgh (UoE), Heriot-Watt University (HWU), the Office of Science and Innovation and the Scottish Funding Council (SFC), expressly to build and capitalise on the thematic alignment of complementary research expertise across the engineering disciplines in both Universities.

The partnership was reinforced in 2013 by an institutional Strategic Alliance that pooled our human and physical resources, enabling us to return 210 academic staff to REF2014. In 2014 we stated that we planned "*to build on our strong position, in terms of people, research expertise and KT processes to continue to deliver a significant impact on engineering practice, under-pinned by a policy of recruiting and developing the highest calibre staff, encouraging and promoting interaction with industry, and facilitating the transfer of results to industry and other research users, either by direct engagement or through company formation".*

We have strategically grown and structured our four original cross-cutting ***Organisational Themes*** to deliver the above vision, by each of them addressing two or more of four agreed interdisciplinary global ***Research Challenge Areas***, as shown in Figure. 1.1.

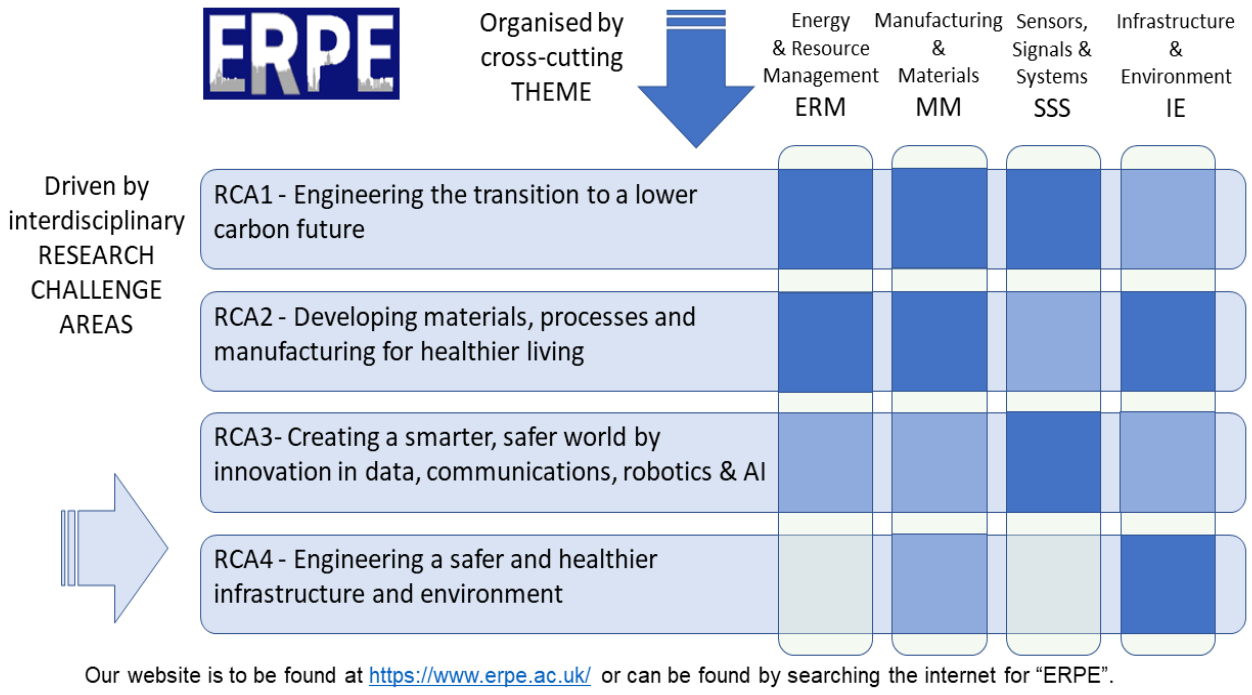

Figure 1.1 - ERPE Research Challenge Areas and Organisational Themes

In sections 1.2-1.5 we present three linked strategies that determine our investments and efforts. They have helped us to deliver our 2014 plans, are key drivers of future planned activity and support ERPE's vitality and sustainability. Our ***Strategy for Development and Growth*** below has been to invest in staff and facilities that, by enacting our ***Research Strategy*** *(p.4)*, has allowed us to shape and align our objectives and effort, enabling us to ***achieve our strategic aims*** *(p.6)* and to ensure that our ***Impact Strategy*** *(p.12)* has been effective. Sections 1.6 and 1.7 describe how we ensure that ERPE operates within an ***Open and Responsible Environment*** *(p.15)* which is conducive to us realising our ***Future plans and achieving the forward vision*** *(p.16)*.

1.2. Strategy for development and growth

ERPE's strategy has been to *expand and sustain a conducive environment for world-class research, within which we co-ordinated investment in new staff and infrastructure, built on evidenced areas of excellence and capitalised on our joint strengths to increase our research income in new areas of activity and work with greater reach, delivering increased impact and addressing our global research challenges and opportunities.*

Investment in New Staff

Since 2014 we have **increased our academic staff capacity by 37% to 288 people** in 2021, appointing 19 new professors and 27 senior lecturers/readers. Strategically focussing on early career development and the vitality of our staff complement we have appointed 62 lecturers, of which 19 are tenure-tracked research fellows. Examples of ERPE's **planned strategic growth** within our Organisational Themes include: 25 new appointments in bio-medical engineering; 9 in multi-scale thermofluids; 10 in composite materials & digital manufacturing and 4 in fire safety engineering.

Investment in New Infrastructure

We **have secured and invested over £100M** to extend our research, doctoral training and impact infrastructure.

We have partnered in a successful bid for £661M investment from the UK and Scottish Governments in Data-Driven Innovation (DDI) as part of the £1.3B Edinburgh and South-East Scotland City Region Deal in 2018. The award exploits the university-based regional strengths in technology and data science, recognising the growing importance of the data economy and the need to tackle the digital skills gap. Over 15 years, DDI will bring in £500M of consequent funding to both institutions to support ERPE-related research and innovation. At the heart of its involvement in the City Deal, ERPE is co-investing £36M to construct the National Robotarium (to open in 2021), building on the Edinburgh Centre for Robotics (ECR) that leads the £36M Offshore Robotics for Certification of Assets Hub (ORCA Hub), funded through the Industrial Strategy Challenge Fund. We have invested £22M in the creation of the Lyell Centre, where the British Geological Survey (BGS) is co-located with ERPE. Together with EPSRC and the Scottish Government, we have invested £12M in the FloWave Ocean Energy Research Facility (Figure 1.2.1), the world's first circular combined current and

Figure 1.2.1 - FloWave

Figure 1.2.2 - FASTBLADE

wave test basin. With EPSRC and Babcock International Group, we are investing £4.1M in FASTBLADE (Figure 1.2.2), the world's first full-scale accelerated tidal turbine blade fatigue test facility.

We have secured a £33.5M commitment from UoE to build phase 1 of the new Engineering Quarter (EQ1) at our King's Buildings Campus (Figure 1.2.3). We have further benefitted by aligned investments of over £21M to co-locate Edinburgh Innovations (EI), UoE's commercialisation arm, in Murchison House close to EQ1, and in the construction of the Global Research, Innovation & Discovery Centre (GRID) at Riccarton (Figure 1.2.4).

Figure 1.2.3 - Planned Engineering Quarter

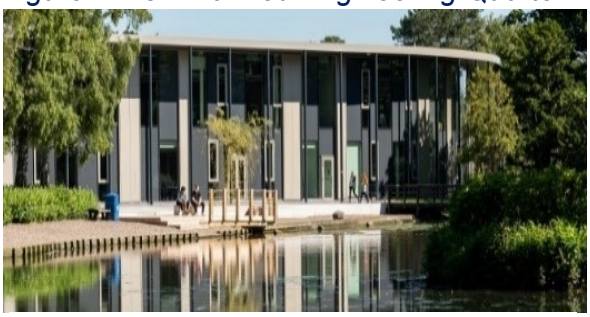

Figure 1.2.4 - GRID Building

We have invested over £11M in new and upgraded laboratories in: laser-based manufacturing, microfluidics, novel combustion engines and bio-medical engineering, and in embedded labs at the Queen's Medical Research Institute (Edinburgh Royal Infirmary).

Growth of Income, Impact and Reach

As a result of this investment, our strategy and the added value of the ERPE partnership, we have increased our competitive advantage to deliver more at-scale engineering research, innovation and impact of international standing. Since 2014 we have:

- **Doubled our research and innovation income**, **winning over £200M of awards and support** from UKRI, UK Government, EU and industry. Included in the above figure is £20M of new funding from the Royal Academy of Engineering and others to support 19 prestigious early to mid-career fellowships. Specifically, our participation in the ORCA Hub (£36M), the Universities Defence Research Collaboration (£12M) and Advanced Care Research Centre (£20M) are all direct results of the strength of the ERPE partnership;
- **Increased our doctoral training cohort by 73%** from 618 to 1068 students and graduated a total of 831 doctoral engineers (EngD & PhD), **86% more than reported in 2014**;
- **Won leadership of, or participation in, 13 CDTs**, amounting to nearly £80M of forward funding from UKRI and industry that will enable us, by 2028, to **deliver more than 1100 doctoral engineers and scientists** into key UK and global industries;
- **Won over £23M of UK and overseas industry funding** and grown our industrial top-tier collaboration by over 30 companies, ranging from multi-nationals to SMEs, including Leonardo, Renishaw, Shell, BP, Total, Alstom, Jaguar Land Rover, Suzlon, BAE Systems, Canon Medical, seebyte, Metrohm Raman, Cubica Technology Ltd and Dstl;
- **Increased our impact with 135 Granted Patents**, based on 42 new technologies where the attributed Lead Inventor was from ERPE and 12 spin-out companies;
- Extended our global reach in **over 50 new international collaborations,** including with: Princeton; MIT, Stanford, Michigan, Illinois, Cornell, Texas Universities and Lawrence Berkeley and Sandia National Labs; ETH Zurich; SINTEF; Federal Universities of Pernambuco Rio de Janeiro; Pontifical Catholic University of Chile; UNAM Mexico; Shanghai Jiao Tong and X'ian Jiaotong Universities; and King Fahd University of Petroleum & Minerals in Saudi Arabia.

1.3. Research strategy

Our strategy has been to *identify responses to global research challenges that will unlock, promote and help to deliver clean growth, smarter and healthier living and sustainable development* and then to *focus our aims, objectives and organisational themes on delivering world-leading, inter-disciplinary, responsible research and innovation with immediate impact and potential for lasting positive change.*

To support this strategy our research portfolio ranges from applied research, impacting on industry and society's immediate to medium-term needs, to more fundamental curiosity-inspired research resulting in longer-term impact.

We propagate diversity of activity within each of the four Organisational Themes to transcend thematic, discipline, school, institutional, and national boundaries and add value through whole-systems research at the intersections of multiple scientific, engineering and policy challenges. ERPE researchers collaborate globally with colleagues from Medicine, Geosciences, Chemistry, Physics, Informatics, Mathematics, Business, Economics, Social and Political Sciences. Figure 1.1 shows how our staff direct their efforts towards national to global imperatives defined, among other places, in: the UK Government's Grand Challenges within its Industrial Strategy; the UKRI Strength in Places Initiative and the United Nations Sustainable Development Goals. We summarise below, for each of our global RCAs, our stated plans in REF 2014 and their strategic aims and objectives now, in 2021. Section 1.4 identifies new awards, leaderships, assets and research highlights as examples of achievement of our strategic aims.

RCA1 – Engineering the transition to a lower carbon future

We aim to address the Climate Emergency by *developing new technologies and processes, and by delivering analysis that advises policy formation, that will help to accelerate society's Energy Transition to bring about a lower carbon, more sustainable future.*

In 2014 we planned that ERPE research would *"uniquely encompass all aspects of the energy cycle: from resource exploration and exploitation, diversification of efficient production, and the development of methods and technologies to reduce and mitigate the impact of CO_2 emissions"*.

Since then we have evolved our research portfolio to extend from natural energy resources (both renewable and hydrocarbon) through the conversion and delivery infrastructure (as electricity or fuel) through end-use (including heating and transport) and beyond to the re-processing, storage and reuse of CO_2 - always taking account of environmental, economic and energy policy effects. We have extended our interests and capacity in ocean energy to include offshore fixed and floating wind technologies. We have also invested to develop and expand the former Institute of Petroleum Engineering into the Institute of GeoEnergy Engineering, to address a much broader range of subsurface energy challenges - going beyond oil and gas to include carbon capture and storage, geothermal energy and renewable energy storage.

RCA2 – Developing materials, processes and manufacturing for healthier living

We aim *to discover, advance and apply novel science, technologies, processes and materials used in the manufacturing and healthcare industries to benefit people of all ages in all sectors of society*.

In 2014 we planned to *"devise solutions for industrially important challenges: the design and fabrication of micro- and nano- scale devices and systems; the development, use and control of high power lasers and laser-driven processes; and the performance of materials at extreme conditions*." We planned "*to grow activity in bioengineering research focussing on technologies to*

assist stem cell medicine, medical diagnostics and bio-sensing, synthetic biology and biotechnology."

Our research capacity has, since then, been extended to enable activities that span the range of length and time scales from molecular processes to new technologies in three key areas: Non-continuum and non-equilibrium fluid mechanics; multi-phase flows, interfaces & phase change; and multi-phase, interfacial, and chemically reacting bulk flows. We have built capacity and infrastructure in the strategic areas of advanced polymer composites and clean combustion technology, the latter within a new Institute for Multi-scale Thermofluids. We have conjoined our capacity in Micro-scale Device Manufacture (MDM) with new staff and facilities in Synthetic Biology to create a new Bio-medical Engineering/Healthcare Technology cluster that has underpinned our emerging diagnostics and sensing focus and allowed us to pioneer the adoption of biological organisms as an engineering substrate. We now work with clinicians from across the UK and beyond, particularly with those in the Edinburgh Medical School's bio-engineering and bio-photonics labs.

RCA3 – Creating a smarter, safer world by innovation in data, comms, robotics & AI

We aim to *exploit the interactions between digital technologies and the world they operate in, sensing, communicating and processing data to extract and act on the information to create and ensure a smarter, safer world.*

In 2014 we recognised that in an environment of increasingly pervasive communications and interconnected sensing, our research had to be planned to *"focus on the theory and technologies underpinning sensor data acquisition, data communication and the ability to store and process large quantities of data.*" We also planned "*to invest in and grow activity in Robotics & Autonomous Systems*."

Our research activities now include and transcend the boundaries between Robotics & Autonomous Systems, Signal & Image Processing, Sensor Devices & Systems and Communications. We use data- and communications-driven innovation to increase the autonomy of robotic and artificially intelligent systems for strategically important sectors, including defence and security, energy and medicine. Our staff combine robotics and artificial intelligence (AI) to exploit synergies in manipulation, control, and robot collaboration in outdoor and indoor applications, and in marine and humanoid settings in the ORCA Hub. Along with other funded activity, this has enabled us to create a world-leading research centre for Robotics & Autonomous Systems (RAS).

Our signal and image processing research spans underpinning theory to novel imaging modalities including agile tomography, parallel and distributed processing, and machine learning methods for advanced signal and image analysis in astronomy and multiple medical imaging modalities. Our research in agile tomography is helping to reduce the environmental impact of aviation and carbon-fuelled power generation, also supporting RCA1.

We engineer novel micro- and nano-scale devices and systems using innovative fabrication processes to manufacture: systems-on-chips; sensors and actuators; single-photon-avalanche-diodes (SPADs) and micro-electro-mechanical systems (MEMs). They are used in many application areas ranging from biomedical engineering to defence. Our staff deliver new wireless connectivity technologies and processes, emerging technologies around Visible Light Communications (LiFi), the Internet of Things and 5G, and beyond.

