

Institution: Queen's University Belfast

Unit of Assessment: 12

1. Unit context and structure, research and impact strategy

A defining feature of this UoA is the ability to sustain a pipeline of world-leading basic science that delivers impact through commercialisation and knowledge exchange. This is essential within the context of post-conflict Northern Ireland; we work with partners across the University, regionally, and beyond, to transform a dependency on traditional manufacturing into a knowledge-based, data-driven economy. Influenced by the UN Sustainable Development Goals, the UoA has, in this period, chosen to focus on eight core research topics: **connectivity and cybersecurity, data analytics, future transport, clean energy, advanced manufacturing, smart, sustainable and resilient infrastructure, advanced liquid materials and advanced composites and polymers.**

We are uniquely geographically positioned between the UK, Europe and the United States, thus remaining at the centre of many initiatives being delivered through the research councils, business agencies and Foreign, Commonwealth & Development offices, to shape UK research in an international context post Brexit. A 30% targeted refresh of staff has significantly enhanced the UoA, translating to the engagement of 45.8 early career researchers (ECRs). Through an innovative development programme, they have been successfully embedded in the UoA research culture and ethos. Concurrently, the UoA has achieved a steady 6.6% growth in its annual research income, resulting in a cumulative total of £115.5M across the REF period.

The UoA has had a number of notable achievements during the REF period:

- 2016 Award of an esteemed Regius Professorship by Her Majesty the Queen to recognise exceptionally high quality research in Electronics and Computer Engineering.
- Securement of 12 prestigious fellowships (including two Research Chair/Senior Research Fellowships), a Royal Society Newton International Fellowship, two UKRI Future Leader fellowships, five RAEng fellowships, a Leverhulme Trust Research Leadership fellowship, and a NERC fellowship, all of which are engaged on projects directly addressing the eight core areas.
- The UoA's Centre for Secure Information Technology has played a major role in establishing the region's world-recognised status in cybersecurity. It is a founding partner in the Global EPIC3 world-wide network of 24 cybersecurity research and innovation ecosystems, in the London-based Cybersecurity Innovation Centre (LORCA), and has helped in creating 1,600 jobs across 40 Northern Irish companies.
- 2015 Queen's Anniversary Prize for Higher and Further Education on Engineering & Technology, awarded to the Centre for Secure Information Technologies.
- Establishment and implementation of a number of major initiatives including a £50M R&D Engineering Centre of Excellence for Biomedical Applications (with Radox Laboratories), a £33M 'Strength in Places' project (with Artemis Technologies), a £10M 'phase 2' Innovation and Knowledge Centre, a €9.3M Bryden Centre for marine and bio-energy research, and a £5M cross-disciplinary William Wright Technology Centre in transport technology.
- Establishment of the £5M Tier-2 Northern Ireland High Performance Computing Centre to support data analytics research. This reflects the institution's joint strength with Ulster University in data analytics, which in terms of research power was ranked by the Alan Turing Institute as 6th in the UK.
- Large scale engagement with industry, evidenced by the contribution of nearly half of the University's 133 Knowledge Transfer Partnerships (KTPs), which has resulted in Queen's being ranked number one in the UK for spin-outs, and has added an estimated gross value of £55M to the economy.
- Continued success in commercialisation: four of the UoA's spin-out companies have secured over £76M in venture capital investment.

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- Development of a strong Equality Diversity and Inclusion (EDI) ethos, evidenced by three of the four UoA schools holding Silver SWAN awards, and by the UoA's leadership in the UKRI-funded Inclusion Really Does Matter 'Support for Equality Network in Science and Engineering' network.

a) Unit context and structure

2015 saw the introduction of a new management structure within the University (Figure 1), leading to the establishment of the Faculty of Engineering and Physical Sciences (EPS) in which the UoA is based. A Faculty Pro Vice-Chancellor (PVC-EPS) and Deans of Education, Research, Postgraduate Teaching and Internationalisation were appointed with the specific aim of achieving the strategic goals of the University's 'Vision 2020' plan. This led to the formation of a new Faculty Executive Board, chaired by the PVC-EPS, consisting of the individual Heads of Schools, supported by Directors of Operations and new faculty-embedded Professional Services staff.

The UoA covers the schools of Electronics, Electrical Engineering and Computer Science (EEECS) and Mechanical and Aerospace Engineering (MAE) as well as the Civil Engineering component of Natural and Built Environment (SNBE) and Chemical Engineering portion of Chemistry and Chemical Engineering as indicated below (CCE). The changes have led to the creation of a number of major new initiatives supporting interdisciplinary research and a reorganization into 18 major research themes/groups across the four schools (Table 1).

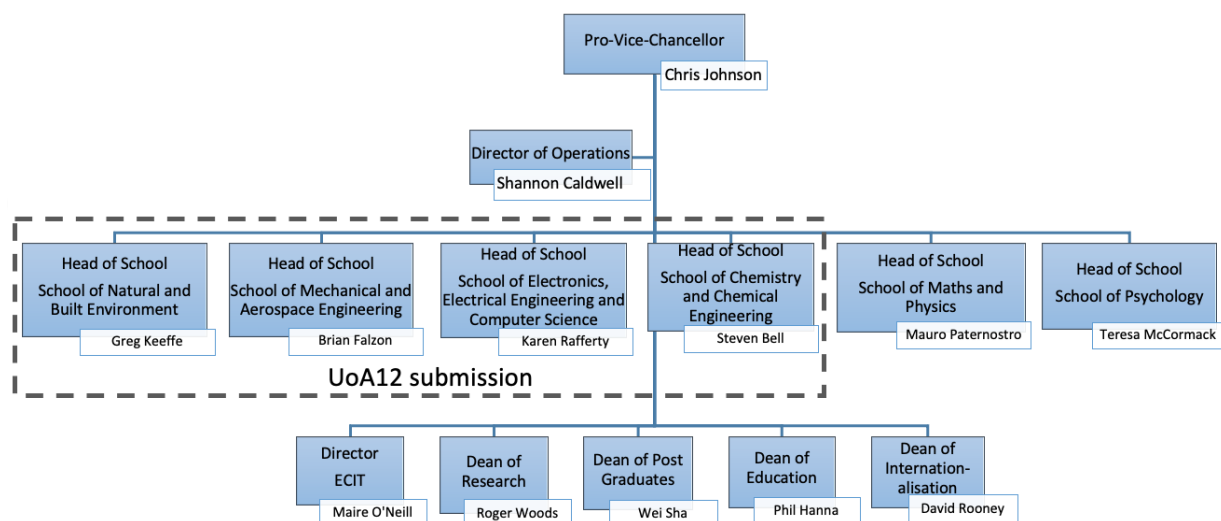


Figure 1. Faculty management structure

To respond to the University's 'Vision 2020' plan and Corporate Plan 2016–2021, the Faculty made a number of major changes, designed to improve each School's capability to best respond to the major societal and engineering challenges of our time. A result has been the establishment of the School of Natural & Built Environment, creating a dynamic, multidisciplinary environment, in which civil engineers collaborate proactively with architects, planners, geographers, paleoecologists and archaeologists. Crucially, the development of a new Global Research Institute, the Institute of Electronics, Communications and Information Technology (ECIT), has linked researchers from a wide variety of electronic and communications disciplines on such a scale that rapid and successful addressing of major societal challenges is possible. The creation of three strong, multidisciplinary Pioneer Research Programmes has acted to stimulate novel interdisciplinary research collaborations to tackle challenges emerging on the global horizon. The changes have seen an increased research profile in terms of high profile staff appointments, improved grant income, increased number and quality of research publications and increased impact as evidenced by the UoA's influence on impact case studies.

Unit-level environment template (REF5b)

- **Institute of Electronics, Communications and Information Technology (ECIT)**: this comprises the Centre for Secure Information Technologies (CSIT) - a leading centre in Europe for cyber security research/innovation, the Centre for Wireless Innovation (CWI) – which invents the underpinning technologies for mobile, medical and space applications and the Centre for Data Science and Scalable Computing (DSSC) - which conducts research into core machine learning and data science for heterogeneous data sources.
- **Centre for Intelligent Autonomous Manufacturing Systems (i-AMS)**: this spans engineering disciplines, computer science, applied mathematics and psychology, and works in partnership with the Northern Ireland Technology Centre to develop innovative technologies and solutions for Industry 4.0. It addresses **advanced manufacturing** by focusing on three areas: (1) virtual sensing, prognostics & virtual factory simulations, (2) flexible automation and robotics and (3) autonomous and intelligent decision making.