We aim *to develop new materials, practices and regulation to make the future urban and rural infrastructure and environment safer, healthier, more resilient and more sustainable.*

In 2014 we planned to *"focus on the relationship between infrastructure design, maintenance and operation, and societal needs to improve the integrity, security and sustainability of infrastructure systems, including the development of novel technologies for sanitation and water quality improvement and computational research to understand the impact of climate change and natural disasters on human systems."*

Our research in IE now includes: exploiting advances in data analytics and sensors for infrastructure resilience; developing enhanced techniques for fire safety in building construction; and addressing UN Sustainability Goals affecting low- to middle-income countries. UK and EU Research Councils support both fundamental and applied interdisciplinary research, conducted with the support of industry partners. The research extends across infrastructure (structural design, construction, maintenance, operation and safety), human wellbeing (societal need, flood risk, water and wastewater treatment) and ecosystem sustainability (river systems). This research encompasses: the assessment, monitoring, and improvement of transport and urban infrastructure; fire safety; advanced structural mechanics and dynamics, granular mechanics and flow technology; novel technologies for sanitation, and water and wastewater treatment; flood risk assessment; environmental flow and eco-morphodynamic modelling, river ecosystem resilience, and the water-energy nexus. This activity is delivered in the context of climate change and adaptation, carbon reduction, and resilience against natural and manmade disasters.

1.4. Achievement of strategic research aims

Our investment to support the growth, research and impact strategies has created an environment within which our growing staff numbers have delivered our research strategy and achieved their aims across RCAs 1-4.

Summed across ERPE, our academic staff numbers have increased by 37% to reach 288 and our UKRI/Government funding has increased by 125% since 2014, EU funding by 127% and industry/other funding by 47%. We have highlighted below, for each of our Organisational Themes, selected research and innovation achievements from fundamental discoveries to industrially-collaborative high-TRL impact, four of which are noted as submitted impact case studies. We have included, where appropriate, hyperlinks to key related outputs.

Energy and Resource Management

To accelerate society's Energy Transition to a lower carbon, more sustainable future, ERM staff have worked with industry to develop new technologies, materials and processes, particularly for the Offshore Renewable Energy Sector where reliability and durability are critical. They have also worked with government to deliver analysis that has advised policy.

Aligned with our aims to address RCA1, ERM academic staff numbers have grown since 2014 by 34% to reach 75 and our research awards have nearly doubled to over £77M.

ERPE's capacity to address RCA1 is underpinned by new and renewed ERPE assets (since 2014) that include **Jeffrey's** leadership of the EPSRC UK Centre for Marine Energy Research (UKCMER) and **Ingram's** leadership of the Industrial Doctoral Centre in Off-Shore Renewable Energy - a collective investment of over £30M that has enabled ERPE and other UK academics to lead the world in collaborative research, innovation and training in tidal, wave and offshore wind energy technology and practice. These and other investments are supported by the FloWave

Ocean Energy Research Facility. **Owens** leads our partnership in the ReFLEX (Responsive Flexibility) project in Orkney, supported by £28.5M investment from Innovate UK, to demonstrate a world-first island-based Virtual Energy System (VES) interlinking local electricity, transport, and heat networks into one controllable, overarching system.

Our leading position was recently reinforced by the appointment of **Maroto-Valer** as UK Champion to lead the development of the new UK Industrial Decarbonisation Research and Innovation Centre (IDRIC), a £35M UKRI and industry investment, that aims to deliver the government's 'net zero' ambitions by addressing the challenges of decarbonising the industrial sector. The twinned £17M investments in the ERPE UK Carbon Capture and Storage Research Centre (UKCCSRC) and Research Centre for Carbon Solutions have created a national hub and network for research, development and innovation in carbon reduction, capture and storage.

Additionally, the International Centre for Carbonate Reservoirs is a £4.7M industry-funded research alliance developing new technologies to characterise high CO_2 offshore geological reservoirs and explore opportunities for CO_2 storage in Brazil, as well as developing related capacity in Brazilian higher education.

In 2019 **Kiprakis** and **Sellar** made, in FloWave, the first ever real-time measurements of flow, performance, and structural loadings in a closely-spaced array of 1.2m diameter scale tidal turbines, also operating under wave loadings, connected to an electricity network emulator (Figure 1.4.1). The resultant findings, (Energies), and further experimental work, underpinned the development of the FASTBLADE accelerated blade fatigue test facility and, working with tidal turbine developers Sabella, Nova Innovations and Orbital Marine Power, were incorporated into the DTOcean+ open-source software suite, now assisting tidal energy array design across the ORE sector.

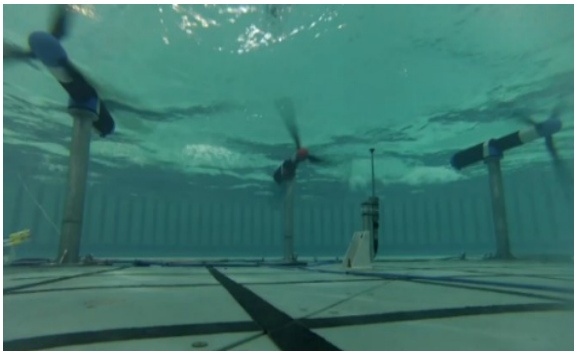

Figure 1.4.1 – Array Testing in FloWave

Sellar worked with engineering multi-national Alstom and subsea instrument manufacturer Nortek to develop a Convergent-beam Acoustic Doppler Profiler (CADP) that was the first field-scale 3D velocimeter capable of directly measuring tidal site turbulence, (J. Meas Sci & Technology). ERPE developed successor technology that can autonomously scan the velocity-field spanning a turbine rotor-plane area. It will be deployed in Fromveur passage, France, ahead of an operational Sabella D10 prototype tidal turbine (Figure 1.4.2) that is also equipped with an ERPE online sensing system that captures the real-time environmental conditions driving power fluctuations and varying dynamic structural loadings.

Figure 1.4.2 – Sabella turbine in Brest

These and other marine current turbine developers have, as a consequence, partnered with **Viola** and **McCarthy** in a new £1.2M EPSRC project to develop fast-acting flexible trailing edges that will enable tidal turbine blades to morph passively and reduce load fluctuations.

Wind, wave and tidal current energies deliver high torques at low speeds to power take-off systems which, without gearboxes, are fundamentally unsuited to conventional electromagnetic

induction in compact high-speed rotary generators. **Mueller** developed two novel C-GEN air-cored low speed, direct drive rotary and linear generators and improved their thermal performance, (IEEE Trans Energy Conv.), leading to their demonstration in the Mocean Energy Ltd **Blue Star Project**, and technology licensing to Vertax Wind, Swift Energy and Mocean Energy. In Project Neptune he and colleagues demonstrated, in Leith Docks, a pioneering flooded 150 kW vertical linear generator (Figure1.4.3).

Figure 1.4.3 - C-Gen

Muradov and collaborators delivered pioneering research (J. Comp. GeoSci) that identifies the principal geologies and oil production conditions where autonomous oil and gas reservoir inflow control valves installed along the well can reduce pipeline choking, resulting in the environmental benefit of a 68% reduction in water usage for cleaning and associated energy reduction. Working with the Norwegian company Inflowcontrol they have demonstrated the potential for an annual economic saving of $2.4M in operating costs. This is described more fully in our Impact Case Study "*Autonomous intelligent control valves enhance oil recovery and environmental sustainability*". Within the BP Centre for Energy Economics, ERM staff delivered underpinning research for the annual BP World Energy Outlook and Statistical Review of World Energy that forecast future energy consumption and production, influencing shareholder investment and company strategies.

Fundamental research by **Viola** on the aerodynamic properties of the dandelion seed discovered that its ability to fly is due to a separated vortex ring; the publication (Nature) garnered news reports in over 30 countries. Based on this curiosity-led work, **Viola** and collaborators in Imperial College London, Cambridge and at Caltech have been awarded an ERC Consolidator Grant (€2M, 2020), "DANDIDRONE: *A dandelion-inspired drone for swarm sensing*" to investigate whether it is possible to develop a manmade flyer that can remain airborne without external power, exploiting the energy in horizontal wind gusts and build the first-of-a-kind wind tunnel in ERPE.

Manufacturing and Materials

MM staff, particularly those in our expanding bio-medical engineering and multi-scale thermo-fluids areas are collaborating extensively with the manufacturing and healthcare industries to jointly discover and deliver the new science, technologies, processes and materials that are urgently needed to positively impact all ages and sectors of society.

MM academic staff numbers have grown, since 2014, by 54% to reach 91 and our research awards have nearly trebled to £48M to develop world-leading technologies for medical science and practice, aligned with ERPE's aims to address RCA2&3.

Our recent investments and co-funded assets to address RCA2 include PROTEUS, a £15M EPSRC Interdisciplinary Research Centre in Healthcare Sensing, in which we are developing and demonstrating the use of fluorescence-based micro endoscopy systems for detection of pathogens in human lungs, and have pioneered the first *in vivo* human clinical studies. Most recently, we have secured £6.1M from EPSRC to support research in transformative healthcare. The new U-Care collaboration will deliver a point-of-care technology platform exploiting short wavelength light to augment therapeutic pathways for some of the biggest challenges facing medicine including the emergence of antimicrobial resistance and cancer therapy. The £20M Advanced Care Research Centre (ACRC), which is funded directly by Legal & General, combines interdisciplinary research in medicine and other care professions, life sciences, engineering, informatics, data and social sciences. As the largest industry investment in the DDI initiative, it aims to improve understanding

of care in later life and to revolutionise how it is delivered. Within ACRC we lead the doctoral training in the £6M pan-disciplinary CDT. We have established the Medical Device Manufacturing Centre (MDMC) which is a £3.2M four-university centre supported by the Advancing Manufacturing Challenge Fund (AMCF). This investment in healthcare research, technologies and practice has returned over £5.8M of consequent funding from UKRI, EU, Edinburgh & Lothians Health Foundation, and the James Black Foundation.

In the PROTEUS collaboration, SPAD array technology developed by **Henderson** (Nature Comms) and image processing algorithms by **McLaughlin** (IEEE Trans Comp Imaging) led to the world's first SPAD line sensor capable of delivering information at rates sufficient for scanning video images of the lung. This new technology provides picosecond resolution and, in the TotalPhoton collaboration, is being exploited by **Altmann**, in time-resolved fluorescence microscopy (Nature Comms). Through a secondment, **Henderson** transferred ERPE SPAD technology into a leading commercial receiver array design and was co-inventor on 26 patent filings, of which 6 have been granted to date. **Henderson** and colleagues have extended the global reach and significant impact of the SPAD research for automated distance focussing in over 1 Billion mobile cell-phone cameras, described more fully in our the Impact Case Study "*Innovation in optical distance sensing drives global adoption in smartphones and other technologies*".

Thomson, in collaboration with Medicine at UoE, is using laser physics in the new U-Care project to develop new sources of deep UV light and the technologies that will deliver this light with cellular precision to advance cancer surgery and combat the emergence of drug-resistant "super-bugs". Figure 1.4.4 shows two images of ex vivo lung tissue obtained down a coherent imaging fibre. The image on the left is ex vivo lung on its own, and the image on the right is ex vivo lung with NBD–PMX SmartProbe labelled bacteria, both displayed as intensity with a threshold applied based on lifetime to highlight labelled bacteria.

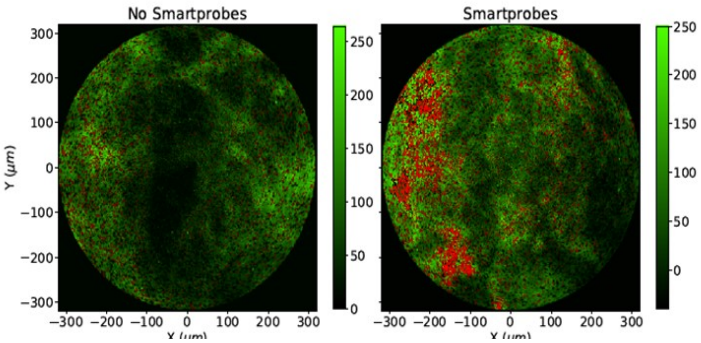

Figure 1.4.4 – Ex-vivo lung tissue after labelling

In the PreCisE collaboration, with Renishaw and Coherent Scotland, **Shephard** and **Hand** have developed a precision laser scalpel for colorectal cancer diagnosis and treatment (Scientific Reports).

Reuben's work on Dynamic Instrumented Palpation led to a spin-out company IntelliPalpDx Ltd formed from joint research (totalling around £1.3M) between ERPE and NHS Lothian Western General Hospital. The ProstaPalp pre-prototype (Figure 1.4.5) integrates the concept of Dynamic Instrumented Palpation into the inside of surgical gloves to screen for early-stage prostate cancer (J. Num Methods in BioEng). Since March 2020, the company has won further support from Scottish Enterprise and **Johnson** has won a RAEng Enterprise Fellowship.

Figure 1.4.5 – IntelliPalp diagnostic

Desmulliez and co-workers won Global Engineering Impact Awards in the Innovative Research (2018) and Humanitarian (2019) categories for the SonoPil project on swallowable, ultrasonic endoscopic capsules with multi-modal sensing, sponsored by National Instruments and 17 other companies (Figure 1.4.6) (Science Robotics).

Figure 1.4.6 – SonoPil Capsule

In the EPSRC IMPACT project, **Murray and McLaughlin** developed globally pioneering approaches for cancer treatment based on implanted miniaturised, wireless sensor chips used to monitor the status of a tumour (Vet Jnl).

In the new Institute for Multi-scale Thermofluids (IMT) **Peterson** and **Krueger** each won highly prestigious ERC Starting grants. **Peterson** was awarded £1.15M and is characterising transient wall heat transfer using line-imaging of gas temperature via hybrid fs/ps rotational coherent anti-Stokes Raman spectroscopy (Proc. Combustion Inst.). **Krueger** was awarded £1.5M and is developing Lattice-Boltzmann models for multiphase flows, at nano- and micro-scales, of blood cell-separation with deformable cell structures (J. Soft Matter).

Reese, Borg, **Zhang**, **Gibelli** and **Pillai** won a globally competitive 3-year $2.8M partnership programme of excellence awarded by King Fahd University of Petroleum & Minerals (KFUPM) in Saudi Arabia. This was the only successful European proposal, funded alongside MIT, Stanford, Cornell, Texas, and W. Australia. **Borg** developed the open-source solvers IPKS2/3D which have been used by KFUPM and Saudi Aramco to quantify the flow properties of shales (J. Comp Physics Comms).

Sensors, Signals and Systems

SSS staff and industry have jointly developed next generation sensing, digital technologies and signal processing algorithms to optimise interactions with their operating environment and sense, communicate and process data, ultimately making the world and society smarter and safer.

SSS academic staff numbers have grown, since 2014, by 58% to reach 71 and our research awards have increased by nearly two thirds to over £61M.

We recognise that ubiquitous computing/communications and data-driven innovation are pre-requisite elements of our response to RCA3 and we now engage deeply with colleagues in the Alan Turing Institute, the Edinburgh City and South East Scotland Region Deal and its associated entities including the Bayes Centre, the Edinburgh Futures Institute and the National Robotarium.

We have won, for a third time, leadership of the £12M UK University Defence Research Collaboration (UDRC) with the Defence Science and Technology Laboratory (Dstl), that brings together all of the major industrial companies in Defence in the UK including Leonardo, BAE Systems and Thales UK, to develop underpinning Signal Processing theory for future defence systems. **McLaughlin** (Nature Comms) and **Mulgrew** (IEEE Trans Sig Proc) have developed new sensing and imaging technologies for Dstl and other defence industry partners, which have been raised to higher TRLs through 11 follow-on DASA and Dstl industry contracts of value £1.1M. The work also led to several licensed technologies including: algorithms for fast Raman spectral un-mixing of chemical species that were embedded in a handheld spectrometer by Metrohm; a novel method for fast back projection code for Synthetic Aperture Radar Systems that was licenced to

Leonardo; and an algorithm that enabled more efficient STAP radar systems and was used in the i-STAR demonstration radar system by Dstl.

We are collaborating with colleagues in Chemistry to address RCA2 and developing novel SPAD arrays supported by a £7.2M EPSRC investment in healthcare technology to deliver 'Optical X-Rays'. ERPE's partnership in the £20M Quantum Imaging Hub conjoins computational imaging and SPAD research to deliver next generation imaging systems. **Tsaftaris** developed deep learning tools for MRI analysis to aid diagnosis of coronary heart disease, supported by the RAEng/Canon Medical Chair award, (J. Medical Imaging).

In ERPE's LiFi Research and Development Centre (LRDC) **Haas** and colleagues, in collaboration with the Fraunhofer Institute for Solar Energy Systems ISE (Freiburg/Germany), produced a single solar cell that received data at a rate of 500Mbps (in 2018) and 1Gbps (in 2019), and achieved 2.5Gbps for multiple PV cells in multiple-input multiple-output mode, in collaboration with St. Andrews University. These data rates and their increases have been fundamental in demonstrating capability and enabling investment and growth of new LiFi technologies. Impacts include the multi-award winning spin-out company pureLiFi securing £21M of external investment, partnering in 200 projects in over 20 countries and leading to multiple world firsts for LED communication products that are now utilised in education, healthcare, defence and commercial applications. This is described more fully in our Impact Case Study "*pureLiFi: The first LED light-based communication system*", which aligns with the SSS vision to address RCA3 and affirms the effects of the first-of-a-kind new technology in the global communications arena.

Developing from **McCann's** leadership of the Platform Grant "In-situ Chemical Measurement and Imaging Diagnostics for Energy Process Engineering" (EPSRC, £1.1M), he and collaborators in the LITECS project (EPSRC, £5.8M, Shell £1M), have deployed Chemical Species Tomography for the first time in the largest civil aerospace gas-turbine engines and in laboratory turbine combustors, (IEEE Trans. Inst. & Meas.), to elucidate key mechanisms for reduced environmental impact (with Rolls-Royce, Siemens, Royal Dutch/Shell, INTA (Madrid) and 5 UK universities) – also generating follow-on funding from the H2020 CleanSky2 project led by INTA (EU, €2M).

Infrastructure and Environment

IE staff have developed new technologies, practices and regulation whose deployment and implementation have contributed to making the urban and rural infrastructure and environment safer, healthier, and more sustainable, specifically improving urban and rural resilience to fire and earthquake hazards.

We have increased IE academic staff numbers to 51 and focussed our research towards UK and UN Sustainable Development agendas, resulting in a more than doubling of our awards to £20M.

ERPE hosts the £4M Centre for Fire Safety Engineering in collaboration with key industry partners (BRE, IFIC Forensics, OFR, Design Fire Consultants and Arup), which provides international leadership in fire safety engineering research, practice, and consultancy. The Centre's research activities have extended to include the critical areas of wildfires, fire safety in informal settlements, and cladding fires. The Centre provides research support related to fire safety to UK government agencies including The Home Office and Scottish Parliament. In infrastructure resilience, IE researchers held grants over £8M related to the EPSRC Centre for Sustainable Road Freight Transport, and the European COST Action Scheme towards autonomous vehicles, aimed at meeting the 2050 target of 80% reduction in CO_2 emissions by road freight transport.

Research on fire performance of timber, concrete, and steel structures carried out by Bisby, Hadden, and Law has informed design codes in the UK (BSI), Europe (CEN), and USA (ACI, ASTM and ASCE) (Proc J. Fire Safety). This has significantly raised awareness of the increased fire hazard posed by use of mass timber in high-rise buildings and has identified mitigation measures for designers around the world, with significant influence on improved safety and resilience. **Bisby**, is a high-level advisor to UK Government (Home Office, Scottish Parliament), professional bodies (RAEng, IStructE, IFireE, RSE, BSI, and CEN), trade associations (The Structural Timber Association), and research and Innovation hubs (CSIC & CENSIS). He was, and remains, a key technical expert advisor to the Grenfell Tower Inquiry and, with **Hadden**, to the Metropolitan Police Investigation into the Grenfell Tower Fire. Law, **Welch**, and **Rush** provided advice to UK Government on Fire Safety (Proc. IStructE). Working in partnership with the Structural Timber Alliance industry body, ERPE staff developed and asserted the first industry guidance for the design and construction for fire safety of timber buildings, now adopted in the UK timber frame sector. This is described more fully in our Impact Case Study "*Improving fire protection regulations, standards and industry guidance to enhance public safety*" which aligns with IE aspirations to address RCA4 to make the urban environment healthier and safer. In collaboration with IVALSA, **Reynolds** has pioneered earthquake-resistant, cross-laminated timber multi-storey structures as a sustainable construction technology for seismic regions (Proc J. Cons & Bldg Mats). **Vasdravellis** pioneered an hourglass design of steel dampers, which enhances the earthquake-resilience of buildings (Figure 1.4.7), (J. Struct Eng). **Sutman** invented a new type of energy pile construction technique which reduces structural risk and environmental impact; the technology is being promoted by Berkel and Co Contractors, US, for deep foundation applications (Figure 1.4.8) (J. GeoMech for Energy and Env). **Cao**, **Pender** and **Borthwick** contributed to theoretical models of landside-induced flood flows (Int J Sediment Res) and barrier lake formation (J. Applied Math. Modelling), critically important to earthquake-prone countries like China. Working with colleagues at Dalian University, PRC, they have described the critical-state behaviour of soil, and informed studies of internal erosion in embankment dams and sand liquefaction under cyclic loads. In collaboration, **Ooi** built upon the Discrete Element Methodology and developed a coarse-graining methodology to model particle flow in silos (J. Powder Tech). Working with **Sun** and **Ness**, they analysed suspension rheology in paste extrusion applications. **Sen Gupta**'s work on arsenic and fluoride removal has resulted in water treatment plants benefiting more than 1,000 villagers near Kolkata, (J. Env. Man.).

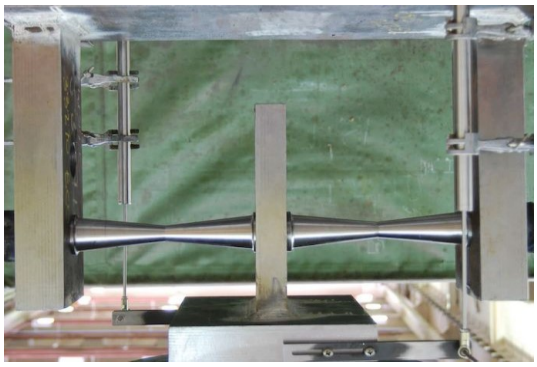

Figure 1.4.7 – Hourglass damper on cyclic test

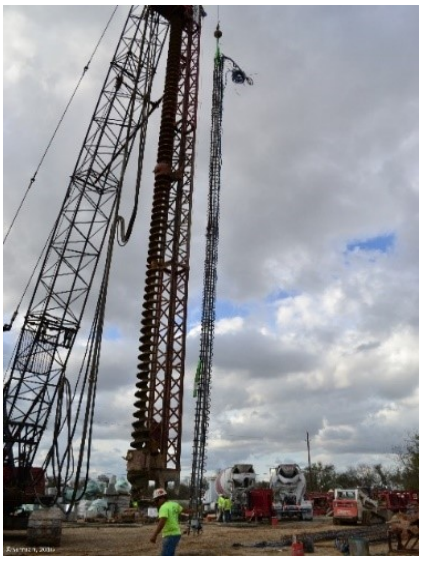

Figure 1.4.8 – Energy pile being installed

1.5. Impact strategy

Our strategy to increase the impact of ERPE's research has been to *develop a common culture, to define and exploit agreed opportunities and to invest to deliver impact as we planned our research effort, managed our assets and exploited the resulting outcomes through industrial, governmental and societal partnerships at local, national and global scales.*

ERPE's Co-Directors of Impact **Smith** and **Hand**, have shared responsibility to maximise the impact of ERPE's research. Reporting to the Heads of School, they co-chair the ERPE Impact Committee whose remit is to support staff and maximise impact.

Common impact culture

ERPE's culture of impact is reinforced amongst our staff as follows:

- In the annual Career Development Review process of academic staff, impact is a key metric of performance;
- We operate clear and specific mentoring schemes to ensure that senior academics connect with junior colleagues to include them in their industry networks. This allows us to engage with stakeholders and users from the earliest opportunity and: develop shared aspirations and ambitions; agree common aims and objectives; jointly deliver the research and collectively exploit the outcomes to deliver the impact sought;
- Training is provided by our commercialisation arms EI and GRID, collaborating with funding bodies and online resources. It includes seminars and dedicated courses, best-practice advice in writing Impact Plans and sharing experience to learn by example from others;
- We cultivate and nurture activity in areas of potential high impact through staff recruitment and development such as the recent investments in biomedical engineering and multi-scale thermofluids. During recruitment, our selection criteria for new academic staff now require 'demonstrated impact' (in the case of senior appointments) or 'impact potential' (in ECRs);
- We publicly celebrate impact using the services of our communications staff, bringing exceptional achievements to the attention of the public and media through our website/social media channels and press releases.

Strategically define, protect and exploit opportunities

ERPE staff use industry-standard planning tools and methodologies, such as the Theory of Change Model, to **identify potential beneficial impact, define the pathways to delivery and exploit the benefits**. ERPE theme leaders help to define impact strategy by horizon-scanning for opportunities (assessing ambition, ultimate goals, and likely impact). The extensive reach of our staff gives us strategically useful oversight of needs, markets, and technology trajectories that we build into our impact planning. This also includes the identification and mitigation of threats, liabilities, and shocks to the delivery plan, and the implementation of monitoring tools to follow progress and adapt/re-align research activities to keep meeting stated targets and achieve impact.

ERPE staff are supported in commercialisation and impact activities by colleagues in EI and GRID, who provide excellent support including:

- Gathering and focussing the distribution of calls for proposals;
- Assistance with proposal writing and submission;
- Partnership brokering;
- Establishment of terms of reference and contractual frameworks;
- Advice on IP rights;

- Assistance with the founding of spin-out companies, including sourcing seedcorn funding;
- Licensing arrangements and filing patents; and
- Outreach and soliciting partnerships on Academic Industry Meeting (AIM) days.

Since 2014, EI and GRID staff have worked with ERPE colleagues to file patents, resulting in 135 being granted based on 42 new technologies which have been invented in ERPE.

ERPE has a long successful history in creating spin-outs, totalling 11 since 2014 including Particle Analytics Ltd, Kenoteq Ltd, Mocean Energy Ltd, MicroSense Technologies Ltd, IntelliPalp DX Ltd, ReOptimise Systems, Photon Force Ltd, Natantis, OGI Bio and Power Enable Solutions Ltd employing over 30 staff and going on to raise over £8.6M in equity and government high-growth investment. As an example, **Desmulliez** and **Flynn** created microwave sensing technology and spun-out Microsense Technologies (established in 2017) which won first prize in the Converge Challenge in 2016, that aimed to incubate new companies. Microsense develops inline monitoring technology now being exploited in 7 global regions to improve productivity, resilience and sustainability in the food, beverage and transport sectors. **Gousettis'** research in Satellite Communication and antenna systems led to a five-month residency of Celestia UK in our GRID facility, resulting in the company establishing themselves in HWU Research Park, creating 18 jobs.

Investment in impact

We have **invested nearly £30M in new infrastructure and commercialisation initiatives within EI and GRID to exploit ERPE research outcomes** by enabling and expanding knowledge transfer, licensed technology transfer, and the formation of companies. Since 2016 EI has increased in size from 65 to 95 staff, among which the EI account team for ERPE consists of 15 staff, including Business Development (8), Consultancy (1), Technology Transfer (1), Company Formations (2) and an Innovate UK/ISCF Bid team (3). Within the investment in GRID, there were 8 new appointments of Business Development Executives to drive additional ERPE impact. ERPE staff can access an established EU/International Support Team to increase their success rates in EU and international proposal submissions. An International Development Research Hub provides multi-dimensional advice and support in the preparation of ODA/GCRF proposals.

As an example of an investment to drive impact from new technology, UoE invested directly £1.7M in the establishment, with **Haas** and colleagues, of the LiFi Research and Development Centre (LRDC). While pureLiFi was spun out in 2011, it has secured £21M of investment since 2014 and is submitted as an ERPE impact case study.

At an individual level, the Principal's Innovation Awards and Principal's Research Impact and Engagement Awards pump-prime new research that will attract consequent external funding and generate impact, as well as recognising outstanding achievement, innovation and creativity in impact and public engagement with research. **Stokes** was a winner and is exploring new functional materials for robotic inspection in severe or hazardous environments. **Hands** also won funding to help develop liquid crystal tuneable micro-lasers. ERPE is a founder member of CONVERGE, which is Scotland's leading company creation programme for staff, students and recent graduates of all Scottish Universities and Research Institutes. Since 2011, the programme has delivered substantial human and economic impact, including training over 400 young entrepreneurs and securing and distributing over £120M of funding. With this support, **Medero** spun out Kenoteq and received £1.7M from the Construction Scotland Innovation Centre to produce the new 'K-brick' that uses recycled construction and demolition waste, with a 90% reduction in energy/CO_2 emissions in its manufacture compared to clay bricks.

Through thematic leadership, we expect and strongly **encourage our researchers to develop strategic local, national and global partnerships within academia, industry, government and society**. ERPE staff members, including **Jeffrey**, **Flynn**, **Hand** and **Lane** serve on pivotal government, research council, national and EU standards and industry foresight bodies, enabling ERPE to plan and invest in high impact research activities that tackle global challenges before or when they arise, as highlighted in section 4.

The responses to global RCAs are by their nature complex and interdisciplinary. To achieve solutions that have real-world impact on challenging problems, ERPE promotes research activity that is institutionally and internationally collaborative in nature, partnering with industry, government, NGOs, and academic institutions. We pump-prime partnership activity through dedicated support of nascent projects, such as providing internal travel grants and seed-corn funding to researchers starting projects involving multiple partners in DAC-listed countries, defined by the OECD Development Assistance Committee. Over 25 staff have received over £1M of internal seed-corn funding to establish GCRF partnerships world-wide to address the challenges of the UN Sustainable Development Goals, including developing local technologies and skills in areas ranging from **Sen-Gupta** developing and installing sustainable water treatment technology in Bangladesh, to **Huang** working with Conservation International and local building trades to improve the cyclone resilience of traditional buildings in Madagascar.

1.6. Creating an open and responsible research environment in ERPE

ERPE has adopted the League of European Research Universities (LERU) Roadmap for Open Science and aims to ensure that our data is FAIR (Findable, Accessible, Inter-operable, Re-useable). ERPE abides by both the original and updated UUK Concordat to Support Research Integrity, with UoE additionally a signatory to the San Francisco Declaration on Research Assessment (DORA). Ensuring adoption of these standards within ERPE is the remit of the Executive Management Committee jointly chaired by the Heads of Schools. It meets quarterly to review ERPE activities and ensure maximum interaction and impact with industry, academia, and wider society from an open, transparent, ethical, collaborative environment that provides state-of-the-art facilities and support for our academic and research staff. Specifically, we:

- Define, for every staff member during their induction, our expectations of **adherence to the principles of responsible research and innovation** and the need to understand the individual, community and societal drivers for their research;
- **Operate within the jurisdiction of the Schools' Ethics and Integrity Committees** reporting ultimately to the Vice Principals. Any lapse in the highest of academic standards must be reported to our Research Ethics & Integrity Officers (**Krueger** and **Shephard)** who, after initial investigation and determination that there is a case to consider, may escalate it. Academic and research staff may then become subject to their University's Procedures for Investigating Research Misconduct, defined in the University's Disciplinary Code;
- Expect, and where necessary train, our staff to **anticipate and understand the wider ethical and societal impacts** of their work through **discussion with industry, policy and societal stakeholders**. This is a compulsory aspect of our pre-submission internal grant review procedures and expected to be revisited through the life of an award. The IMPACT programme sought patient views on implementation to guide technology development;
- **Implement the principles of the** UK Forum for Responsible Research Metrics, including robustness, humility, transparency, diversity and reflexivity;

- **Provide free, open online external access to our publications** via Edinburgh Research Explorer and the Research Portal to ensure that our research results are transparent and have wide reach. ERPE supports its staff to make their research outputs Open Access. Green Open Access is our preferred route to ensure wider participation without access to publication funds. We have, however, invested in comprehensive support for open access and implementing Plan S from 2021, to ensure that output arising from publicly-funded research is published in compliant Open Access journals;
- **Provide free and open online access to as much as possible of our raw data and experimental results** (via PURE, Edinburgh Datashare and UKERC Energy Data Centre), particularly where they are obtained or used in extreme/hazardous environments;
- **Nurture academic freedom and encourage an open approach to conducting research.** Our staff lead many multi-partner national and EU consortium projects with around 15% of our published outputs being collaborative across ERPE;
- **Ensure transparent dialogue and outreach** with industry, government, NGOs and the wider publics through: annual assemblies; research colloquia; AIM days; doors-open days; public lectures and schools engagement, all of which are evaluated to refine future plans.