Divisions	Research Themes/Groups	Research topics
Electronics, Electrical Engineering and Computer Science (EEECS) (68.75/55.0)	<ul style="list-style-type: none"> • Centre for Secure Information Technology • Centre for Wireless Innovation • Data Science and Scalable Computing • Energy, Power and Intelligent Control • Artificial Intelligence 	<ul style="list-style-type: none"> • connectivity and cybersecurity; data analytics • connectivity and cybersecurity • data analytics • clean energy; advanced manufacturing • data analytics; smart, sustainable and resilient infrastructure
Mechanical and Aerospace Engineering (MAE) (38.8/38)	<ul style="list-style-type: none"> • Advanced Manufacturing and Processing • Bioengineering • Clean Energies • Composite Materials and Structures • Future Aircraft • Simulation Technologies 	<ul style="list-style-type: none"> • advanced manufacturing • composites and polymers; advanced manufacturing • clean energy • future transport, composites and polymers • future transport • advanced manufacturing; future transport
Chemistry and Chemical Engineering (CCE) (9.4/8)	<ul style="list-style-type: none"> • Advanced Materials and Nanotechnology • Green and Sustainable Chemistry • Multi-phase Flows, Reactors and Process Intensification • Theoretical and Applied Catalysis 	<ul style="list-style-type: none"> • advanced composites and polymers • clean energy; advanced liquid materials • clean energy • clean energy, advanced composites and polymers, advanced liquid materials
Natural and Built Environment (NBE) (23.05/33.6)	<ul style="list-style-type: none"> • Intelligent and Sustainable Infrastructure • Water and Energy Resources • Global Environmental Resilience 	<ul style="list-style-type: none"> • smart, sustainable and resilient infrastructure; data analytics; advanced composites and polymers • clean energy; smart, sustainable and resilient infrastructure • smart, sustainable and resilient infrastructure

Table 1. School, Research Themes' organization and relationship to research topics (includes details included of number of returned academic staff /REF2014 returned academic staff)

- **Centre for Materials & Advanced Technologies for Healthcare (MATCH):** An interdisciplinary research initiative with the Faculty of Medicine, Health and Life Sciences, this comprises leading researchers from the UoA and is centred on healthcare technology. It focuses on creating: (1) smarter technologies that are biocompatible and strongly antimicrobial; (2) future therapies to enhance solubility, bioavailability and stability of novel medicines and (3) optimization of strategies and technologies for enhancing patient care.
- **Sustainable Energy Research Centre (SERC):** this addresses the **clean energy** and **advanced liquid materials** themes and acts as a focal point for the technological aspects of energy research. It also incorporates Queen's University Ionic Liquids Laboratory and the Competence Centre in Advanced Sustainable Energy (an industry-led research centre funded through Invest NI's Competence Centre programme, covering all forms of renewable energy including marine, wind and bio-energy as well as energy systems).

While both the Global Research Institute and Pioneer Research Programmes directly relate to the schools in the UoA (Figure 2), they also take a strong and active multidisciplinary approach. MATCH is engaged with the schools of Pharmacy, Biological Sciences, Medicine, Dentistry & Biomedical Sciences and Nursing & Midwifery; and SERC with the School of Biological Sciences and a number of external institutions (e.g. Agri-Food and the Biosciences Institute). The £1M ECIT-led Leverhulme Interdisciplinary Network on Cybersecurity and Society project engages with the Senator George J. Mitchell Institute for Global Peace, Security and Justice by providing 30 studentships; and the recently funded Leverhulme Interdisciplinary Network on Algorithmic Solutions incorporates EEECS and the Schools Of Law, History, Anthropology, Philosophy and Politics (HAPP), and Maths and Physics (M&P). The EPSRC-funded 'Advanced Research Into Creative Circular Economies for Plastics via Technological-Social Transitions' project unites UoA researchers with the Schools of HAPP and Psychology.

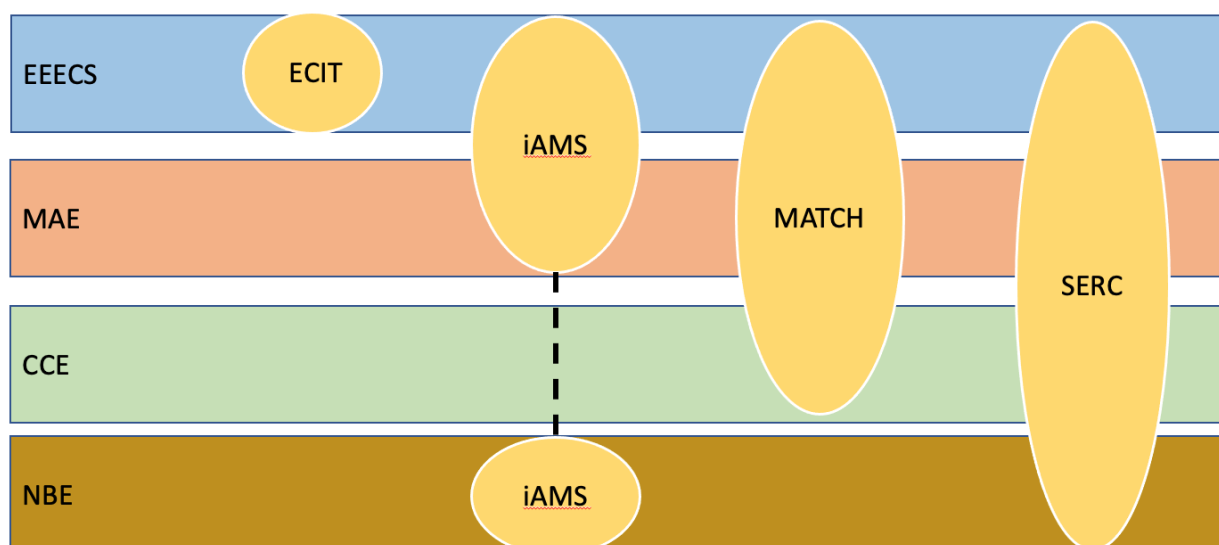


Figure 2. Global Research Institute/Pioneer Research Programmes relationship to individual Schools

During the period, funding for a number of Innovative Training Networks (ITNs) was secured and the UoA was a founding member of two major international collaborations: the UK-Jiangsu 20+20 World Class University Consortium (involving 20+ Chinese and 20 UK universities) focused on advanced manufacturing, environmental engineering and healthcare and; the UK-China University Consortium on Engineering Education and Research (involving 6 UK partners) focused on areas of energy and intelligent manufacturing.

b) Research strategyProgress against REF 2014 strategic aims

The UoA was returned under separate sub-panels in REF 2014. Their specific strategic aims can be summarised as follows:

- high performance software design, programming applications and knowledge-driven large-scale intelligent systems (**REF2014:UoA11**);
- materials, energy and manufacture with a multidisciplinary focus (**REF2014:UoA12**);
- higher performing antennas, context aware wireless, cybersecurity and cryptographic hardware, electric network Integration of high penetration renewables (**REF2014:UoA13**);
- structural materials, composites, structural health monitoring, renewable energy, marine renewables, groundwater, soil, and water management (**REF2014:UoA14**).

During this REF period, the UoA's focus has been to bolster key areas of research, whilst driving forward solutions to primary economic and social challenges. There is a strong and necessary emphasis on interdisciplinarity. This approach has led to the establishment of eight core research areas (highlighted at the start of the statement) which involve, in many cases, multiple schools (Table 1, Figure 3). These are detailed below:

Connectivity and cybersecurity: CSIT is the UK's Innovation and Knowledge Centre for cyber security. It has comprehensive excellence in cybersecurity and cryptographic hardware; achieved through the expansion of its activities in (1) applied cyber security technologies, (2) network security (3) industrial control systems security and (4) security intelligence. Founded in 2009, CSIT's mission is to couple major research breakthroughs in the field of secure information technologies with a unique model of innovation and commercialization. This enables it to drive economic and societal impact across the nation.

Combining two previously separate areas of research (namely high frequency electronics and wireless communications systems) has utterly transformed the wireless communications research; resulting in the UK's largest grouping in physical layer wireless communications. It comprises 17 academics and 50 researchers and is ranked 28th globally in telecommunications centres, and 4th in Europe (2019 Shanghai Rankings for Telecommunications). Its global impact has seen the granting of 6 patents, numerous British Council awards, a Royal Society Newton International Fellowship and the 2017 Newton Prize.