1.7. Future vision and plans

ERPE's vision for the future is to deliver research, innovation and training whose impact and reach will continue to drive the global transition towards net-zero carbon with economic, environmental and social benefit in a world that we have demonstrably helped to make safer and healthier. We will expand collaboration across thematic, institutional and international boundaries to remain world-leading as we address global research challenges.

We will invest time and money to increase the proposal intensity, success rate and collaborative reach of all staff, particularly ECRs and colleagues new to the UK funding arena, who were recruited as part of our structured expansion and planned ventures into newer areas of activity. We will invest in the construction and occupation of the remainder of the Engineering Quarter at King's Buildings to bring our increased staff and research students in the Organisational Themes physically closer together in greater, more conducive space and to enable us to grow further doctoral training programmes. Specific plans and objectives *for each of our global RCAs* follow.

RCA1 – Engineering the transition to a lower carbon future

We will build further capacity and collaborations to: invent and apply robotic and AI systems for prognostic monitoring of offshore energy assets; synthesise and demonstrate intelligent materials to animate working surfaces; develop technologies that exploit extremely high and low temperatures for energy conversion and storage in generation and transport; and discover and develop disruptive technologies and policies for real-time data acquisition and energy system management. Specifically, we will:

- Contribute to the UK government's 'net zero' ambitions through our leadership of the Industrial Decarbonisation Research and Innovation Centre;
- Build on the EPSRC £1M platform grant and exploit the unique capabilities of the new laboratory facilities for Clean Combustion and Agile Tomography and establish an international Research Centre in Sprays & Spray Technologies to drive CO_2 reductions;
- Work with our societal, industry and academic partners in Sub-Saharan Africa, South Asia and Latin America during the UK Presidency of COP26 to co-create projects that access the £1B UK Government commitment to the Ayrton Fund to address the UN Sustainable Development Goals (SDG7-10) and propel their clean energy transition; and

- Continue the transition in GeoEnergy Engineering from industry funded research focused on hydrocarbon production, to expand activity in geological storage of CO_2 and energy storage.

RCA2 - Developing materials, processes and manufacturing for healthier living

We will expand our capacity in translational bio-photonics and bio-medical device technologies, deepen our through-process bio-manufacturing expertise to create a fifth ERPE theme in bio-medical engineering. Specifically, we will:

- Leverage on the award of one of six national centres for synthetic biology to Edinburgh (£13.2M), build on the EPSRC platform grant 4MD, the investments in the MDMC and the most recently secured £7.6M EPSRC Transformative Healthcare Technologies for 2050 award, to develop and translate technologies with impact over the next 30 years; and
- Work with Babcock International, University of Strathclyde, Fife Council and Fife College to establish a world-class advanced manufacturing park in Rosyth, incorporating: large-scale machining and composites manufacturing facilities; FASTBLADE; a digital skills academy and an innovation centre for SMEs in advanced robotics for hazardous materials handling in nuclear and offshore asset decommissioning.

RCA3 - Creating a smarter, safer world by innovation in data, comms, robotics & AI

We will develop the next generation of intelligent sensing and autonomous systems, embracing opportunities emerging from advanced sensing (Quantum techniques, new materials and algorithm developments), data-driven innovation, and the growing use of robotics, autonomy and machine learning. Specifically, we will:

- Build on ERPE's existing investment in the National Robotarium to establish the UK's leading innovation hub for robotics and autonomous systems;
- Support regional industry in wireless and satellite technologies, strengthening ongoing partnerships with Xilinx, Commscope, Leonardo, Honeywell, Celestia, Sofant and Alba Orbital;
- Collaborate with clinicians to develop new AI methods embodying machine learning and image analysis to aid the understanding and diagnosis of disease;
- Develop new design and fabrication technologies for micro- and nano-scale devices in new materials, enable their integration into systems and use our first-in-the-UK thermal scanning probe nanolithography technology for fast prototyping of nanoscale structures/devices; and
- Explore more efficient use of data to bridge between traditional signal processing and modern machine learning in the context of risk resilience and verifiability.

RCA4 - Engineering a safer and healthier infrastructure and environment

We will capitalise on the Edinburgh and Southeast Scotland Regional City Deal to expand our research activities in Future Infrastructure and Data Driven Innovation in Infrastructure and Environment. Specifically, we will:

- Build on the £156M University and UK government investment in the Edinburgh Futures Institute, our membership of the UK Collaboratorium for Research into Infrastructure and Cities (UKCRIC), our links to the Alan Turing Institute, the National Robotarium and the Bayes Centre to access the UKRI Strength in Places Initiative and establish an interdisciplinary Edinburgh Water Centre with the two universities' schools of biology, business, chemistry, geosciences, law, mathematics, medicine, policy studies, and sociology; and
- Build on existing, and form new, international partnerships in Africa, North America and China aligned to the UN Sustainable Development Goals (SDG7-10).

2. People

Both Universities, and ERPE, subscribe to the three clear principles of the Concordat to Support the Career Development of Researchers. We strive to ensure and increase the attractiveness and sustainability of the careers of our academic and research staff and enable them to deliver in quantity, the highest quality and most impactful research for the benefit of global society and the UK economy.

2.1. Staffing strategy

We recognise that ERPE's most essential and valuable asset is our staff. Our **vision** is *to be a place of first choice in the minds of academic and research staff and doctoral students around the world*. Our strategy is to *attract and recruit the best people and then to develop and enable them to achieve their best* on a world-platform in an environment that *ensures equality, diversity and inclusion*.

Our staffing strategy is grounded in ensuring research and teaching excellence, shaped by thematic and discipline needs, and informed by wider necessities such as critical mass and Equality, Diversity and Inclusion (EDI). We select academic and research staff according to their ability to contribute to research and teaching, their strategic fit to the aims of ERPE themes and RCAs, and their opportunities for career development in the ERPE environment. To realise our vision (*p.1*) we aspire to ensure that all academic staff, from the most senior Professor to the newest tenure-tracked Fellow, pool their talents within a rich environment that promotes collaboration, cooperation and collegiate activity. To maintain our research excellence, we foster and nurture a diverse community of academic practitioners, senior postdoctoral researchers and doctoral students, drawn from many different academic backgrounds, supported by IT, business development, administrative, and technical support-staff. Our succession and contingency planning includes having deputy appointments for all key strategic positions across ERPE.

Growth in staff numbers

In 2014 we returned 210 staff. ERPE is now able to return 288 academic staff distributed as shown by Organisational Theme and current grade (Figure 2.1).

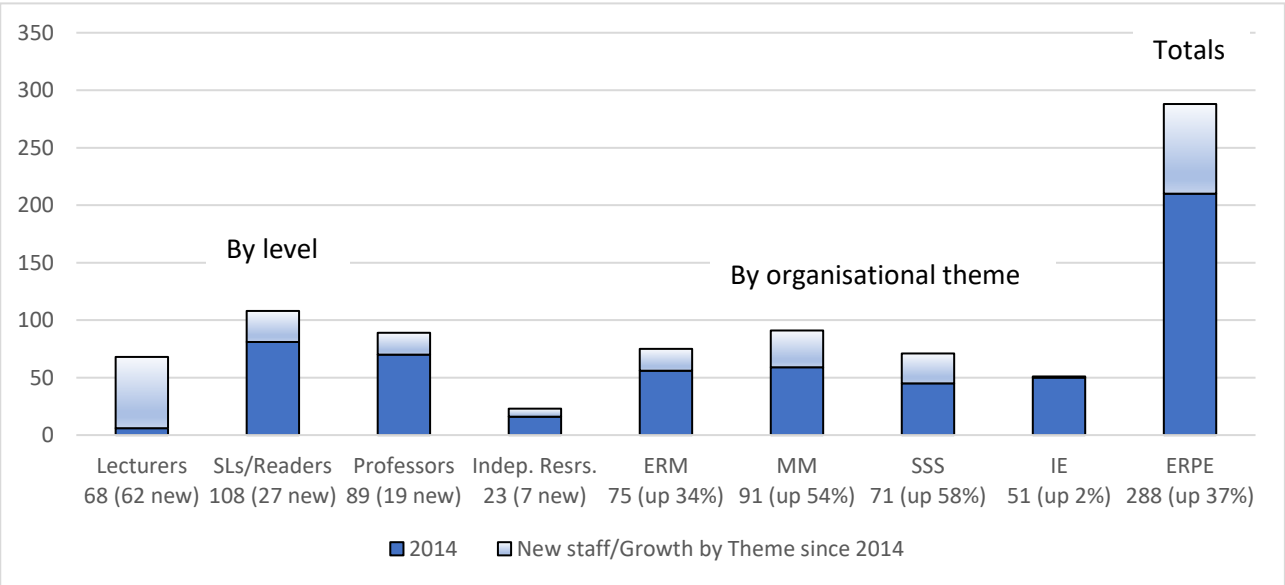

Figure 2.1 - ERPE Staff distribution and growth since 2014 by level and organisational theme

ERPE has recruited strategically to 115 academic posts to expand our academic staff complement by 78 and replace 37 departures. Indications of ERPE strategy driving vitality within the environment include that:

- Over 90% of our 68 lecturers are new appointments, replacing those who have been promoted within ERPE or who have made an onward career move to a new institution;
- Two organisational themes have grown by more than 50%;
- Our academic staff capacity has increased by 37%;
- Professional (admin/finance/facilities) and Engineering (IT/marketing & PR/tech services) support staff numbers have grown by 36% to 83, and by 15% to 113 respectively;
- To address areas of high opportunity in key areas, we have developed many of our ECRs into leadership roles.

Specifically, in RCA2, the 2015 cluster-hiring of Profs **Linne** (ex-Chalmers) and **Reese** (Regius Professor of Engineering and RAEng Chair in Emerging Technologies, now deceased), **Peterson** (ex-Sandia National Lab) and **Borg** and **Krueger** (appointed as Chancellor's Fellows now Readers) founded our highly successful Institute for Multi-scale Thermofluids with research income to date of £10M. The success of this nucleus has been used as a model for investment, in 2020, for beyond the REF2021 period, through appointments of two new Profs (**McHale**, **Zhang**), two Senior Lecturers (**Ledesma**, **Wells**) and three Lecturers (**Attili**, **Wang, Haeri**) in this area. **Ó Brádaigh** was appointed to build a Polymer Composites Group, in which we have invested in six new appointments from senior lecturer to Chancellors Fellow (**Roy**, **M^{c}Carthy**, **Alam**, **Yang**, **Martinez-Hergueta**, **Robert**).

While pursuing new opportunities in ERPE we also ensure that we support existing areas of excellence, such as our renewable energy activity. To strengthen the Electrical Power Engineering activity, **Finney** was appointed as Chair in Power Electronics, augmented recently by the appointment of **Judge** and **Morstyn** as Lecturers. To provide strategic leadership in energy storage we appointed Prof **Rampen**, who originally was a member of research staff who pioneered digitally-controlled hydraulic transmission systems and founded the company Artemis Intelligent Power before returning to ERPE. He was a key member of the Artemis team that won the 2015 RAEng MacRobert Award. Prof **Krumdieck** (formerly University of Canterbury in New Zealand) brings leadership in transition engineering and Prof **Busch** left Shell to join ERPE and provide leadership in low-carbon energy systems.

To strengthen our signal processing and communications activity we appointed as Lecturers **Altmann**, **Ding, Halimi, Mota, Repetti**, **Ben Smida**, **Song** and **Lei Wang**. This has underpinned our contribution to computational research in the £20M Quantum Imaging Hub and the £12M UDRC, as well as leading Celestia to locate their UK facility on Heriot Watt Research Park.

To support and increase the return on our investment in major new facilities, we have made four appointments to the new post of Senior Experimental Officer: **Davey** (FloWave); **Steynor** (FASTBLADE); **Johansen** (Clean Combustion Lab) and **Lloyd** (Carbon Capture and Separation) to drive and exploit the facilities' inventory, research and industrial/academic engagement.

We offer attractive lab start-up packages (typically CF/BRL/L £15k+a funded PhD; SL/R £30k+a funded PhD; and Prof £50-100k+2 funded PhDs). New academic staff joining an area strategically targeted for investment and growth are often attracted to and join a new or expanding research environment.

We aim to achieve a balance between senior staff (with research eminence, and strong leadership) and early career staff (with obvious future potential): 62 appointments have been at

Grade 8 with the specific aim of attracting the best talent worldwide in the emerging areas relevant to our thematic needs.

Our Chancellor's Fellowship and Bicentennial Research Leaders schemes provide a route for outstanding postdoctoral researchers to become full-time academics benefiting the health of the discipline and their personal career development. **Carter**, **Friedrich**, **Medina-Lopez**, **McCracken**, **Repetti**, **Robinson**, **Sanna**, **Sellar**, **Shek**, **Thomson** (**Camilla**), **Yaghoobi-Vaighan**, **Vallejo**, **Bandiera** and **Robert** were all PDRAs in ERPE who (via a competitive process) were appointed Chancellor's Fellows in ERPE as part of their already burgeoning career development. They are joined by external appointments, including **Van den Bremer**, **Van der Weijde**, **Menolascina**, **Song**, **van der Speck**, **Giorgio-Serchi**, **Mota**, **Garcia**, **Lau**, **Reynolds**, **Chitnis** and **Wang**. To help our rising stars establish themselves as independent researchers, we plan a controlled increase in their teaching and administrative workload, over the first five years of appointment, from an initially lower than average level. That ERPE is a highly attractive environment is reflected in our recruitment of young global talent, for example bioengineering's **Menolascina** (ex-MIT) who joined as a Chancellor's Fellow in 2016, has since won an EPSRC Future Leader Fellowship and founded OGI Bio, winning a 2020 Scottish Edge Award for his mini-bioreactor technology.

2.2. Staff development and support

Staff Selection

Our academic recruitment process ensures that appointees have clear communication skills and have (or exhibit potential to gain) strong leadership skills. In addition to the normal interview processes this includes delivery of short research seminars and teaching lectures and some social interaction, after which staff and student views are sought in confidence. Candidates for Chair positions are also assessed in a separate line management/leadership evaluation.

Staff Development and Progression

Both ERPE Universities use rigorous processes to support and develop all staff throughout their careers. Academic and support staff benefit from an annual Career Development Review to explore their ongoing aspirations within the context of ERPE's research needs and their School's teaching activities. Clear research and teaching statements identify necessary levels of excellence for progression of staff who make significant contributions in either domain, and/or who are delivering evidenced impact. All categories of staff activity are key to our strategy and their development is planned, balanced and refined to be competitive within the University promotions processes. We offer guidance in preparing for promotions, exercised through line managers and mentors, as well as dedicated central staff. We are fully committed to academic and research staff development in research and innovation through a portfolio of "personalised" CPD activities delivered by the Institute for Academic Development and the Research Futures Academy including: Grant-writing Workshops; Compulsory Supervisor Training; How to manage your Research Teams; Strategic Leadership Programme; Research Ethics and Integrity; Enterprise and Innovation and Effective Collaborations.

Progression recognises sustained contribution to ERPE success and teaching excellence; **Chalmers** joined ERPE as a Lecturer in 2010, her developing research independence saw promotion to SL in 2015 and then to Reader in 2020, having graduated 5 PhDs and generated £1.8M of income as a PI. As E&D Coordinator her leadership has contributed significantly to EPRE's two Bronze Awards in Athena SWAN assessments. **Kersaudy-Kerhoas** graduated from HWU with a PhD and, after joining ERPE, went on to win a five-year RAEng Fellowship. In 2017 she won the £1.3M EPSRC Healthcare Technology Challenge Award and founded Natantis whose

microfluidic biosample preparation technology was supported by a Scottish Enterprise HGSP award. In 2019 she was promoted to Professor and in collaboration with the UoE Medical School, has established the MKK Lab in Clinical Microfluidics. We aim to retain staff through career development and progression. Over 25% of our Readers, Senior Lecturers and Professors joined as research staff and were promoted to and through lectureships.

Support and Training

ERPE recognises the importance of developing momentum as soon as possible in a new Lecturer's appointment. We are also acutely aware of the pressure that this places on colleagues and we provide extensive support and training for academics at all career stages, via a parallel research mentoring scheme for new academics that complements the line management structure.

Our PDRA champion (originally **Krueger** now **Medina-Lopez**) has created an early-career 'community', through PDRA-driven activities. A 'buddy scheme' first trialled in ERM is being rolled out across ERPE. The PG Research Committees in ERPE also bring the PDRA and PhD communities together, with emphasis on professional training and gaining chartered status. PDRAs also have access to several local initiatives, such as Café Synthetique.

We organise an annual symposium for early career researchers to raise awareness of career development opportunities, encourage networking, and inform strategies for career advancement within academia and beyond. The 2018 symposium covered a wide range of topics including role-balancing, time-management and mental wellbeing. Our Strategic Leadership in Research Programme uses experienced investigators and research leaders to provide participants with a clear trajectory toward running a major grant, centre or network. Section 3.5 describes the support systems that help ECRs to propagate, nurture and develop effective industry collaboration.

Across ERPE there are many examples of 'on-job' training and collegiate support. For instance, all research proposals from any staff member at any level of seniority are rigorously peer-reviewed by colleagues in the research domain and recorded within our Worktribe systems, in addition to being further independently checked for compliance with institutional and funder's expectations. For new lecturers and ECRs this is a key component of their development in the reviewing and writing of winning proposals. Our strategy to support recently appointed staff has assisted many to win prestigious fellowships and awards, including: **Peterson**, **Krueger** (ERC); **Bandiera**, **Menolascina**, **Hanley**, **Robert**, **Gyongy** (EPSRC); **Ness**, **Lucquiaud**, **Papanicolopulos**, **Tsaftaris, Altmann, Halimi, van den Bremer** (RAEng); **Angeloudis** (NERC); **Reynolds**, **Van der Weijde** (Turing); **Anagnostou**, **Podilchak**, **Georgiadis** (H2020 MSCA); **Crichton**, **Ding**, **Mota**, **Marques-Hueso**, **Shek**, **Suphi-Edren**, **Law**, **Jia**, **Sun**, **Semiao** (New Investigator Awards).

Specific examples of rapidly developing track records among newly appointed ECRs includes:

- **Medina-Lopez** joined us on a Talentia Fellowship to complete a joint PhD with ERPE and the University of Granada, before becoming a PDRA working in ERM. She became a work-package leader in DTOcean, a multi-national EU project before being appointed as a Chancellor's Fellow in Data Driven Innovation. She made important contributions to securing two CDTs, IDCORE and SENSE: the Centre for Satellite Data in Environmental Science. She is now a member of the management teams of both CDTs.
- **Thomson** (Camilla) completed her PhD in Edinburgh after working in industry as a Consulting Engineer and was then appointed as a PDRA in ERM. After that she was appointed as a ClimateXChange Fellow, supporting the Scottish Government's carbon reduction planning, before being appointed as a Chancellor's Fellow in Energy (Policy, Economics and Innovation). She is now working to support the ISCF PFER programme's EnergyREV project.

- **Thomson** (Robert) was awarded his PhD by HWU in 2006, quickly advancing to Professor within the Institute of Photonics and Quantum Sciences (IPaQS) where he leads a research group exploiting photonics to develop new types of instrumentation, for applications ranging from astronomy to medicine. He leads the recently awarded £6.1M U-Care project.

Sabbaticals and study leave

ERPE has a positive and pro-active study-leave and sabbatical policy that encourages academic staff to apply for and gain relief from local teaching and administrative responsibilities to spend between 3 and 12 months advancing their research, teaching, and impact activities at another globally leading institution, or by secondment to industry/government. We aspire to have 1-in-7 of our academics on sabbatical or secondment at any one time. Academic staff can apply for one semester of sabbatical leave following every 4 years of service, or for two semesters following 6 years of service. Sabbatical leave is granted based on the likely step-change or impact that beckons. Examples of successful sabbatical leave include:

- **Davies** (Prof) spent his sabbatical at Rice University in USA, EPFL in Switzerland and INRIA Rennes in France that led to three collaborative publications, one in the Society for Industrial and Applied Mathematics Journal of Imaging Science and two in IEEE Transactions on Information Theory. His sabbatical and collaborations formed also led to two awards to ERPE in Compressed Quantitative MRI, one joint with **Wiaux** and the other with the UoE Centre for Clinical Brain Sciences (EPSRC, £0.9M), and ultimately to the ERC Advanced Grant "C-SENSE: Exploiting low dimensional signal models in sensing, computation and signal processing" (EU, € 2.2M).
- **Hopgood** (Senior Lecturer) developed a collaboration with Agilent Technologies, whose exchange of knowledge led to algorithms and an underlying concept that Agilent sought to patent. He secured an externally supported RAEng Industrial Secondment to spend a sabbatical working with Agilent applying signal processing techniques to electrophoresis analysis. The outcomes of this work formed the basis of an EPSRC award "Next-Generation Sensing for Human In-Vivo Pharmacology- Accelerating Drug Development in Inflammatory Diseases" (EPSRC, £1.5M), in collaboration with the UoE Centre for Inflammation Research and GlaxoSmithKline.
- **Altmann** (Lecturer) spent a sabbatical at the University of Michigan that resulted in three publications, one in the Journal of Nuclear Materials Management, one in IEEE Transactions in Nuclear Sciences and one in Scientific Reports. The visit strengthened the collaboration with the Consortium for Verification Technologies (US CVT) - a $25M US research program.

Continuing Professional Development

The ERPE Universities are committed to continuing professional development of our staff and their registration with professional bodies such as the IMechE, IET, ICivE and IChemE for the intrinsic benefits that this provides to ERPE and our staff. Our universities offer CPD programmes and training which link directly to proposal development for early career staff, IP courses to assist those focused on commercialisation of their research and career shaping towards professional, learned society and HEA Fellowship, Senior Fellowship and Principal Fellowship. We also offer mentoring and support to help staff gain membership (and fellowship) of engineering institutions.

ERPE provides Leadership and Management training, offering different courses tailored to career stage, often externally sub-contracted to specialist management development consultants. For new staff these include: Leadership Workshops; What Does Leadership in Research Look Like?; Time Management; Performance Management and Managing Team Conflict. For more senior academic staff and potential Heads of School, both Universities offer Senior Leadership

Programmes. Accessing such opportunities and other research and teaching career development is formally reviewed annually, at all levels of seniority, in the Career Development Review (with a 100% annual completion rate).

2.3. Equality, Diversity and Inclusion

Both ERPE Universities are committed to continual improvement of the working environment in ERPE to enhance its diverse community, united by agreed shared goals and efforts to ensure equality of opportunity. We have appointed Prof **Ingram** as a Director of Diversity & Inclusion (D&I) and ERPE enforces institutional Dignity and Respect Policies with a zero tolerance approach to bullying, harassment or discrimination.

We ensured full equality and diversity in the preparation of the REF2021 submission by:

- Creating and maintaining a gender, race and age/experience balance in the governance, delivery and internal review teams;
- Ensuring that all members of the REF Team had completed unconscious bias training;
- Sharing responsibilities and duties for leadership, review, accrual and delivery with due regard for diversity;
- Creating a supportive working environment for the team (in person and latterly at distance) that encourages freedom of expression, mutual respect and shared value/understanding of the critical importance of the preparations and the REF process itself;
- Embodying career development and training as a reason for inclusion in the REF Team.

We adhere to the principles of full equality and diversity in all aspects of our operation, including: access to support for submission of funding applications; obtaining internal pump-priming or seed-corn funding; opportunities for conference attendance, sabbaticals and training; aspiration and access to leadership roles; and research-related promotion and reward procedures.

Gender

We aspire to attain a well-balanced staff gender profile. In the last census 11% of our academic staff self-identified as female, this has now risen to 14%, just over the sectoral norm. Our policies to encourage further rebalancing are defined in our current Athena SWAN Action Plans and are affirmed by our two recent successful Bronze Awards. Our proactive approach to improving the gender balance includes:

- Each School having a dedicated E&D team, chaired by a Director of Diversity & Inclusion (reporting to the Head of School) with 15 members from academic and support staff;
- Our appointment and training of 14 Equality Impact Assessment (EqIA) Champions who have systematically conducted EqIAs on new and updated School policies;
- Our introduction of a sabbatical programme specifically intended to give grade 8/9 female academic staff opportunity to strengthen their CVs and cases for research-related promotion;
- ERPE mentors and supports all staff seeking promotion but, since 2013, over half of our current female academic staff complement have applied for promotion with 100% success rate;
- The Molly Fergusson Initiative that promotes engineering as a career for women and to support our female academics. It is named after an Edinburgh graduate and the first female Fellow of the ICE, and is led by **Thomson** (Camilla), a recent Chancellor's Fellow;
- A commitment to celebrating the achievements of our outstanding female academic staff. Two of ERPE's senior professors (**Maroto-Valer** and **Ocone**) recently featured in the Royal

Society of Edinburgh's "Women in Science" exhibition. **Thomson** (Camilla) and **Maroto-Valer** were recently included among the Top 50 Women in Engineering;

- All of our CDTs have dedicated E&D plans. For example, the IDCORE has piloted a scheme to encourage diversity in its student body, to stress long-term positive outcomes for its diverse community, and to highlight support for maternity leave. In the 2019 entry, 45% of IDCORE's applicants were female and we welcomed 5 women and 6 men (from a variety of ethnic and discipline backgrounds) onto the programme;
- We address the issue of potential isolation that frequently arises from low representation in small cohorts by supporting cross-cohort activities, cross-CDT events and links to the wider PhD student communities within the institutions. Isolation is reduced by running female-only events (e.g. hackathons) and support groups, such as Women in Robotics Edinburgh (WiRE).

Disability

UoE hosts and supports a network for staff with disabilities and/or that are carers that makes available resources on accessible technology, carer and disabled staff support, building accessibility, transport/parking and fire safety. Staff Disability/Information Officers provide one-to-one support and aid staff with accessibility problems. While there is no requirement for any staff member to disclose any protected characteristics (including disability), line managers are required to support them to enable them to research and contribute productively by ensuring that suitable adjustments are put in place, liaising with the Occupational Health Units, Disability Services, Counselling Services and Chaplaincy Centres.

ERPE is assisted in determining policies that support staff with protected characteristics (e.g. disabilities) to enable them to productively engage in research by its leadership of **Inclusion Matters** projects, (EPSRC, £6.9M):

- **Pender** leads DISC which focuses on enabling and developing careers for researchers who are disabled or have chronic health problems;
- **Robertson** leads eBase which aims to improve gender and BME inclusion across engineering and the physical sciences research;
- **Chalmers** co-leads VisNET that seeks to increase the participation of women academics in international and industrial collaborations.

Positive Working Practice

ERPE follows both Universities' procedures and policies for access to funds, promotion and reward, appointment to leadership roles and sabbaticals, all of which have been subject to Equality, Diversity and Inclusion Assessments. Promotion and appointment boards always include women members.

Both Universities provide support structures for parents before and after the arrival of a child. The required procedures for risk assessment at work during pregnancy are in place. We regularly promote and support parental leave and monitor uptake to ensure that we exceed sectoral average metrics. Maternity coaching schemes are offered before and after maternity leave with budgets to enable returning staff to restart research.

To ensure that staff and research students feel supported, whether returning to work following parental, personal or sick leave, or those managing long-term illness, or with caring responsibilities, we provide a renewed induction programme. This includes a refresh of the cultural induction and a 'Return to work' checklist to make their welcome and return systematic. We also

consider workloads and offer financial support to returning staff to enable them to attend conferences and relevant training courses.

Additionally, well before the Covid-19 Pandemic, all staff were encouraged to work flexibly, from home or off-campus, where appropriate to increase the effectiveness or impact of their work, as well as recognising additional external demands. Budgets were made available to ensure that home-working was properly and safely equipped.

Both ERPE Universities seek to appoint all academic staff to open-ended contracts; (in the case of Chancellors Fellows, beyond a probation period). Appointments are normally full-time, but may alternatively be part-time (in agreement with the staff concerned to enable them to balance family and professional life), and all new appointees are supported by mentors over their early career with us.

All leadership posts are advertised internally to all staff. In their annual Career Development Review (CDR), staff members discuss readiness for promotion with their line managers, as well as assessment of the workload allocated to, and taken on, by each member of staff. Part-time and flexible working arrangements are available to all staff members in accordance with institutional policy and in discussion with the relevant Line Manager; typically around 5% of colleagues routinely make use of such arrangements. We encourage strong but flexible commitment in working practice and expect staff to participate in training courses on leadership, media interaction, unconscious bias, stress management and work-life balance.

Sexual & Gender Identity

Both Universities offer specific resources and support for staff and students and have an active Staff Pride Network for LGBTQ+ staff and allies, which gained national recognition in the Stonewall Scotland Network of the Year 2018.

Ethnic, Religious and Cultural Diversity

ERPE is an outward-looking, diverse community, with nearly half of our academic staff, research staff and students originating from over 100 countries outside the UK, and from every continent. This diversity is a consequence of the global reach of ERPE's activities supported by Edinburgh Global, whose regional offices seek out research and teaching partnerships, and attract talented staff and students from every continent. This is enhanced by HWU's international teaching activities in Dubai, Malaysia, Brazil and China, where ERPE academic staff deliver local programmes, many for over 15 years. The remit of the Director of Diversity & Inclusion includes helping to ensure that the ERPE environment is supportive to all ethnicities. We have widened participation to increase the number of BAME staff (at all levels of seniority) as well as the number of BAME doctoral and undergraduate students. A recent analysis suggests that 27% of ERPE staff in grades 7 and above identify as of BAME origin and 20% of ERPE staff in promoted positions identified as BAME. Responding to the findings and recommendations of a University-wide committee, all staff are made aware of how to recognise, respond and counter forms of everyday racism. Across all ERPE campuses, we offer multiple religious prayer spaces, multi-cultural catering, and we promote a culturally sensitive approach to dress and conduct.

2.4. Research students

Growth and contribution to sustainability of research community and discipline

A key part of our strategy for growth and vitality is to attract, develop, nurture and integrate into our environment an expanding community of the very highest quality of doctoral researchers, working with us to address the global RCAs1-4. Since 2014 we have:

- Grown our postgraduate researcher PhD community, as shown in Table 2.4, by 73% to nearly 1100, largely through successes in establishing 13 new CDTs (*p.32*);
- Graduated 831 doctoral engineers (EngD, PhD) – 86% more than our REF2014 total;
- Secured additional industrial sponsorship and secondments for doctoral training and increased our global reach.

	RCA1	RCA2	RCA3	RCA4	Total
Graduations	305	245	151	130	831
Growth (+%)	154	123	18	49	86
Registrations	354	339	231	144	1068
Growth (+%)	49	137	80	32	73

Table 2.4 ERPE Doctoral Community and Graduations

We consider nurturing and graduating our community of over 1100 doctoral engineers to be one of our most significant contributions to the sustainability of the community and well-being of several engineering disciplines and manufacturing sectors.

Impact

Industrially sponsored, supported or engaged projects benefit reciprocally and mutually the industrial partner, the PhD student and enhance ERPE's impact. These projects align with our strategic vision and the needs of our existing and future Industrial Project Partners across many sectors including renewable energy, oil & gas, healthcare, assisted living, construction, defence, space, automotive, security, manufacturing & materials, nuclear, digital media and education.

Recruitment and training

All doctoral training opportunities are openly advertised and filled in the national and global marketplace with full EDI compliance, subject only to any requirements or restrictions of funders.