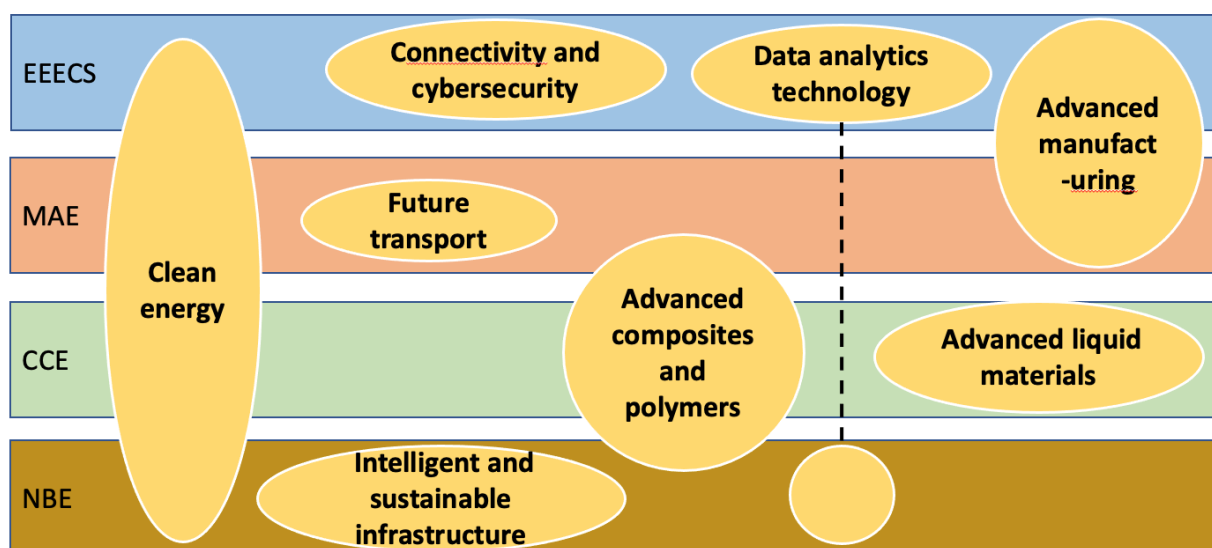


Figure 3. Exemplar research areas included within the research strategy

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In **Data analytics technology**, researchers have created techniques which, unlike comparator research groups, include the sensor and the computer hardware in the algorithmic design space. This creates end-to-end optimization of modern machine learning, which in turn has led to a number of innovations with notable impact, for example: robust face recognition (which operates across the range of identities and noise profiles found in existing camera setups); significantly more efficient neural networks (operating on 2W chips versus 150W); enormous speed up of identity search algorithms (resulting in 30000% reduction in search time). This expertise has led to the spin out of two visual analytics companies, one of which, Anyvision, is an internationally recognised leader in computer vision technology. These achievements are central to the ambitions being espoused in the AI Council and UKRI's 'AI review: Transforming our world with AI' reports.

Unique aspects of this work includes the "any device virtualisation" for edge and future cloud architectures and AI techniques, which include sensor and the computer hardware in the algorithmic design space. Again, this creates end-to-end optimisation of modern machine learning. Measures of esteem within this period include: Distinguished Member of the ACM, 2018; Silver Medal, 2018; and IEEE Certificate of Merit, 2016. Data Science and Scalable Computing was the first UK research group to receive direct funding from the Defence Science and Technology Agency of Singapore - a recognition of the world-leading expertise in multi-modal deep learning applied to defence.

Future transport has been strengthened through the showpiece, cross disciplinary William Wright Technology Centre engaged in world-leading bus technology research and the £33M 'Strength in Places' project, 'Decarbonisation of Maritime Transportation – a Return to Commercial Sailing'. Led by Artemis Technologies, this latter project builds on Belfast's maritime heritage and world-leading expertise in advanced manufacturing and renewable energy with the aim of developing zero emissions hydrofoil ferries and a maritime transport system of the future.

The William Wright Technology Centre has established new partnerships with operators in Hong Kong and Latin America that are being developed into longer term strategic research project. It has benefitted from an investment of over £1.5M by the Wright Group with an additional £4M from funded projects. It employs 9 post-doctoral researchers, 10 postgraduate students and a development engineer. Since 2017, it has been awarded an interdisciplinary EPSRC Prosperity Partnership, 2 Innovate Integrated Delivery Programme (IDP) projects and an Advanced Propulsion Centre Advanced Route to Market Demonstrator project.

Building on our vast expertise in geometric modelling, a unique in-house expertise has led to a long-term collaboration with Rolls-Royce on defining and automating the creation of innovative and efficient structural models which will be used to understand the requirements of future generations of aircraft engines. The School has held multiple EU and UKRI awards related to this research area over the years and has received substantial funding directly from Rolls-Royce.

Major contributions through the UoA - via the Bryden Centre for Advanced Marine & Bio-Energy Research into biomass and marine-based renewable energy sources - has fostered impressive work towards **clean energy**. This €9.3M 'virtual centre of competence' was funded under the INTERREG VA Programme, which supports cross-border research. By expanding research in marine renewables, successful commercialization and diversifying into tidal current, off-shore wind and solar energy, the centre has bridged the gap between academic research and industry needs. Extended strategic collaboration focusing on the challenges of network integration of high penetration renewables in the wide area has been established with AES, EirGrid, GlenDimplex, NIE Networks, SONI, and Statnet. Due to the ratio of available renewable resources to land mass, the electricity grid across Ireland is recognized as a world-class test bed. Phasor measurements units (installed on 44 sites) now facilitate innovative research on a power system operating at up to 65% non-synchronous generation. This work resulted in an IET GTD Premium Award in 2017 and an Innovate UK project with AES (at the time, Europe's largest grid connected Battery Energy Storage System).

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A £7.5M investment in the Northern Ireland Technology Centre by Innovate UK, the Aerospace Technology Institute and the university has significantly strengthened **advanced manufacturing** by creating an open access “Digital Enabled Manufacturing Technology Factory”. In collaboration with industry, it aims to develop and demonstrate advanced manufacturing and digital technologies. i-AMS fosters interdisciplinary, manufacturing research across engineering, computer science, psychology, and mathematics, with the aim of addressing the challenges of Industry 4.0. Research programmes have focused on (1) the development of machine learning based approaches to monitoring, optimization, predictive maintenance and control of manufacturing systems and processes, (2) the control and coordination of autonomous vehicles and robots, and (3) virtual reality/augmented reality and haptics for enhanced immersive experiences. Novel research on ‘Low-cost process monitoring for polymer extrusion’ was recognized with an Institute of Measurement and Control ICI Prize (2015).

Current research into **smart, sustainable and resilient infrastructure** has built up major activities into sustainable construction materials, life cycle assessment of materials, and structural health monitoring. The work goes from fundamental research through to direct application with examples of major focus areas including: sustainable, low carbon precast concrete infrastructure; novel low carbon geopolymers; and extending bridge life by developing the world’s first fibre optic Bridge Weigh-in-Motion system. The UoA has grown its expertise to address the impact of climate change, including the growing global challenge of flooding and the scarcity of clean, potable water. It has expanded its research into sustainable management of peatlands and contaminated water, soils and groundwater. There are interdisciplinary approaches taking place that explore the environmental impact of marine renewables and coastal processes.

Advanced liquid materials research has been mostly undertaken by CCE staff (multidisciplinary team involving chemical engineers and chemists) in the Queen’s University Ionic Liquids Laboratory, an academic/industry partnership established to exploit QUB’s lead in ionic liquid technology. Ionic liquids, or deep eutectic solvents, have complex structures, which can be precisely engineered to deliver specific sets of properties. Applications include: battery electrolytes and hydrogen storage media, superhydrophobic coatings and high-performance lubricants, solvents for polymers, media for metals separations, and components of emission control systems. The team has a collaborative research partnership with Petronas, which was strengthened by seven new first phase, research projects with a total value of £2.4M (2020). Further funding plans for years 4-5 aim to reach higher technology readiness levels. All projects are broadly related to the area of sustainable chemistry and chemical engineering, enabling Petronas to develop transformative low-carbon technologies across their business portfolio.

The team working on **advanced composites and polymers** is leading the field in next generation materials for lightweight smart nano-enhanced composites. This meets the needs of future transportation by upgrading performance, improving fuel efficiency and ameliorating crashworthiness. A £6M Northern Ireland Advanced Composites and Engineering Competence Centre, (a collaboration between academia and 17 industry participants, namely Bamford, Collins Aerospace, McFarlands, Spirit and others) was created as a locus for this activity; and it has a focus on researching new composites and on structural health monitoring. In 2021, the UoA will host the International Conference on Composite Materials, the field’s foremost international conference, attracting 1500-2000 delegates from over 40 countries. The Polymer Processing Research Centre celebrated its 20th anniversary in Sept 2016 by refocussing its core activities in polymer engineering and offering significant potential to provide new solutions needed to provide step changes in technological advances. We recognise that investment is needed to maintain competitive advantage, and so have recently established a new polymer laboratory.

c) Impact strategy

The UoA represents a core part of the University’s enterprise strategy and has had a demonstrable track record in establishing close relationships with industrial partners, in

Unit-level environment template (REF5b)

identifying commercial opportunities and by encouraging the creation of - and support for - spin out companies. A lot of this activity is coordinated through eight dedicated business development personnel in ECIT and is able to avail of the EPSRC Impact Acceleration Account. The UoA's expertise and activities are seen as an important strand for the strategy of InvestNI, the Northern Ireland investment agency, in attracting inward investment into Northern Ireland.