ERPE runs induction sessions for all new postgraduate research students, typically held over two half-days, twice annually, at the start of the first and second semesters. These are organised in collaboration with colleagues in Academic Development and externally contracted organisations.

All PhD students have a template training plan, with compulsory core courses in Writing and Presenting and optional training, for example concerned with needs, aspirations, subject areas and work-life balance issues.

We run an annual Thesis-writing Workshop offered to PhD students at all stages of their studies. The workshop is led by a senior academic and includes practical exercises aimed to bring students to an excellent understanding of both the research and training aspects of PhD study, and how to apportion their efforts accordingly.

Monitoring and staff training

Our monitoring and progress review processes are prescribed by our institutional requirements and practice, including: defined schedules for meetings; internal peer scrutiny and review at seminars; regular stage-gating of progress; independent review by discipline-related staff and defined expectations for publishing outcomes of the research.

To ensure that we provide the highest quality and most conducive PhD supervision we organise courses that are attended by new academics, and other academics whose previous supervisor training was more than 5 years earlier.

The personalised CDT Technical Learning Portfolio approach is designed to give students a flexible working pattern thus maximising retention of students with personal circumstances e.g. for carers or those with health-related issues.

Each year the individual and joint ERPE Graduate Schools hold postgraduate research conferences to showcase work being done by postgraduate students across the four themes. The conferences provide opportunities for 1st year students to find out about the wider research activities in ERPE, and for 2nd year students to make oral presentations and exhibit posters.

3. Income, infrastructure and facilities

ERPE's accrued research funding in the REF2021 period is double that reported in 2014, confirming the partnership's added-value and the success of our funding strategy. All themes have increased their awards by amounts ranging from 64-194%.

Since 2014, while our academic staff cohort has increased by 37%, UKRI/Government funding has increased by 125%, EU funding by 127% and industry/other funding by 47%.

Table 3 summarises by funding source the external research income awarded to ERPE directly or indirectly over this return period. Most of these awards are associated with large high-impact longer-term collaborative projects that we have been selected to lead, with large components sub-contracted to other UK and EU partners. Most of the remainder are collaborative projects where we have been selected by the lead organisations to make significant contributions as a sub-contractor. The others are direct awards to ERPE alone.

Funding Source	Themes' Awards (£)				Totals
	Energy & Resource Management	Manufacturing & Materials	Sensors, Signals & Systems	Infrastructure & Environment	
UKRI	23,519,850	30,394,351	37,683,905	7,869,966	99,468,071
UK Charities	978,467	2,749,649	1,159,647	3,850,746	8,738,509
UK Gov.	5,242,841	1,883,963	4,743,922	1,356,638	13,227,363
UK Ind.	15,745,487	1,733,417	3,586,659	1,010,126	22,075,688
Oseas Ind.	16,087	100,000	809,387	415,726	1,341,200
EU/other	14,241,582	8,830,848	12,080,142	3,373,049	38,525,620
Oseas/other	17,208,610	1,965,607	1,170,375	1,216,119	21,560,710
UK Other	237,000	78,000	156,000	35,000	506,000
Totals	**77,189,923**	**47,735,834**	**61,390,035**	**19,127,370**	**205,443,161**
2014	39,151,229	16,210,638	37,497,346	£9,063,776	101,922,989
Growth (%)	**97**	**194**	**64**	**111**	**102**

Table 3 – Research Awards by Organisational Theme and Funding Source

3.1. Research funding strategy and income

Our research funding strategy is that:

At the **ERPE partnership level**, we pursue major research and training grants (typically within multi-institutional consortia) that will address key global RCAs 1-4;

As **staff groupings** within UoE and HWU, we pursue joint funding that enables continuity and long-term development of established activity or supports the creation of new core activity;

As **individuals**, we act to win support for our research, but maximise opportunities for new recruits to develop major new research topics, resulting in their eventual leadership of awards; and

We pursue funding **for major new research facilities**, driven by and to support our rapid expansion, which we can share and use to drive industrial and academic collaboration.

To address contemporary challenges and deliver increased impact, we have invested in new capacity specifically in bio-medical engineering; multi-scale thermofluids; composite materials & digital manufacturing and fire safety engineering, and built funded relationships with major industry partners, including Babcock International Group and Leonardo. We have invested in engineering laboratory facilities embedded within a clinical research setting, including at the Queen's Medical Research Institute at the Royal Infirmary of Edinburgh teaching hospital.

In 2014, we were aware that our external research funding intensity (*income/FTE/annum*) was a little lower than we believed consistent with sustained international research excellence. We

therefore agreed an additional strategic objective to increase it substantially and committed to an explicit (rather than aspirational) annual running average target for the total of new awards per ERPE academic staff member, which would be reviewed annually. That target progressively increased from £200k to £230k/FTE/annum and was exceeded at fiscal year ends of 2016/17 and 2017/18. Focusing the target on awards (as opposed to consolidated research income) enabled near-real-time monitoring and timely strategic response, as well as ensuring transparency for staff.

There followed a period of rapid recruitment, particularly of new Lecturers and of academic staff from outside the UK, with some staff joining ERPE to replace retiring and onward-moving staff who held significant awards. This reduced our *income/FTE/annum* and we therefore invested time and money to recover the volume and increase the competitiveness of proposals of all staff, particularly those new to the UK funding arena and to increase their collaborative reach. We highlight below, in each of the above categories, key awards exceeding £1M in value and others that are strategically or otherwise significant.

ERPE income at partnership level by RCA

The added value of our partnership in ERPE is evidenced by the growth of our significant collaborative awards, with ERPE staff either leading/co-leading (CL) as shown in Tables 3.1.1–3.

RCA1 – ERM staff have won over £77M in low-carbon energy generation, storage, transmission and end-use research	**Funders**	**£M/ €M**	**ERPE leads / Co-leads (CL)**
UK Industrial Decarbonisation Research and Innovation Centre	UKRI/ Industry	25.0/ 10.0	Maroto-Valer
UK Centre for Marine Energy Research, established in 2004 by ERPE	EPSRC	5.3	Jeffrey
Supergen Offshore Renewable Energy Hub	EPSRC.	9.1	Jeffrey(CL)
Energy Revolution Research Consortium	EPS/NERC	8.2	Ingram(CL)
Centre for Advanced Materials for Renewable Energy Generation	EPSRC	2.1	Kiprakis
National Centre for Energy Systems Integration	EPSRC.	5.4	Harrison/Flynn(CL)
UK Carbon Capture and Storage Research Centre, established in 2010 by ERPE	EPSRC	24	Chalmers/ Lucquiaud
ORIGIN	EU FP7	€4.3	Owens
ReFLEX - decarbonising Orkney energy system	Innovate UK	28.0	Owens
International Centre for Carbonate Reservoirs	Industry	4.7	Geiger
Petronas Technology Centre	Industry	6.2	Sorbie/Mackay
ADNOC CO_2 injection and enhanced oil recovery	Industry	3.0	Sohrabbi
Shell - Exploration Geoscience/Energi Simulation - Carbonate Reservoir Simulation Chairs	Industry	2.2	Underhill/Geiger
BP/Total FAST and ESEM Imaging Centres	Industry	3.9	Geiger

Table 3.1.1 - RCA1 Collaborative Awards

RCA2 – MM and ERM staff have won high-value awards totalling nearly £48M	**Funders**	**£M/ €M**	**ERPE leads / Co-leads (CL)**
SynthSys-Mammalian Biology Research Centre	BBSRC	11.4	Elfick/Rosser (Joint chair in Eng)
SynbiCITE Innovation and Knowledge Centre (IKC) in Synthetic Biology	EPSRC	5.1	Elfick/Rosser(CL)
Multi-modal manufacturing of medical devices (4MD) Platform Grant	EPSRC.	1.3	Hand
Medical Device Manufacturing Centre – Advancing Manufacturing Challenge Fund	ERDF/ City Deal	3.2	Hand, Desmulliez, and Elfick(CL)
Centre for Innovative Manufacturing in Laser-based Production Processes – 40 companies	EPSRC	5.6	Hand
IMPACT Programme Grant - implantable microsystems for personalised anti-cancer therapy	EPSRC.	4.3	Murray/ McLaughlin(CL)
QuantiC - UK Quantum Technology Hub	EPSRC	21.0	McLaughlin(CL)
'Touch and Tell' and PROTEUS Healthcare Technologies IRC projects	EPSRC	13.0	Thomson (R)/ McLaughlin(CL)
U-Care: Deep ultraviolet light therapies - Transformative Healthcare Programme Grant (2021)	EPSRC	6.1	Thomson (R)
SonoPil, Programme Grant - minimally invasive capsule for gastrointestinal diagnosis and therapy	EPSRC	8.0	Desmulliez(CL)
Advanced Care Research Centre in later-life care	Industry	20.0	Underwood(CL)

Table 3.1.2 – RCA2 Collaborative Awards

RCA3 – SSS and MM staff have won major research programmes totalling over £61M	**Funders**	**£M/ €M**	**ERPE leads / Co-leads (CL)**
National Robotarium - Edinburgh & SE Scotland City Region Deal	Scottish Government	36.0	Lane,Petillot, Erden,Wang& Stokes(CL)
ORCA Hub - Robotic systems & AI for asset integrity management in offshore energy sector	EPSRC/ Industry	36.0	Lane, Petillot and Stokes(CL)
DANDIDRONE: A dandelion-inspired drone for swarm sensing	EU ERC Consolidator	€2.0	Viola
Connect-R - industrial-scale self-building modular robot for hazardous environments	Innovate UK	£6.0	Stokes
TOUCAN Programme Grant - Towards Ultimate Convergence of All Networks	EPSRC	5.8	McLaughlin
Cleansky2	EU H2020	€2.0	McCann
LITECS Programme Grant	EPSRC	5.8	McCann/Liu
UDRC Programme Grants "Signal Processing 4 the Networked Battlespace" and "Signal Processing in the Information Age	EPSRC/Dstl	7.9	Davis (M)/ McLaughlin and Mulgrew
SATCOM Research Centre	EPSRC/ESA	10.0	Gousettis
REVOLVE and TESLA Innovative Training Networks	EU/Airbus /Thales	€5.8	Gousettis
DORADA Marie-Curie project	EU	€1.5	Gousettis

Table 3.1.3 – RCA3 Collaborative Awards

The volume of awards made to groups of ERPE staff collaborating across themes has increased significantly since 2014. Tables 3.1.4 - 7 highlight, *by Organisational Theme*, some of the more significant, including 13 CDTs of total value approaching £80M.

Energy and Resource Management	**Funders**	**£M/ €M**	**ERPE leads / Co-leads (CL)**
Supergen Marine Grand Challenge - FlowTurb; TeraWatt & EcoWatt2050; EDRIVE	EPSRC	3.5	Venugopal/Side/ Mueller
INTEGRATE and RESTLESS projects on energy storage using hydrogen in low carbon networks	EPSRC	2.8	Freidrich/ van der Weijde
Wave Energy Scotland projects EMERGE and C-GEN Neptune	Scottish Government	5.0	Jeffrey/ Mueller
16 European Ocean Energy consortium projects	EU FP7/H2020	€70.0	Jeffrey, Mueller, Ingram, Forehand and Sellar(L)&(CL)
Morphing-Blades: New-Concept Turbine Blades for Unsteady Load Mitigation	EPSRC/ Industry	1.1	Viola/McCarthy(CL)
DETECT, GWatt and 3D printing low-carbon sub-surface energy technology projects	UKRI/EU	2.0	Busch/den Hartog/ Geiger

Table 3.1.4 - ERM Collaborative Awards

Manufacturing and Materials	**Funders**	**£M/ €M**	**ERPE leads / Co-leads (CL)**
FASTBLADE, MARINCOMP and POWDERBLADE composite materials wind/tidal turbine blade projects	EPSRC/EU	3.0	ÓBrádaigh/ McCarthy/Roy
CO_2 separation in industrial energy processes – six projects	EPSRC	4.9	Brandani/ Ferrari
ThermaSMART mart thermal management of high-power microprocessors using phase-change	EU	€1.7	Valluri
Characterising transient wall heat transfer using line-imaging	EU/ERC	€1.2	Peterson
Lattice-Boltzmann modelling of multiphase flows at nano- and micro-scales	EU/ERC	€1.5	Krueger

Table 3.1.5 - MM Collaborative Awards

Sensors, Signals and Systems	**Funders**	**£M**	**ERPE leads / Co-leads (CL)**
Sensor Signal Processing Platform Grant	EPSRC	1.0	McLaughlin
In-situ Chemical Measurement & Imaging Diagnostics for Energy Process Engineering Platform Grant	EPSRC	1.3	McCann
INITIATE distributed test-bed for future Internet research	EPSRC	1.7	Hass
Towards 100 Gigabit Wireless Networking by Light (Go-by-Light)'	EPSRC	1.1	Haas

Table 3.1.6 - SSS Collaborative Awards

Centres for Doctoral Training	Funders	£M	EngD /PhD	Industry Partners	ERPE leads / Co-leads (CL)
IDCORE Industrial Doctoral Centre for Offshore Renewable Energy (1)/(2)	EPSRC/ NERC/ Industry	12.7	100	30	Ingram
WAMSS Wind & Marine Energy Systems (1)/Structures (2)	EPSRC	10.3	115	35	ÓBrádaigh/ Mueller(CL)
Oil & Gas	NERC/HEI/ Ind.	13.6	128	16	Underhill
Geoscience and Low Carbon Energy Transition	NEOEnergy /HEI	6.9	48	8	Underhill
Embedded Intelligence	EPSRC	3.6	62	19	Flynn(CL)
Intelligent Sensing & Measurement	EPSRC	4.9	60	18	Underwood(CL)
Robotics&Autonomous Systems (1)/(2)	EPSRC	13.5	141	65	Lane/Hastie
Applied Photonics (1)/ Imaging, Sensing & Analysis (2)	EPSRC	9.6	61	32	Reid
Soft Matter & Functional Interfaces	EPSRC	4.8	80	18	Koutsos(CL)

Table 3.1.7 - ERPE CDT Awards

Individual level

Individual academic staff across ERPE have won many prestigious awards helping to deliver our research and impact strategies across RCAs1-4. Staff in the IE theme have secured over £19M of funding from UK and EU Research Councils for both fundamental and applied research. As part of their career development, ERPE has supported over 30 successful applications from young to mid-career academic staff for prestigious chairs sponsored by the RAEng and Royal Society as well as fellowships and advanced grants. Tables 3.1.8 – 11 highlight key awards by recipient:

RAEng Chairs	Funders	£M	ERPE recipient
Emerging Technologies – Multi-scale design, from molecules to machines	RAEng	1.3	Reese (Now deceased)
Emerging Technologies - Engineered cells for combined diagnostics and therapeutics	RAEng	1.3	Rosser (Joint Eng Chair)
Canon Medical Chair in Healthcare AI	RAEng	1.3	Tsaftaris
Arup Chair in design of new buildings against catastrophic fires.	RAEng	1.7	Bisby

Table 3.1.8 - ERPE RAEng Chairs

ERC Advanced Grants	Funders	€M	ERPE recipient
MILEPOST- Microscale Processes Governing Global Sustainability	EU	2.0	Maroto-Valer
C-SENSE **-** developing new sensing, computation, and machine learning algorithms, one of only 69 awarded to UK	EU	2.2	Davies (M)
TotalPhoton **–** developing camera technology operating 10-100 thousand times faster than those using existing nano-scale technology	EU	2.3	Henderson

Table 3.1.9 - ERPE ERC Advanced Grants

Fellowships	Funders	£M/k	ERPE recipient
Bayesian methods for efficient low-energy imaging and sensing	RAEng/Industry	0.6M	Altmann
Advanced Computational Methods For Smart and Extreme Imaging	RAEng/Industry	0.6M	Halimi
Molson Coors - Industrial Fellowship	RAEng/Industry	30k	Gerogiorgis
Agilent Technologies - Industrial Fellowship	RAEng/Industry	30k	Hopgood
C-Capture Ltd demonstrator CO_2 absorbers	RAEng/Industry	42k	Lucquiaud
New Paradigms for the Flow of Particulate Material	EPSRC	1.4M	Ocone
Sandia National Labs (US)/AstraZeneca UK Ltd	EPSRC	1.2M	Hanley
LWEC Fellowship on 'Water Resilient Cities'	EPSRC	1.1M	Beevers

Table 3.1.10 - ERPE Fellowships

GCRF and Environmental Sustainability Awards	Funders	£M	ERPE recipient
Improving Fire Resilience of Informal Settlements	EPSRC/ESRC	2.4	Rush
Centre for Sustainable Road Freight	EPSRC	4.4	Walker(CL)
Recycled bricks for sustainable construction	RAEng/Industry	1.7	Medero
Discrete-element modelling of elongated cylindrical particles applied to geo-hazards	RAEng/Industry	2.0	Papanicolopulos

Table 3.1.11 - ERPE GCRF and Environmental Sustainability Awards

3.2. Infrastructure and facilities supporting research & impact

ERPE has a mature infrastructure within which we deliver, research, training, engagement, and impact. To exploit and capitalise on opportunities for substantial growth in staff numbers and facilities, we have invested over £100M since 2014 in major infrastructure and laboratories.

Major Infrastructure

The **FloWave Ocean Energy Research Facility** (Figure 1.2.1) was launched in 2014, to emulate, at up to 1/20th scale, real sea conditions at candidate sites for wave, tidal, and offshore wind energy converters. The facility is fully equipped with LA-VISION underwater Particle Imaging Velocimetry (PIV) equipment, oceanographic equipment including acoustic Doppler current profilers (ADCPs) and QUALISYS motion capture cameras. There is a fully equipped and staffed workshop providing client support and rapid prototyping. ERPE is currently investing (with EPSRC and Babcock International Group) a total of £4.1M to build **FASTBLADE** at Rosyth Dockyard (Fife) (Figure 1.2.2) using regenerative hydraulic motors designed by Artemis Intelligent Power. These facilities are available for external research use, both nationally and internationally, as dedicated Small Research Facilities (SRFs). Other new co-investments include the £22M **Lyell Centre,** supporting subsurface energy systems research and, in partnership with Orkney Islands Council, an investment of £7.5M to create a new purpose-built innovation campus around our International Centre for Island Technology, aiming to grow research capacity in renewable energy systems in island locations.

Laboratories

We have invested over £2M in a new **Clean Combustion laboratory** to underpin the expansion of the new Institute for Multi-scale Thermofluids focusing on sprays, IC engines, and other chemically reacting flows. An additional £1.8M has been invested in an optically accessible, high

pressure and temperature spray research chamber and an optically accessible engine. Consequent to this, **Linne** and **Peterson** won £2.2M from ERC and the EPSRC Strategic Equipment program and established a Small Research Facility in Sprays which is the UK's most comprehensive laser diagnostics capability. We have also invested £0.75M in a new **Agile Tomography Laboratory** to expand research on in-situ chemical and particulate measurement and imaging diagnostics for energy process engineering and to pioneer in-situ chemical species tomography in aero-engine exhausts.

We have invested £0.75M in the **Composites Testing and Processing Laboratories** to upgrade processing and test equipment (presses, ovens and resin transfer machines), a unique platform for testing structural components from offshore renewable energy assets (Max Load 4MN), and a full-scale half-joining bridge which has delivered £0.33M of tests for Highways England.

We have established photonics laboratories at the **QMRI Healthcare Technology Accelerator Facility**, with a new building hosting a state-of-the-art laser facility with dedicated biological and tissue handling labs and are investing £3.2M funding (partly from the Advancing Manufacturing Challenge Fund) to establish a translational Medical Device Manufacturing Centre.

In 2016 we installed the UK's largest cryostat (donated by General Electric Co) into our **High Temperature Superconducting Laboratory**, providing a unique test facility for developing the next generation of electrical machines for energy and transport applications. ERM staff also developed Neptune, a 75 kW back-to-back ocean energy, linear generator rig to test flooded operation. A £3M investment, partly from EPSRC, allowed us to install a **Cryo-FIB SEM** (capable of high-resolution 3D imaging of soft matter systems) in a new Nanomaterials and Catalysis Laboratory.

Figure 3.2 – Basement fire simulation in Rushbrook Fire Lab

The **Rushbrook Fire Laboratory** (Figure 3.2.1) is ERPE's principal laboratory for fire experiments using state-of-the art fire testing hardware, including a Cone, Bomb and Furniture Calorimeters and Fire Propagation Apparatus. This facility has impacted design knowledge and construction practice of new and re-clad urban buildings.

3.3. Sharing of infrastructure and facilities

We highlight below five examples of shared infrastructure and facilities in ERPE.

- The UoE **Edinburgh Parallel Computing Centre** has hosted the UK's **UKRI National Supercomputing Facility** (ARCHER) since 2013 and, from 2020, has run the £82M **Service Provision and Computational Science and Engineering** services for the next national supercomputer (ARCHER2), making available to ERPE staff and the UK community one of the fastest fully general purpose (CPU only) systems in the world.
- ERPE was a partner in the establishment of the **Edinburgh Centre for Robotics** which includes the £36M **ROBOTARIUM** and **MOBOTARIUM** facilities. The ROBOTARIUM enables humans and robots to work together in physically separate indoor spaces, and accommodates field robotic systems (comprising humanoids and unmanned vehicles). The MOBOTARIUM comprises a human-driven sensorised and connected mobile vehicle equipped with LiDAR, RADAR, video, GPS and INS sensors for research on driver assistance and vehicle autonomy.

- The **Edinburgh Genome Foundry** (Figure 3.3.1) with **Menolascina** as Deputy Director, is a shared research facility located in the School of Biological Sciences that features robotic assembly of massive DNA fragments (for academic and industrial customers) in order to engineer cells; EGF is a founding member of the Global Biofoundries Alliance.
- Since 2014, **FloWave** has been shared to test about 60 industrial and academic technologies for wave, tidal and offshore wind energy conversion, earning £1.85M for re-investment in ERPE. It has also enabled pre-commercial development of wave energy conversion technologies including EDRIVE-MEC, PolyWEC, and WEPTOS.

Figure 3.3.1 - Genome foundry

- The **Centre for Science at Extreme Conditions** (CSEC) with **Kamenev** as Deputy Director is a shared initiative that brings together researchers from the UoE Schools of Biological Sciences, Chemistry, Engineering, GeoSciences, and Physics & Astronomy, with interests in materials and technology under extremes of pressure, magnetic fields, and temperature.
- The **Edinburgh Climate Change Institute**, (ECCI) was the world's first centre dedicated to technology and policy innovation to reduce carbon. In 2013 it was rated by BRE as the most sustainable retrofitted building in the UK. It is an inter-disciplinary environment within which we support start-up companies and drive carbon innovation.

Figure 3.3.2 – ECCI

3.4. Benefits in kind

We highlight below five examples of software licensing, data sharing, partnering in CDTs and examples of direct support for collaborative projects delivering shared impact at a greater scale.

- Simulation-based research in ERPE benefits from software licenses worth at least £100M per annum (at market value), donated by major industry vendors including Schlumberger, Computer Modelling Group Ltd., Weatherford, HIS Markit.
- Staff in ERM benefit by having access to datasets from producing geological reservoirs worth over £500M, at market value.
- In the IDCORE CDT, 45 Students have industrial placements with 22 companies for which the estimated total in-kind time and office cost contribution is around £0.9M. Our Phase 4 CDT in Applied Photonics, with 40 students engages with 35 companies (including Thales, Leonardo, Canon Medical and many more) contributing a total of £1.4M of direct funding. The WAMSS CDT with Strathclyde and Oxford has an in-kind contribution from industry of over £5.7M. These are three cases selected from thirteen CDTs.
- Since 2017 ORCA Hub has leveraged industrial in-kind contributions of £0.8M including: donation of wind turbine blades; use of software; sharing best practice and lessons learned reports; ROV data; use of facilities and asset drawings and models.
- Lucquiaud's EPSRC Impact Acceleration Award for pilot-scale demonstrations of a novel chemical analysis sensor received over £1M of in-kind contributions from Shell, Mitsubishi, Hitachi, and SaskPower. Experimental facilities worth £0.5M have been donated by Shell to Busch and den Hartog at the Lyell Centre to support carbon capture & storage research.

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

ERPE's staff deliver interdisciplinary and cross-cutting research, innovation and education that addresses our Research Challenge Areas with lasting positive impact on the research base, global environment and society in a time of climate and health emergencies affecting an increasing and ageing population.

In the sections that follow we describe how our environment has enabled collaborative research in ERPE and with other global universities, industries and policy and societal stakeholders. We conclude by summarising briefly, indicators of wider influence, contributions to and recognition by the research base.

4.1. Arrangements to support research and effective collaboration

Staff selection, development and training

At the recruitment stage we look to our new Lecturers for evidence of potential to engage externally and to more senior staff for demonstrated success in network building and collaboration. All new academic staff participate in our bi-annual ERPE "Grant Writing Workshop". A key element is "Positive Partnerships & Collaborations" which shares best practice in interactions with academic colleagues and industry at technical and managerial levels. Between 10 and 20 ERPE staff take part in the annual Heriot-Watt Crucible to help broaden their networks and interdisciplinary collaborations and deliver more impact. In colleague's annual Career Development Reviews with Line Managers there is a specific requirement to discuss networking strategies to agree research and engagement-based objectives for the coming year.

Staff of the Universities' commercialisation arms, EI and GRID, and Research Support Services, provide in-depth advice to ERPE researchers on the preparation, initiation, and execution of projects (many of which require considerable expertise in financial and legal management).

Funding initiatives

A Fellowships College has been developed for ECRs seeking to apply for an independent fellowship, providing evaluation, advice and training. Funding is available to pump-prime collaborative activities through the use of EPSRC and other Impact Acceleration Accounts, and discretionary funding is available to enable start-up and spin-out companies to utilise and benefit from ERPE laboratory facilities. To help stimulate collaborative projects between ERPE, industry and other institutions we run annual 'Impact Festivals' attended by researchers from ERPE, other universities and external stakeholders. These measures and interventions, combined with the enthusiasm of our ECRs and new fellows, has resulted in over 30 of them winning personal support from ERC, EPSRC, RAEng, NERC, Turing, H2020 MSCA or New Investigator Awards.

Collaborative Advisory Boards

ERPE has an Engineering Development Advisory Group (EDAC), composed of senior industrialists and alumni, that advises at Head of School level on overall strategy, development fundraising and industry engagement.

Each engineering teaching discipline within ERPE has its own Industry Liaison Board comprising industry and policy colleagues to offer insight and guidance to ERPE staff on key issues and challenges.

All major collaborative research projects have Industrial Advisory Groups, such as the GeoEnergy Engineering Strategic Advisory Board that supports our activities through advice on industrial needs and providing financial and in-kind support. This led to the award of the Queen's Anniversary Prize, recognising its sustained excellence in sub-surface research.

Each CDT has its own Industry Advisory Board comprising senior colleagues from sponsoring companies and ERPE staff who review annually our direction of travel and assist with the preparation of proposals, leading to the continuation of many CDTs into phase 2 (*Table 3.3.4*).

Specifically, in the Dstl UDRC collaboration we have a project management team (trained to PRINCE II) that provides full administrative and organisational support to the academics and researchers. The success of this strategy for UDRC is shown by that, between phase 1 (2009) and today's phase 3, we have licenced technologies to Leonardo, MBDA and Thales.

The above measures, building upon the diligence of our academic and research staff and doctoral students and increased collaboration with companies, have resulted in a significant increase in the volume and success rate in our proposal writing with consequent increases in awards across organisational themes ranging from 64 to 194%.

4.2. Collaboration beyond ERPE

To address the global RCAs1-4 at meaningful scale, our national and international collaboration beyond ERPE includes partnerships associated with specific projects and partnerships in research and doctoral training. Through our leadership or participation in 13 CDTs (*p.32*), ERPE academic and research staff and doctoral students engage in over 250 collaborations with UK, EU and global industrial partners benefitting by extensive access to data, facilities and staff. We show below five examples each of Global, European and National project-specific collaborations.

Global

- **Borg**, **Zhang**, **Gibelli** and **Pillai** lead a partnership grant with King Fahd University of Petroleum & Minerals (KFUPM) in Saudi Arabia that exploits our new modelling capability in collaboration with major oil/gas companies including Saudi Aramco.
- **Linne** leads a 4-year joint programme between UoE and Xi'an Jiaotong University funded by the K.C. Wong Foundation to exchange early career researchers. He and **Peterson** collaborate with Sandia National Laboratories on the application of hybrid femto/picosecond rotational coherent anti-Stokes Raman scattering for time-resolved, line-images of temperature.
- ERM academics led the EPSRC UK Centre for Marine Energy Research from 2004 to 2018 with collaboration across 15 UK and 8 global universities. **Jeffrey** and **Ingram** helped to establish mirror centres in Mexico (CEMIE-Oceano), Chile (MERIC), Canada (FORCE), USA (New England MREC), Ireland (MaREI), Taiwan and China. Strategically this consolidated UK academic capacity in every continent and established the UK as world-leaders in research, translation and deployment of wave and tidal energy technology.
- **Corbett**, **Lewis**, **Mackay**, **Sohrabi**, **Macbeth**, and **Geiger** have contributed to capacity building at several universities in Brazil through training more than 500 students and the employment of 20 researchers at different universities in Brazil, with direct impact on over £5M of industry investment in Brazil, and the establishment of the £15M state-of-the-art laboratory at the Federal University of Rio de Janeiro.
- **Doster** and colleagues are collaborating with Princeton University and Lawrence Berkeley Lab on a $1M joint project on CO_2 storage working with ETH Zurich, University of Melbourne and Montan University of Leoben. **Geiger** is collaborating with the University of

Calgary in a joint research project focusing on software development that is used commercially by Shell, Petronas, Petrobras, Equinor, ExxonMobil, and IBM Research.

European

- To improve performance and efficiency of heat engines for reduced environmental impact from aviation and land-based generation, **McCann** has developed capacity and UK/international collaborations (Rolls-Royce, Siemens, Royal Dutch/Shell, INTA (Madrid) and 5 UK universities) in chemical species tomography with demonstrations in labs and in civil aerospace engines.
- **Haas** and colleagues, in collaboration with the Fraunhofer Institute for Solar Energy Systems ISE (Freiburg/Germany) and St. Andrews University, have produced solar cells that can receive data at some of the highest rates in the world and partnered in 200 projects in over 20 countries. They led the IEEE task group that developed and set global standard ISO802.11.
- **Forehand** and **Ingram** worked with Scuola Superiore Sant'anna, Italy, to develop and patent a dielectric elastomer wave energy converter.
- Through the EU Projects MARINCOMP and POWDERBLADE, **Ó Brádaigh** has developed novel carbon fibre reinforced powder epoxy composites for the marine renewables sector (Suzlon, ÉireComposites, Orbital Marine Power, Toray Carbon Fibres Europe, Swiss CMT) that reduce the lifetime cost of energy.
- **Goussetis** co-ordinates SATCOM related Research that has attracted over **£**10M of awards including €2M from the European Space Agency that supports 22 PhD studentships in collaboration with Airbus DS and Thales Alenia Space. He also co-ordinates the EU **DORADA** project that brought about Celestia's investment in 18 new jobs in the HWU Research Park.

National

- ERPE staff in the ORCA Hub, led by **Lane,** are collaborating with the Offshore Renewable Energy Catapult and its industry partners to: translate UK-wide robotics research outcomes into products and services for the offshore renewables' industry; jointly train doctoral and masters' students and develop the UK strategy and roadmaps for offshore robotics technology.
- ERPE staff, led by **Masterton**, are members of the 15 university UK Collaboratorium for Research on Infrastructure and Cities (UKCRIC).
- **Smith** (Sean) worked with Scottish Enterprise, Scottish Funding Council and industry to establish the *Construction Scotland Innovation Centre* (CSIC). Since 2014 it has secured £7.5M with £2.2M investment to support academic buy-outs to work with industry, built a 4,000m^2 Innovation Factory, supported over 260 industry projects and leveraged £14M from industry.
- **Davies** leads the UDRC programme for knowledge transfer through licencing of algorithms and consultancy work in radar and sonar imaging, chemical detection, sensor networks, and electronic warfare; the stakeholders include BAE Systems, Leonardo, SEA Ltd, seebyte, Metrohm Raman, Cubica Technology Ltd, and Dstl.
- **Sherlock** and **Ó Brádaigh** are establishing an advanced manufacturing park in Rosyth, working with Babcock International, Fife Council and Fife College that will provide research, training and facilities in offshore robotics and composite materials.