For two successive years (2019, 2020), the university has been ranked first in the UK for commercialising academic research (Octopus Ventures). Currently, 1954 employees are employed in 37 active spin out companies.

Recent UoA12 successes include:

- **AnyVision**, a leading computer vision company specializing in face, body, and object-recognition software, which closed a £60 million Series A financing round in 2019.
- **TitanIC Systems Ltd.** who has developed pioneering technology to accelerate data search and analytics, was acquired in 2020 by Nasdaq-listed Mellanox - a company with revenues of \$1.33B.
- **Analytics Engines Ltd.**, who develop data analytics software, has secured several investments of up to £1.5M during the period allowing it to expand to 20 people.
- **Green Lizard Technologies Ltd.** (founded 2015) specializes in green chemistry technologies for the sustainable energy, chemical and recycling industries; and has secured over £14M in projects to date.

Other on-going spin out company activity includes: **Amphora Non-Destructive Testing Ltd** (2002, sold August 2014 and now trades as Amphora NDT Ltd) which provides equipment for on-site monitoring of concrete; and **Sengenja Ltd** (2007), which provides ingenuity in sensing solutions using optical sensors, and is involved in high profile projects including high speed rail.

KTP performance was ranked as 'The Best of the Best' in the UK in 2019, with the UoA being engaged in 65 of the institution's 133 KTP projects during the REF period. This is estimated to have generated up to £28.5M net additional gross value added and, following completion of all 65 of UoA12's KTPs, will rise to an estimate of £55M (Table 2). A project from the UoA with Bullivant Taranto Ltd., was awarded best overall KTP in 2013; and in 2014 **Taylor** was awarded UK KTP Ambassador.

	Completed UoA12 KTPs	All UoA12 KTPs
KTP Grant from Innovate UK	£3.56M	£6.90M
Company Contribution	£2.01M	£4.15M
Total Partnership Budget	£5.55M	£11.05M
Estimate of RoI, net additional GVA	£26.7M- £28.5M	£51.8M - £55.2M

Table 2. Value for UoA12 KTPs for the period 2014-to date

A number of specific examples of impact related to the eight core areas include:

In **Connectivity and cybersecurity**, advanced security has been demonstrated in the creation of a fully homomorphic encryption hardware design, which provides encryption speed improvements of a factor of 130 compared to equivalent software designs. This was selected as an IEEE Trans. on Computers 'Editor's pick of the year 2016'. This advanced encryption technology has also been used by Thales, in a demonstration model to address electronic component counterfeiting in industry.

In **smart, sustainable and resilient infrastructure**, research into concrete technology has enabled the Northern Irish concrete industry to sustain their position as UK market leaders by providing new, leaner products; and allowing for safer, cleaner working environments. QUB-led structural health monitoring and assessment has been practically applied by the Northern Ireland Department for Infrastructure to 30 bridges. The UoA is leading the development of a regional

Digital Twin network for Northern Ireland which will replace existing management databases for key Infrastructure, including 6,000 bridges across the region. Monitoring has been applied to the Irish Four Courts Building in Dublin, Senator House in St. Paul's Quarter, The City of London. It has safeguarded key civil infrastructure, such as Ballylumford power stations (by sustaining corrosion-damaged chimneys and providing a saving of £1M) and the Thames Tideway Tunnel.

Activities to ensure current and future **clean energy** supply include: the commercial deployment and operation of Aquamarine Power Ltd's full-scale Oyster 800 Wave Energy Converter; creation of the Tidal Turbine Testing (TTT) research programme (consisting of three commercially driven projects bringing research to realisation through collaborations with Ocean Flow Energy, Schottel Hydro, and Sustainable Marine Energy); and cross-institutional collaborations with the ORE Catapult, UK and CNR-INM (formerly INSEAN), Italy, funded by Invest NI-sponsored TTT2 (£125K) and TTT3 (£665K) projects.

In addition, the UoA's development of a peatland model proved central to the Irish Government's National Peatland Strategy, where it underpins development of site-specific conservation and management strategies across the Republic of Ireland's network of Special Areas of Conservation and National Heritage Areas. This improved management of Ireland's network of protected peatland directly resulted in the Irish government avoiding €9m in potential European Commission fines.

d) Future strategic aims and goals for research

In combination with pursuing the existing strategy, the UoA can play a key role in a number of other major arising opportunities. For example, it plays a key role in the Belfast Region City Deal, which is focused on delivering economic growth and recovery through a collaborative, cross-sector approach. The UoA is leading two of the five projects, namely the creation of a Global Innovation Institute (GII) and an Advanced Manufacturing Innovation Centre (AMIC). These activities will drive digital innovation and sector growth, supporting Northern Ireland businesses, and create a transformational £190m proposition for new R&D facilities in AI and data analytics. It has the potential to provide the Northern Ireland economy with almost 5,000 jobs, a £200m annual GDP uplift and an 18% productivity uplift in key sectors.

GII: a £53.4m project which aims to catalyse digital innovation in key sectors within the Belfast region through creating challenge-led solutions for the data-driven economy; and by providing domain-specific expertise across the One Health spectrum. The ambition is to bring together people, data, and systems for the benefit of society within the Belfast Region and across Northern Ireland. The GII's purpose is to help foster the growth of a large and distinctive Innovation District, employing over 20,000 people, and growing 500 companies by 2035. It will be capable of offering bespoke solutions in secure, connected intelligence to international companies, This will be underpinned by a distinctive and flexible high-performance computing capability. The GII will co-locate and expand research expertise from the University's three Global Research Institutes, namely ECIT, the Institute of Health Sciences and the Institute for Global Food Security. A 6,900m² facility, accommodating a critical mass of 500+ people (multidisciplinary research expertise, engineers, public and private sector partners, fledgling businesses, and business development professionals), the GII will both anchor and nurture the creation of a Global Innovation Quarter in Belfast, comprising a community of businesses linked by a common digital innovation thread.

AMIC: This £87M project will be the springboard for innovation in manufacturing in Northern Ireland which accounts for 11% of total employment and more than 15% of GVA. The Centre will be a partnership between industry, universities and government, and will be primarily focused on working with companies based in advanced manufacturing and materials engineering. The sector has annual sales of £7.2B, employs 45,000 staff and invests more than £200m annually in R&D. AMIC will establish a new state of the art facility, the Factory of the Future, by incorporating three existing innovation focused units: (1) the Northern Ireland Technology Centre, (2) the Polymer Processing Research Centre, and (3) Northern Ireland Advanced

Composites and Engineering. It will focus around six themes: (1) Digital and Automation; (2) Polymers Processing; (3) Composites Manufacturing; (4) Metals and Assembly; (5) Precision and Photonics; and (6) High Value Design, Verification and Prototyping. AMIC will provide a unique environment for companies to develop prototypes, scale up, and experiment with new processes, materials and smart technologies. It will encourage and foster technology pull-through from university laboratories to a pre-commercialisation scale. It will focus on industrial sector strengths and niche areas of Northern Ireland, such as polymers and composites, materials handling, aerospace defence and space, advanced construction, transport, photonics, food and drink, and pharma. As well as involvement in the Artemis Technologies project, AMIC is also a member of the £66m Strength in Places bid of Seagate, which aims to create a nano-manufacturing corridor in Northern Ireland. This bid has recently passed the outline stage.

Infrastructure for a changing environment: Major transformational, collaborative and transdisciplinary research will be undertaken with the aim to develop smart and resilient natural and built infrastructure solutions for our changing environment. Through a series of major grants, it will engage with globally leading industrial partners and asset owners to drastically reduce carbon emissions from our natural and built infrastructure, whilst also adapting to extreme weather events resulting from climate change. Transformation to net-zero carbon will be pursued through a portfolio of solutions, such as efficiencies arising from digital transformation, advanced low carbon materials, full implementation of the circular economy, effective restoration of peatlands and the development of clean marine renewables (wave, tidal, floating solar and offshore wind power). The UoA will exploit existing climate adaption strengths, including managing groundwater resources to ensure provision of potable water resources during periods of drought, mitigating the effect of extreme rainfall events and sea-level rise, and reducing negative impacts on health and wellbeing from pollution.