4.3. Engagement with key research users, beneficiaries & audiences

Our Impact Strategy (*p.12*) described how we ensure that our research meaningfully addresses the real needs of contemporary global challenges. Since 2014 industry engagement has increased by over 40% and consultancy funding by over 50%, aided by the appointments of **Finney** at UoE as 0.4FTE Director of Industry Engagement, supported by **Cameron** as the Industry Engagement Manager, both of whom have fostered participation in the Offshore Renewable Energy and Energy Systems Catapults and partnerships with Canon Medical, Huawei, Toyota, Siemens Gamesa, Renishaw, Leonardo, Shell, BP and Total. We show below, by each RCA, five selected engagements with key stakeholders – beginning with Knowledge Transfer & Capacity Building and leading on to Technology Translation & Commercial Growth.

RCA1 – Engineering the transition to a lower carbon future

ERM staff engage with industry through CDTs, H2020 projects, and Innovate UK projects to deliver impact addressing the needs of RCA1&2.

- **Jeffrey** leads ERPE's Policy and Innovation group that works with UK and overseas governments and industry to produce sectoral strategy and roadmaps for ocean energy, commercialisation strategies, and cost of energy models. They lead the European Energy Research Alliance Ocean Energy Joint Programme and chair the IEA Ocean Energy Systems initiative. As Wave Energy Scotland's (WES) Head of Strategy and Internationalisation, **Jeffrey** works closely with companies funded by their Novel Wave Energy Converter, Power Take Off, Structural Materials and Manufacturing Processes initiatives.
- **Underhill** provides advice and training to Shell employees, covering all aspects of exploration geoscience. **Macbeth** was seconded to TU Delft and Shell and **Geiger** to the new Aramco Research Centre in Houston.
- **Pender** led the Scottish Oil and Gas Innovation Centre (OGIC), one of eight Scottish Government innovation centres, which aimed to create 500 jobs and £850M GVA by 2023.
- **Ingram** and **Sellar** have worked with Alstom, Orbital Marine Power, Nova Innovations, Sabella, Nortek, and Ingeteam to develop a Convergent-beam Acoustic Doppler Profiler (*p.7*). Through a £3M Stage 2&3 PTO project funded by WES, **Mueller** developed two novel C-GEN generators for the Mocean Energy Blue Star Project (Figure 4.3)

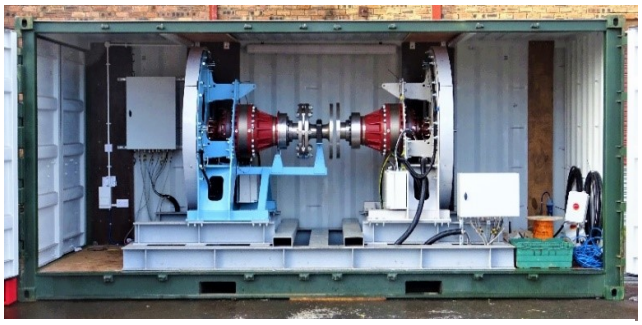

Figure 4.3 – C-Gen Mocean Generators

- **Robinson** and **Mueller** received funding from ICURe to commercialise Energy Storage and Generator Control technologies respectively. The latter led to a spin-out, ReOptimise Solutions Ltd, led by two former ERPE researchers, Echenique Subiabre and Crozier.

RCA2 – Developing materials, processes and manufacturing for healthier living

Medical discoveries, partnerships and impact are growing rapidly in RCA2, aligned with and confirming our strategy to focus and concentrate activities in photonics and signal and image processing for application to imaging in bio-medical engineering.

- **Hand**, **Desmulliez** and **Shephard** are using their medical device manufacturing expertise to assist Scottish SMEs to translate medical device concepts to commercial products, supported by £3.2M from ERDF and the Edinburgh City Region Deal.

- **Thomson (R)**, **Henderson** and **McLaughlin** worked with respiratory medicine clinician Dhaliwal to provide solutions for sensing deep in the lung disease diagnosis (PROTEUS), and are developing UV-light based treatment in EPSRC Transformational Healthcare grant U-Care.
- **Shephard** and **Hand** have ongoing collaboration with leading colorectal surgeon Jayne (Leeds) to develop systems for minimally-invasive early-stage cancer surgery. **Desmulliez** collaborated with oncologist surgeon Steele to develop a capsule-based ultrasound imaging system. **Thomson** worked with Renishaw to convert a 'craft-built' Raman probe system for oesophageal cancer diagnosis into a low-cost device manufactured using laser inscription.
- **Brandani** and **Ferrari** founded and direct the Adsorption Research Industrial Consortium of Air Liquide, Air Products, Exxon-Mobil, and Hitachi, all of which now use ERPE experimental protocols in their research laboratories.
- **Kersaudy-Kerhoas** has spun out Natantis (supported by Scottish Enterprise's High Growth Spin-out Programme) to commercially develop a microfluidic device for faster, cheaper cancer diagnosis and treatment monitoring.

RCA3 – Creating a smarter, safer world by innovation in data, comms, robotics & AI

Collaborations in SSS to address RCA3 have expanded to align with our aims to create better interactions between digital technologies and their environment, acting on the information to increase safety and quality of life.

- **Mulgrew** provided expert advice and technology transfer in radar signal processing to Leonardo, via his industry chair.
- **Davies** (M) advised Dstl on its in-house Data Science research programme. This collaboration across Universities and with industry provided the synergy to grow our existing strength in defence signal processing and benefit by new collaborations with machine learning activity in Computer Science, specifically allowing us to invest in new capacity in SSS (**Crowley** & **Qin**).
- **Lane** led the UK's national robotics innovation strategy RAS2020, which has informed £400M of UK Government and £150M of industrial investments to date, and the new UK Industrial Strategy Challenge Fund. He also leads a UK National Robotics Enterprise and Robotics Growth Partnership under the aegis of the Minister of State for Universities, Science, Research & Innovation and BEIS.
- **McLaughlin** is on the Board of Scotland's Innovation Centre for Sensing, Imaging and IoT technologies (CENSIS) that works with private and public organisations to overcome technology barriers and drive business transformation.
- **Haas,** his colleagues and **Wang** are engaging with industry in field trials of LiFi, including an in-flight demonstration with Airbus Germany and two 5GRuralFirst projects in Orkney.

RCA4 - Engineering a safer and healthier infrastructure and environment

To increase the health within and safety of the urban and rural infrastructure and environment, IE and ERM staff engage with industry, society and policy-makers.

- **Bisby, Law**, **Welch**, and **Rush** have provided extensive and varied advice to UK Government on Fire Safety in high buildings and those built from new timber materials.
- **Viola** led a pioneering study at the beginning of the COVID-19 pandemic that was among the first to measure the effectiveness, inherent weaknesses and dangers of improper use of face coverings in reducing virus transmission, (IEEE J. of Eng in Med & Biol). This fed into the UK government's national advice on wider spread and better-informed use. Signal AI

estimated that, in the first month of availability, the results preprint had an estimated reach of 4B people.

- **Beevers** collaborates with SEPA, Scottish Water, and the Environment Agency to identify future catchment scale hydro-hazard (floods and droughts) hotspots to inform the UK's medium-term response to climate change.
- **Laghrouche** worked with Tarmac on construction and testing of a slab track to assess the long term settlement of embankment design to high-speed standards necessary to support HS2.
- **Ooi** and **Hanley** worked with CPI, industrial users and software providers, and successfully applied their particle scale models to support industrial innovation in particulate processes.

4.4. Engagement with diverse communities and public

ERPE staff engage extensively with communities of all ages from global to local environments applying or communicating the outcomes of our research. Five examples at each level follow.

Global

- **Lucquiaud** directly engaged with the general public on climate change technology via the world's first MOOC on Carbon Capture and Storage, attracting 6,800 learners from over 140 countries.
- **Adeloye** is working in an interdisciplinary research project on 'Sustaining Himalayan Water Resources in a Changing Climate' as part of an effort to help ensure water security for 40 million people facing climate change and anthropogenic impacts.
- **Venugopal** (Figure 4.4.1) led several UK India Education and Research Initiative knowledge transfer projects, including 'Tidal Energy for Sustainable Village Electricity Supply in the Indian Sundarbans Biosphere' that involved local village communities, government ministers and local development agencies.

Figure 4.4.1 - Venugopal and Sundarbans village elders

- Funded by Innovate UK and the EPSRC Impact Acceleration scheme, **Sen Gupta** (Figure 4.4.2) is also working with local collaborators and communities in West Bengal, Bangladesh and Mexico, to install solar/diesel powered arsenic removal systems in rural water supplies. The process only uses atmospheric oxygen and no waste or sludge is produced during operation to produce up to 10,000 litres/day.

Figure 4.4.2 – Inauguration at Comilla, Bangladesh

- FloWave was filmed by the SlowMo Guys in October 2018 for a YouTube video that has been viewed worldwide over 16 million times.

National

- In 2019, we celebrated our Year of Health and hosted events ranging from family fun days to industry conferences, and from exhibitions to schools' competitions, all to showcase our innovations in healthcare, diagnosis and treatment. We engaged with over 18,000 people throughout the year in schools competitions and health technologies festivals.

- **Haas** and co-workers presented Li-Fi at the Royal Institution 2015 Faraday Lecture, broadcast by the BBC to an estimated 2 million viewers, and delivered the TED Global Talk, "Forget Wi-Fi: Meet the New Li-Fi Internet", reaching 2.8 million views online.
- **Bisby** appeared as an expert presenter in 10 episodes of the engineering documentary series 'Impossible Engineering' which continues to air internationally; and also appeared the BBC2/PBS Nova documentary 'Rebuilding Notre-Dame: Inside the Great Cathedral Rescue'.
- **Welch** was featured on BBC2 Newsnight in June 2017 in the context of the Grenfell Tower fire investigation, and has led to an insurance industry publication and training videos used by UK fire and rescue services.
- **Bridle** won the Royal Society of Edinburgh Innovators Prize for Public Engagement in 2016, was appointed a Member of the STFC Advisory panel on public engagement and won an EPSRC Fellowship to co-create resources to showcase diversity of engineering careers to primary pupils and families.

Local

At a local level, ERPE staff regularly organise and deliver outreach activities to disseminate ERPE research and engage with the public. Platforms include: the Midlothian Science Festival, the Cabaret of Dangerous Ideas, Native Scientists, Scottish Energy Forum, and the Edinburgh International Science Festival (EISF).

- As part of the National Museum of Scotland's major exhibition on robots in 2019, **Lane** co-created a virtual interactive experience of the NASA Valkyrie robot that attracted 60,000 visitors, receiving significant media coverage.
- In 2017, building on our lead role in the European Robotics Forum and the Edinburgh Centre for Robotics, in our Year of Robotics initiative **Lane** and colleagues reached directly more than 1,800 school pupils and 13,000 members of the public and had an estimated media reach of over 25M.
- ERPE, through **Chalmers, Laurenson, Rush** and others, deliver the Primary Engineer programme in Scottish schools. Over the last 12 years it has created an engineering curriculum that includes teacher STEM skill development and engineering classroom projects.
- **Ingram** hosts an annual Doors Open Day in FloWave that routinely attracts over 400 visitors. He also hosts the Junior Saltire prize where Primary/Secondary school pupils are helped to build and test their own designs for marine energy converters.
- **Erden** delivered an interactive public exhibition on 'Robot-assisted surgery', reaching over 2000 people at the EISF.

4.5. Contributions to the research base and recognition

We encourage and recognise service on high impact factor international journals. Around 50% of ERPE academic staff, at all levels, lead or serve on editorial boards of one or more key journals. These include: **McLaughlin** as Senior Area Editor for IEEE Transactions on Computational Imaging, **Hopgood** as Editor in Chief of the IET Proceedings on Signal Processing, **Forde** as Editor of Construction & Building Materials, Elsevier Science, **Bisby** as Editor of the Fire Safety Journal; **Koutsos** as Editor in Chief of the Proc. IMechE, Part N: Journal of Nanomaterials, Nanoengineering & Nanosystems.

Editors in Chief	12
Associate Editors	48
Members of Editorial Boards	83

Table 4.5.1 – ERPE Governorships and senior office bearers

Around 50% of ERPE senior staff are elected Fellows of one or more Royal societies or learned societies with chartered status. We encourage and value this peer and professional recognition and seek to ensure that our expanding numbers of new Lecturers, ECRs and doctoral students engage with the professional institutions and learned societies through student, associate and full membership leading to chartered status. We encourage and recognise committee membership and service as summarised below. We also show there the significant external responsibilities and recognition of ERPE staff.

Fellowships of Royal Societies		Fellowships of Learned Societies	
FREng	15	FIStructE	2
FRSE	28	FIESIS	2
FRSA	5	FIEEE	8
FRSC	3	FIET	15
FRSB	2	FICivE	6
		FIChemE	4
		FIMechE	8
		FInstP	8
		FGSoc	4
		FIEnergy	2
		FIMM	2
		European	2
		Other	18

Table 4.5.2 – ERPE Fellowships

We encourage, create and foster opportunities for leadership and external contribution, partly for initial and continuing professional development, but more importantly to gather and share strategic wisdom and consequent opportunities for industrial, research and academic impact.

	National	EU	Global
Leadership of research consortia	37	24	17
Leadership or membership of advisory boards (not editorial)	53	19	8
Committee membership of learned societies, professional institutions, charities & trusts	50	12	14
Membership of grant and fellowship awarding bodies	18	20	3
Honorary Chairs		4	18
Invited Keynotes	8	20	43

Table 4.5.3 – ERPE Significant External Responsibilities and Recognition

Jointly, ERPE in ERM staff were recognised with the *2015 Queen's Anniversary Prize, recognising sustained research and innovation in subsurface energy systems*. Selected examples of individual awards held include:

- *Commanders of the Order of the British Empire* – **Lane**;
- *Officers of the Most Excellent Order of the British Empire* – **Ocone**, **Sen Gupta**;
- *RSE Dr Patrick Neill Medal for outstanding contributions to the field of biomaterials and tissue engineering* - **Melchels**;
- *Gold Medal of the Institution of Civil Engineers* – **Borthwick**;
- *Dr honoris causa from Budapest University of Technology and Economics* – **Borthwick**;
- *Cavaliere dell'Ordine della Stella d'Italia, in recognition of contributions to scientific and technological research, conferred by the President of Italy* – **Brandani**;
- *RAEng MacRobert Award* – **Rampen**; *RAEng Blavatnik Award* – **Medero**;
- *Tucker-Hasegawa Award Int Assoc for Automation and Robotics in Construction* – **Bosche**;
- *Royal Society Wolfson Research Merit Award (2016)* – **Davies**;
- *IStructE Oscar Faber Medal* – **Law**;
- *Hinshelwood Prize from Combustion Institute* – **Peterson**;

- *2020 WES Top 50 Women in Engineering for exceptional attainments made in sustainability and shaping the world* – **Maroto-Valer**, **Thompson**
- *2019 FT Top 100 Influential Women in Engineering* – **Ocone**;
- *2018 SRUK/CERU Merit Award* - **Maroto-Valer**;
- *IET Global Innovation Awards* – Transport, **Maroto-Valer**; Ambient wireless energy harvesting, **Song**; Intelligent Systems – **Robu**; Power Network Prediction and Control – **Flynn**;
- *Alfred Wegener Award of the European Association of Geoscientists* – **Geiger**;
- *British Renewable Energy Agency Award for Decarbonisation of Transport 2018* – **Flynn**;
- *Society of Petroleum Engineers:* Industry Grand Challenges – **Laghrouche**; Production and Operations – **Sorbie**;
- *National Instruments Global Engineering Impact Awards 2019* – SonoPil, **Desmulliez**; Remote Teaching – **Drysdale**.