Creating a productive and resilient society: A good indicator of the areas of most pressing need were identified in the Industrial Challenge Fund. They include smart sustainable plastic packaging, industrial decarbonisation, Faraday battery challenge and leading-edge healthcare, all of which align with the UoA's research strengths. The UoA will look to enhance productivity by achieving sustainability through circularity of resources, through exploiting advances in industrial digitalization, and through automation to transform manufacturing processes; as well as exploring new opportunities in materials research and technology. Resilience will be ensured by the transition to low-carbon heat and by developing future transport solutions. The activities will build upon the research and development strengths of the Northern Ireland Advanced Composites and Engineering Centre, the Northern Ireland Technology Centre, the Polymer Processing Research Centre, the William Wright Technology Centre, the Queen's University Ionic Liquids Laboratory and associated Pioneer Research Programmes. A key focus will be to broaden reach in resource management, carbon capture, catalysis etc., to allow a more sophisticated multifaceted approach to be developed.

Improved health: In healthcare, we will continue to build on the strong interdisciplinary ties with the School of Pharmacy through MATCH and on the responsive work to Covid such as the software development in the successful rollout of track and trace and the asymptomatic testing in Northern Ireland. We will enhance this activity through the Health Innovation Research Alliance Northern Ireland, an alliance of universities, health organisations and other industry bodies, established to drive and support ambitious growth in Northern Ireland's Life & Health Sciences sector. It will provide clinical as well as industrial input and will engage more fruitfully with the Faculty of Medicine, Health and Life Sciences to devise innovative healthcare solutions. An additional focus will be on engineering healthier environments and technologies to improve healthcare treatment.

2. People

a) Staffing strategy and staff development within the submitted unit:

Staffing priorities within schools are determined by Heads of School (HoS) and Research Directors (DRs) as part of formal rolling three-year strategic plan, created through the assimilation and integration of annually updated inputs from each research theme. Considerable effort goes into ensuring staff engagement at all planning stages. A key, strategic goal has been in strengthening the major investments in ECIT, i-AMS, MATCH and SERC as highlighted in Figure 3. This has seen an increase in the number of staff in EEECS since REF2014 (see Table 1), particularly associated with ECIT and i-AMS. Monitoring is performed through relevant key performance indicators generated by the UoA which has an active and continuously on-going academic staff recruitment policy based on the merit principle and promoting EDI best practice.

Even though the UoA is regional, the academic staff is diverse in international make-up, with 58% from the UK, 12% from the EU, and 29% from other countries. Since REF2014, 51.8 new academic staff have been appointed, 11 academic staff have retired, 7 have taken voluntary severance and 39 have left with 5 changing contracts and 4 of them being no longer returnable. The UoA has invested in 43 ECR appointments, which has added to research-active academic base, helped in succession planning and acted to reduce overall age profile: 74% of staff are now aged 55 and below. Overall, 20 staff were promoted to senior lecturer, 11 to reader, 11 to professor and 3.2 FTE world class professor equivalent appointments created. In addition, as part of our staffing strategy, 15 staff hold visiting/adjunct Professorships. The UoA has hosted 5 Marie Curie Fellows and has seen the appointment of 12 prestigious fellowships.

	Male	Female	Total
Combined UoAs 11,12,13,14 (2014)	132 (88%)	18 (12%)	150
REF 2021 Submission	131 (83.5%)	26 (16.5%)	157

Table 3. Comparing Gender in 2014 and 2021

An improvement in gender balance has been achieved since REF2014 as indicated in Table 3. There is a clear 'strength of opportunity' for all and we highlight a number of notable key leadership appointments in the UoA, including both a female EEECS HoS and Regius Professor since the last REF. Diversity and inclusiveness are core activities led by the Diversity and Inclusion Team. Online Training is provided via the University website and UoA12 are a specific activities are listed below. Details of the profile of Black, Asian and Minority Ethnic (BAME) and disabled staff are given in Tables 4 and 5 respectively.

	Count	Percentage (%)
BAME	34	21.7
Not Known	11	7.0
White	112	71.3

Table 4. Details of BAME staff (157 in total)

The UoA is represented by both technical and academic staff on the Technician Commitment Steering Group, and is committed to ensure greater visibility, recognition, career development

Unit-level environment template (REF5b)

and sustainability for our technical staff. Uniquely, through ECIT, 22 engineers are employed on industrial style contracts and are tasked for technology transfer. In 2012, in recognition of its supportive learning and development culture, the ECIT institute was the first UK University unit to be accredited with the Investors in People national standard.

	Count	Percentage (%)
No	124	79.0
Not Known	27	17.2
Yes	6	3.8

Table 5. Details of staff disability

Focus on Early Career development:

A key priority is to support and develop our ECRs. A dedicated start-up grant is provided, typically comprising PhD leverage as a springboard for independent research, with support from an experienced supervisor. All new staff are assigned an independent mentor and all female staff are offered Queen's Gender Initiative mentoring from outside of the School, as part of Athena SWAN. A dedicated budget for ECR development supports networking events, the organisation of upskilling and training events and provision of 'proof of concept' grants to support more ambitious research proposals. These funds are assigned to ensure capacity building and create sustainable career paths.

The UoA supports over 300 members of research staff and has a Postdoctoral Research Fellow forum which has dedicated events to support careers such as our annual conference, industry liaison workshop, Postdoctoral Research Fellow appreciation week including prizes. The UoA has set up peer reviewer and review panels. All our research staff are members of the Faculty Postdoc society, which aims to:

- Increase integration of research staff into UoA life;
- Help research staff, particularly those new to Belfast, to get to know other researchers;
- Increase the voice and visibility of research staff;
- Provide greater opportunities for interactions, discussion and dissemination of ideas and collaborations;
- Provide valuable social and networking opportunities.

All postdoctoral staff get 10 development days which can include experience of building up a career outside academia. The UoA has adopted a Postdoctoral Development Centre model which provides discipline-specific advice and guidance, promotes a positive culture, and facilitates a community for all researchers.

The UoA hosts twelve externally secured prestigious Fellowships which benefit from membership of the University's new 'Fellowship Academy'. It provides professional and career development support for both research fellows recruited through the University's 'Illuminate' scheme and staff holding high profile, externally funded fellowships. All, 3-year externally funded, independent Fellows, new and existing, receive enhanced benefits in line with the 'Illuminate' Scheme: starting salary at AC3; track to a permanent academic post, lecturer at year 3 and senior lecturer at year 5, subject to meeting the relevant criteria and; a PhD studentship (if not available through their Fellowship).

Significant funding in the £1M Global Challenge Research Fund (GCRF) is provided by the Department for the Economy, enabling ambitious projects at the UoA (e.g. Newton, UKRI). A portion of this has been ring-fenced for ECRs to allow funding of pilot projects and/or networking events with collaborators in development assistance countries.

Staff development:

All academic staff undergo annual appraisal using a recently revised Personal Development Review, undertaken by a reviewer identified by the Head of School. It focuses on career development and provides support and guidance for research strategies and opportunities in funding, multidisciplinary research, publication opportunities, and leadership/management training. It is a forum to discuss readiness for promotion. A recently reviewed academic workload allocation model is used to ensure a fair administrative and teaching load allowing all research active staff to have sufficient time allocation for research. Staff can apply for sabbatical leave for either one semester or one year which is different than a leave of absence which may be funded from external sources.

Staff can access an extensive training programme which is integrated between the Schools and the University, encompassing the Postgraduate Certificate in Higher Education Teaching and a wide range of courses, including supervising research students, report writing, grant/fellowship applications, leadership training, intellectual property, entrepreneurship and career development. The Schools provide subject specific training (either in house or via external bodies) in health and safety, instrumentation, analysis of data and technique specific courses. Of particular note is the bespoke leadership development course developed for senior lecturers, readers and chairs.

Early career staff undergo a 3-year probation, with associated support. A senior academic mentor and a committee (comprising of the HoS, a designated mentor and the relevant Directors of Research and Education) reviews progress against an agreed development plan and provides advice and guidance on grant applications, publications, funding possibilities, teaching methods, research directions and appropriate training and development opportunities. All grant applications are reviewed by at least two senior colleagues. Probationers have reduced teaching loads starting at 33% and reaching 100% after 3 years with no large administrative duties. Mandatory training, including PhD supervision and the Postgraduate Certificate in Higher Education Teaching, is an integral part of probation. There is a startup package for early career staffs usually involving receipt of a PhD studentship and start-up funding of up to £30K.

All staff can bid for UoA equipment funding. University equipment funding is also available, with priority traditionally given to collaborative bids. Most analytical services are *gratis*. The UoA is supported with studentships from the budget provided by DfE and can be bid for via a research proposal mechanism based on scientific merit. Partial funding of studentships is available to encourage interaction with industry with some available via a QUB wide competitive process, including those specifically ring-fenced for interdisciplinary research. Additional opportunities include 45 studentships via the Leverhulme Interdisciplinary Networks on Cybersecurity and Society and Algorithmic Solutions, 20 via the Collaboration in Training and Innovation for Growing, Evolving and Networked Societies COFUND Doctoral Training Programme, and 5 per annum to NBE staff from the QUADRAT programme. All studentships come with consumables funding. A central university conference fund enables inter-institutional networking.

There is a vibrant and extensive seminar programme of international speakers that acts to keep staff keenly abreast of recent developments and knowledge (both within their specialist area, and more broadly, from cogent disciplines). Staff can benefit from the Leadership and Management Framework, a tool co-created by academics and professional services staff, which offers support staff at the UoA access to best practice leadership strategies.

b) Support mechanisms for, and evidence of the training and supervision of, PGR students:

A dedicated Admissions Team in the UoA supports PGR development. All PGR students are assigned at least two supervisors and, through the student information system lifecycle platform, training events and meetings are formally logged. Our Graduate School has been ranked 'Best Postgraduate Student Experience Initiative' in the 2020 UK-wide 'Find a University's Postgrad Awards', providing both specialist disciplinary study and high-level, transdisciplinary skills training.

Each School has a Postgraduate Research Director who chairs the School Postgraduate Research Committee and is responsible for Continuous Action for Programme Enhancement, which forms the basis of each School PGR Action Plan (which in turn feeds into the Faculty PGR Action Plan). This ensures a highly creative and supportive environment for our PGR students.

Table 6 has been created using the information only available in 2019 and 2020; and gives some details of progress. With regard to Covid-19, PhD students reporting a negative impact on their work ranged from 14% of the cohort in EEECS through to 66% in CCE.

	2019	2020
Pass/referral/fail	47/2/0	51/2/0
Pass/deferred or fail of differentiation within 1 year	48/3	69/3

Table 6. PhD progression details for 2019/2020

The externally funded doctoral initiatives (QUADRAT, REMEDIATE, COFUND), the Leverhulme Interdisciplinary Networks and the Bryden Centre provide students with access to world-class bespoke training, to extensive networks, to specifically summer schools (REMEDiate) and to specialist field courses (QUADRAT). In addition, industry sponsored PhDs have allowed us to provide timely and innovative research-led solutions to industrial challenges, whilst simultaneously training PGR students to be industry ready.

The types of support mechanisms in place to support PGR training include:

- A range of university training courses including; theoretical development, research design, data analysis and presentation, and write up.
- Induction events where the chair of the School Postgraduate Research Committee outlines its purpose, training courses available, the role of supervisors and periodic reviews.
- A range of individual schools' activities including:
 - an annual Research Day enabling all PhDs to present their work and receive constructive feedback (**NBE, CCE**);
 - a 3 minute thesis competition and chance to present in the Sir Bernard Crossland Symposium (**MAE**) or to go on to the National 3MT competition (**CCE**);
 - a PhD Teaching Apprenticeship Programme giving PhD students valuable mentoring support and teaching experience (**EEECS**);
 - a 3-year **PhD Structured Development Plan** providing specific technical and employability skills development (**EEECS**);
 - Careers workshops with guest panellists from both Industry and academic pathways at which advice is given on career development and opportunities (**CCE**).
- Research seminars where high-profile external speakers present their work, giving our PhD students access to the leading new developments in their field.

Unit-level environment template (REF5b)

The types of support mechanisms in place to support PGR supervision include:

- Allocation of two supervisors and an academic panel (involving an independent chair and expert) who monitor progress.
- Initial review within three months involving assessment of the initial idea and the merit of the PhD.
- Differentiation at nine months assessing student's idea and theoretical development, and initial research design. The result determines progression in their PhD.
- The Annual Progress Review (every April/May) assesses ongoing theoretical development, methodological positioning, conduct of fieldwork, analysis of findings, chapter completions and contribution to knowledge and supervision level.

In addition to the university's extra funding for research, utilisation of the furlough scheme and generic 3 month contract extensions provided last Summer, the Faculty has developed a broad range of support activities available to the UoA. These include a cross-faculty mental health initiative providing access to clinical support for mental wellbeing (informed by the Clinical Psychology team alongside the Students Union and PGR representatives), fitness activities, and social/wellness events, e.g. pet shows, bake-offs. More recently, the UoA has benefitted from Faculty Staff and Student Wellbeing Strategy, which has established a Mental Health Ambassadors Programme, involving 24 staff and students receiving training from Action Mental Health, EPS Wellbeing Lecture Series, and input from three new wellbeing pillar groups (focussing on social, physical and psychological issues).

c) Evidence of how the submitting unit supports and promotes equality and diversity.

The UoA is strongly committed to equality of opportunity and to creating and sustaining an environment that values and celebrates diversity as set out in its EDI Policy. With the university nationally recognised, **EEECS**, **MAE** and **CCE** hold Silver SWAN awards, thus representing one of the strongest engineering returns in the UK. This Award requires all staff to complete an e-learning equality and diversity training programme ("Think difference, Act differently"). Through its gender initiative, the University has actively sought to improve the working experience of women. All staff must take the "DiversityNow" online training, which raises staff awareness across a range of equality and diversity issues. Women are visible in all promotional material. Career development information is widely distributed to staff, and promotion panels have representation from across the University, ensuring a fair process.

Since 2015, the UoA has led the EPSRC-funded SENSE Network partnership on 'Inclusion Matters' with the universities of Warwick and Glasgow. The mission is to improve Schools through connecting people to support collegiality, equality and inclusion, understand the attitudes of academics towards gender equality initiatives and build training tools aimed at improving their perception in engineering and physical sciences.

Events attended by UoA staff and postgraduate students include:

- Unconscious Bias workshops
- Parental Leave workshop
- 'Understanding Imposter syndrome' workshop
- 'How an 'All in' approach can revolutionise workplace culture' course by Josh Levs, a leading global expert on issues facing modern fathers in the workplace
- School Family Fun Days, e.g. summer barbecues, Christmas events, where staff are invited to bring along family and friends
- Week of 'Celebrating EDI' events e.g. lunches serving International cuisine with the university's Great Hall decorated with flags from various countries.
- International Women's Day Charity Events with invited speakers (e.g. WaterAid)

In addition to organizing events, the SENSE working group is currently establishing the following:

- **An Academic Apprenticeship Programme** for contract research staff planning to pursue an academic career, providing a valuable teaching experience with one month of

Unit-level environment template (REF5b)

funding. It now includes teacher training, academic mentoring, associate membership of the Higher Education Academy and a CV clinic. Formal evaluation from both researchers and academic mentors is provided on completion, resulting in 11 research staff being appointed into academic roles since its introduction (4 female/7 male).

- **A Promotion Ready Process** providing applicants with feedback and mentors to help strengthen their applications. In EEECS, the impact has been that 16 members of staff have been promoted (3 female /13 male) including one female to Professor (from SL) and two to Senior Lecturer, a success rate of 94% since 2017.
- **Gender Bias Language sessions** exploring language in STEM further education, including course descriptions, brochures, course materials and spoken language and helps users to spot language issues and, crucially, how to use more inclusive language.
- **A Women's Leadership programme** upskilling our female staff and students with the knowledge and behaviours, necessary to confidently and successfully navigate their future leadership journey.
- **An Advanced HE Aurora leadership development programme** supporting mid-career women with the potential to progress into more senior roles.
- **Safe Harbours** to allow staff to raise concerns about their work environment **outside of the existing line-management structure.**
- **Invited talks from Industry to learn from Best in Class organisations about the work they are doing with regards to Equality Diversity and Inclusion.**

SENSE also works closely with the Economic Strategy Branch within the Northern Ireland Department for the Economy, the Equality Commission Northern Ireland (ECNI) and Diversity Mark NI to champion gender balance in STEM.

Other SWAN activities include sponsorship for academic staff/PhD researchers to attend the Women and Leadership at the Changing World Conference, the week-long Women's Leadership Conference and the prestigious Space Camp. Funded events include the SWAN sponsored breakfasts and a public panel talk about the Irish aviation pioneer Lilian Bland. In some schools, there is an annual Careers Workshop for postgraduate students and a postgraduate Mentoring Scheme. Guidelines for embedding diversity into lectures has been given, as well as information concerning unconscious bias. The UoA has secured a relationship with AESSEAL, who have gifted a £50k, 2-year grant for activities supporting women in STEM.

The retention and promotion of academics and researchers, and in particular female staff, is critical. Flexible working patterns are promoted and our workload allocation model ensures that research is not swamped by an uneven balance with respect to administration/teaching. The returner's policy for maternity or adoption leave and flexible working policies exist; this latter initiative has led to an increased number of male staff taking paternity and other leave, enhancing morale. We make significant efforts to accommodate all working patterns when arranging meetings. EDI activities are now classed within the workload allocation model, to recognise their importance and their positive influence on all aspects of school life. We regularly promote our family friendly policies, both in encouraging health and wellbeing at work and also to promote a healthy balance of home and work commitments.

3. Income, infrastructure and facilities

a) Income

The restructuring of the UoA and investment in the Global Research Institute and Pioneer Research Programmes have enabled us to build critical mass in the strategic areas highlighted in section 1 and, through building on the collective strengths of the staff, to increase and sustain a diversified funding portfolio. During the assessment period, the UoA has increased its proportionated external award income from £12.6M p/a in 2014 to £18.3M p/a in 2020. As can be seen from Figure 4, the UoA has sustained an average growth of 6.6% p/a in annual research income (spend) over the assessment period. As shown in Figure 5, the Unit has maintained a

Unit-level environment template (REF5b)

diverse source of research income, strengthening the vitality and sustainability of our research portfolio.

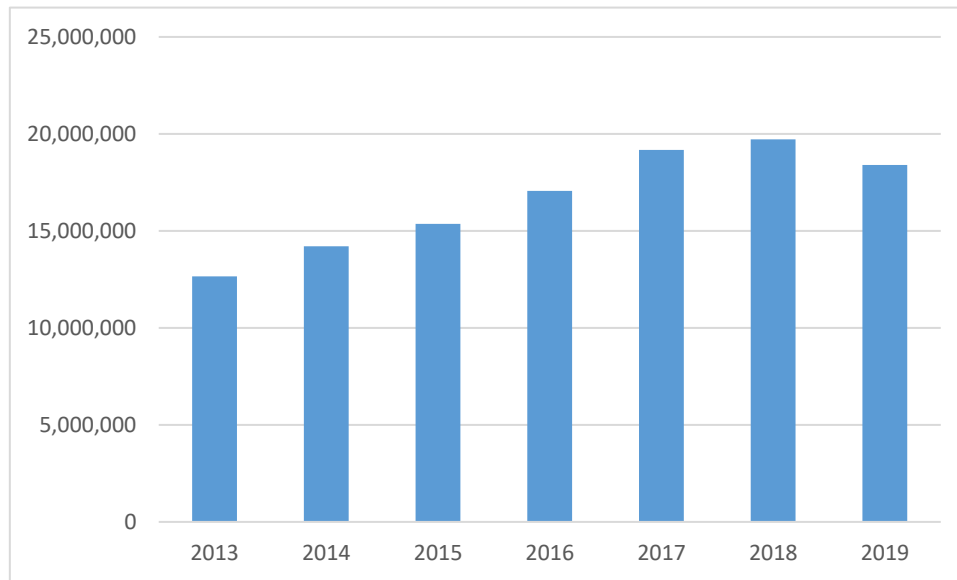


Figure 4. Annual research income spent (2019 figure looks smaller due to major grant achievement in earlier year)

The UoA has aimed to develop a portfolio of grants concentrating on large multidisciplinary projects, support and mentor young staff in applying for research fellowships. The result has been the award of 12 research fellowship with a combined income of over £4M including 2 Research Chair/Senior Research (**Duong, Falzon**), a Royal Newton International and RAEng Chair (**Duong**), a UKRI Future Leader (**Ng**), 5 Royal Academy of Engineering (**Almeida, Cotton, Lydon, Moura, Simmons**), a Leverhulme Trust Research Leadership (**Yurduseven**), a Leverhulme Trust (**Matthiou**) and a NERC award (**Newton**), most of whom have been appointed to permanent posts.

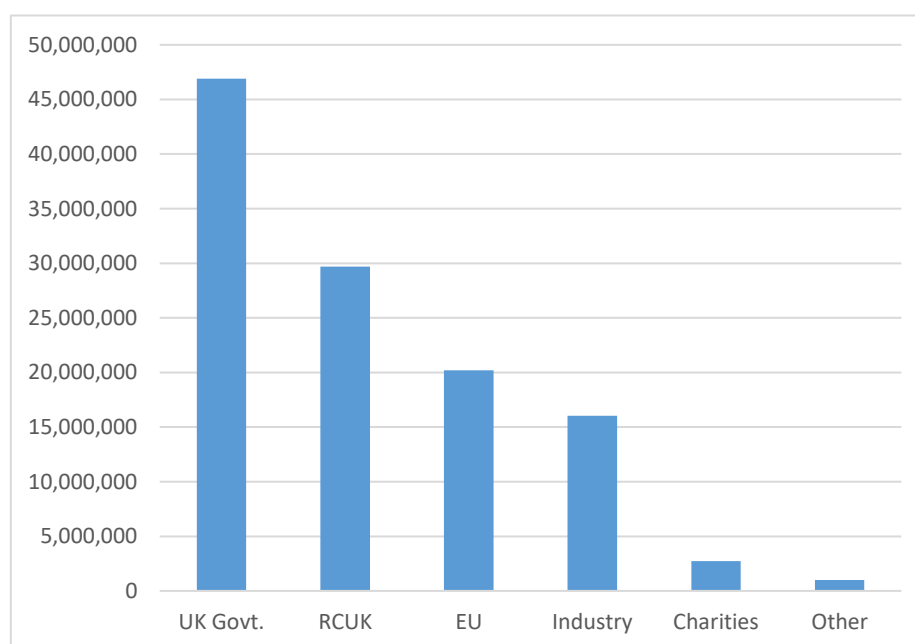


Figure 5. Research grant portfolio by source awarded during REF period.

Research grant portfolio: Many major investments have acted to strengthen the core areas:

Connectivity and cybersecurity has been strengthened through a number of strategic grants: (1) a £10M 'phase 2', Innovation and Knowledge Centre grant from EPSRC/Innovate UK/Invest Northern Ireland, allowing leveraged additional funding of around £15M; (2) a £5M EPSRC/NCSC funded Research Institute in Secure Hardware and Embedded Systems (RISE); (3) a £1.9M award as delivery partner on the £13.5m UK Government funded London Office for Rapid Cybersecurity Advancement (LORCA); (4) a £1.3M EPSRC International Centre to Centre 'Secure IoT Processor Platform' Research Collaboration with Cambridge, Bristol, Birmingham, NUS, NTU, (2019-2022); and the renewal of the Academic Centre of Excellence in Cyber Security Research. CSIT led a 4-year, €3.8M EU H2020 SAFEcrypto project in the area of post-quantum cryptography, and has participated in a number of other major projects including a €4M EC Horizon innovative training network on virtual reality audio for cyber environments (EU, €303k) and Uniserver and PRECYSE (EU, €1.25M). Industry engagements include the 2018 establishment of the £1M Keysight Technologies millimetre-wave laboratory. Global societal and economic impact is evidenced by four British Council awards totalling £571k; and a Royal Society Newton International Fellowship.

Data analytics technology: Significant research grant income includes co-ordination of the €4.8M EU H2020 Uniserver project (€1.0M), SERT (£960K), Biohaviour (£790k), GEMSCCLAIM (£350k), ENPOWER (£350k), and HPDCJ (£220k); as well as EPSRC grants in programming languages (£660k) and data centres (£140k). The group are also involved in a five-year EPSRC University Defence Research Collaboration Phase 3 project. DSSC was the first UK group to receive direct funding from the DSTA of Singapore - recognition of our world-leading expertise in multi-modal deep learning applied to defence. The group has undertaken a leadership role in electronic systems, an EPSRC-funded eFutures national network (£485k). An international collaboration has been established with Rice University and University College Dublin (£319k). There have been a number of collaborations: pathological cancer image analysis with Philips Digital Pathology Solutions (£298k), industry communication security with Plextek (£223k), and lip-reading aided in-car speech recognition with Liopa Ltd. (£145k).

Future transport: In its first year (2017) of operation, the William Wright Technology Centre secured £703k (£3.2M total award) through the Innovate IDP13, in conjunction with partners Wrights and Go-Ahead Group. In 2018, a further £738k (£3.99M total award) was secured through the Innovate IDP14 for new projects in ultra-low emission bus development (NextGenEV). In 2019, a £2.62M EPSRC Prosperity Partnership application was awarded with a wider remit to develop both the vehicles and the infrastructure for new zero-emissions transport. Currently, discussions are ongoing to expand the Centre with new partnerships with JCB, Translink, Graysons and other operators in UK, Hong Kong and Latin America.

Clean energy: A number of research units across the UoA are making major contributions in power systems design and renewable energy. The UoA leads the €9.3M Bryden Centre for Advanced Marine & Bio-Energy Research (EU INTERREG VA Programme, €3.9M). This Centre supports cross-border research into biomass and marine-based renewable energy sources by bridging the gap between industry research needs and academia in sustainable energy. The UoA continues to expand its world leading research on marine renewables (12 awards, £3.0M), with successful commercialisation and recent diversification into tidal current, off-shore wind and solar energy. Highlights include the deployment and operation of Aquamarine Power Ltd's full-scale Oyster Wave Energy Converter (WEC), the H2020-funded LiftWEC project (£2.8M total award), the commercially driven Tidal Turbine Testing suite of projects, MARINET 1&2 (FP7, £392K and H2020, £159k) supporting trans-national access to wave and tidal testing facilities and the QUB-led H2020 Powerkite project (€5.1M - total).

A range of power systems research has been undertaken and has strategic collaboration have been extended with AES, Statnet, SONI, EirGrid, NIE Networks and GlenDimplex, focused on the challenges of network integration of high penetration renewables and wide area. The

electricity grid on the island of Ireland is now recognized as a world class test bed. Phasor Measurements Units (PMUs) installed on 44 generation and transmission sites now facilitates innovative research on a power system operating at up to 65% non-synchronous generation. Our project with AES (Innovate UK, £364k) supported the commissioning of, what was at the time, Europe's largest grid-connected battery energy storage system (Kilroot power station). Within the Queen's University Ionic Liquids Laboratory, an academic/industry partnership with Petronas has been established to exploit QUB's lead in ionic liquid. It has been strengthened by seven new first phase, research projects with a total value of £2.4M project in March 2020 with plans for the successful projects to be funded in the second 4-5 year cycle.

Advanced manufacturing research has been enhanced by ATI, Innovate and QUB investing £7.5M in a state-of-the-art advanced manufacturing technology facility. A number of major research projects have been secured including: (1) *Autonomous marine systems* projects with Rolls-Royce: 'Machine Executable Collision Regulations for Marine Autonomous Systems' (MAXCMAS, £1.3M (£179k to QUB)) and with Artemis Technologies Ltd as part of their £33.1M Strength in Places research programme 'Decarbonisation of Maritime Transportation - A return to Commercial Sailing' (QUB, £1.5M); (2) *industrial digitilisation (I4.0) projects* 'COREF (Connected Reconfigurable Factory)', a £10.3M ATI/IUK funded project with Thales (£1.1M), 'Digitalised Surface Manufacturing', an EPSRC NetworkPlus led by the University of Manchester (£1M), the EPSRC-funded Q-PreMan project (£358k) and an Complex Vehicle Borne Systems funded by Thales (£306k) and; (3) *an £1.6M industry energy management project* on optimising energy funded by EPSRC and led by Brunel University.

Smart, sustainable and resilient infrastructure has seen an expansion in research grants and collaborative projects with industry in prefabricated energy-efficient buildings (€5M H2020 RE4; £409k to QUB), the €1.1M FP7 EiroCrete project on sustainable, low carbon, pre-cast concrete (£418k to QUB); and the £1.2M LowCoPreCon Newton project (£387k to QUB) on novel low carbon geopolymers. Over the REF period, 26 KTP projects have been successfully awarded in increasing production, reducing waste, increasing structural efficiency and enhancing durability in our built infrastructure. Intelligent civil and geotechnical infrastructure has been supported by 3 USA-Ireland projects. A key highlight has been QUB leading on a €3.7M, REMEDIATE Marie Curie ITN (£458k to QUB) for improved decision-making in contaminated land site investigation. Collaborative research teams have been established investigating infrastructure resilience and the safe use of natural aquifers for potable water provision which has resulted in EPSRC, £1.5M SALINA (£1.1M to QUB) and CACTUS (£285k).

Advanced liquid materials: Queen's University Ionic Liquids Laboratory associates 18 academic members from EPS, made up of a mixture of chemists and engineers, predominantly from CCE. Industrial members pay an annual membership fee, as well as contribute to joint projects under a range of funding mechanisms. Through ionic liquid research, the Laboratory addresses the major societal challenges: energy storage, urban mining through plastics recycling and critical metals recovery, CO₂ and biomass valorisation, as well as water purification. Over the REF period, £4.4M of funding has been secured for more than 15 different projects. The funding included a £150k BBSRC project on new Technology for the Isolation and Production of Biopolymers and Proteins, a £100k EPSRC project on Application of Zwitterionic Salts in Development of Protein-Resistant Surfaces, a £110k Invest NI project on the valorisation of CO₂, a £110k Invest NI project on plastic recycling and a £240k CASE Invest NI project on Redox Flow Batteries (involving CCE, MAE and EEECS). The largest sponsor, Petronas, has invested £13.75M since 2007, including £2.4M in 2020 – the funding that supports transition of Petronas beyond oil and gas, into a carbon-neutral future.

Advanced composites and polymers: The Polymer Processing Research Centre has actively re-focussed its core activity to emphasise research collaborations more widely in the University. Within the past year, £900k of funding has been secured through the EU Interreg Programme 'Renewable Engine', which has been used to establish a new research group in rotational moulding (1 postdoctoral researcher and 3 PhD students). On the commercial side, the centre has been successful in winning a major training contract for staff from the Omani petrochemicals

giant Orpic (Feb 2018), which will see 11 of its staff based in the UoA for up to 6 months. The first major contract of this kind for Queen's, it is planned to build on this success through wider links industry and academia in Oman and other Gulf States. The Centre has also been successful in gaining School/Faculty support for a new in-house additive manufacturing facility, designed to rapidly establish it as the leading unit for this emerging research technology.

More widely, other developments have included a number of biomedical projects including a £1.0M project as part of the £50M investment in an Engineering Centre of Excellence for Biomedical Applications; and the €3.3M EU H2020 BioImplant ITN - a European Industrial Doctorate – EID - programme providing world-class multidisciplinary skills to 12 ECRs through an integrated research and training programme in the area of bioabsorbable medical implant development.

b) Infrastructure

The UoA is based across four buildings: (1) the David Keir Building (NBE & CCE), (2) the Ashby Building (EEECS & MAE), (3) the Computer Science hub (EEECS) and (4) the ECIT Building (EEECS). The UoA has benefitted considerably from the University's £700m Capital Development Programme, including £14M to establish the architecturally iconic, world-class Computer Science hub in Belfast, which houses computing acceleration and AI research facilities.

The ECIT building houses a substantial amount of EEECS research and has seen a commitment of £11M in new staff and a new building. Since its founding in 2004, ECIT has benefitted from a £37M development (2009) and a £30M EPSRC/InnovateUK Innovation and Knowledge Centre Cybersecurity investment. ECIT currently houses 180 staff. Its approach overlays an academic research environment with an infrastructure that is more common in a high-technology company, but in a manner that neither compromises research quality nor curtails speculative "blue-sky" thinking. This involves locating engineering staff with strong industrial experience directly alongside academic researchers. These engineers support industry engagement, create "proof-of-concept" prototypes, support SMEs and facilitate new spin-out companies.

c) Facilities

The UoA led the establishment of the £5.0M, Kelvin-2 Tier-2 high performance computing centre (EPSRC, £2.1M). The platform offers 8000 Dell-based cores and 32 specialist graphics processing units with a high performance 2 Petabyte of scratch storage, interconnected via a high-speed network with low running costs. An Imaging and Patterning Centre has been established (EPSRC, £1.8M) with the School of Mathematics and Physics. This has facilitated the purchase of a £420k Nanoscribe Laser Lithography and 3D Printing System allowing structures with submicron precision to be created; and direct writing into photoresist for 2D patterning at a scale between that of conventional photolithography and e-beam lithography.

EEECS

ECIT houses a number of state-of-the-art facilities including two purpose-built anechoic chambers for far- and near-field tests and measurements. The 5 x 5 x 10m³ chamber (Figure 6), was refurbished in 2019, bringing its range of operation from 433 MHz to 50GHz. It is equipped with three MVG/Orbit positioners, allowing for Azimuth and Roll as well as transmission roll, making the chamber capable of dual linear measurement. A new, £1M, millimetre-wave research lab was opened in 2018 as part of a collaboration with Keysight Technologies, Inc. It includes a state-of-the-art N5247A PNA-X Non-Linear Vector Network Analyzer, E8361C PNA Microwave Network Analyzer with N5260A mmWave controller and a N9040B UXA Signal Analyzer; it provides unprecedented measurement and instrumentation capabilities for microwave and millimetre-wave experiments.

Unit-level environment template (REF5b)

Technologies in iAMS include next generation CNC and PKM Machining Centres, collaborative robot and AGV platforms, high precision metrology tools and laser-based fabrication, forming, and joining systems.

NBE

NBE has a number of world-class research facilities that underpin structural and environmental research projects. It has benefitted from the Central Research Infrastructure Fund and the EPSRC ECR Capital Investment Award. Two teaching laboratories are aligned to support research needs. These are in addition to the facilities listed below:

A £230K investment in the **Concrete and Heavy and Light Structures Laboratories** has offered a range of structural and environmental testing rigs, including a large Dartec 600kN capacity hydraulic actuator (with loading frame and strong floor), a small Dartec 160kN hydraulic actuator, a Zwick Universal testing machine (retrofitted with a heated test chamber and video extensometer) and a refurbished large environmental chamber; which enable structural and material testing over a wider range of temperature and humidity.

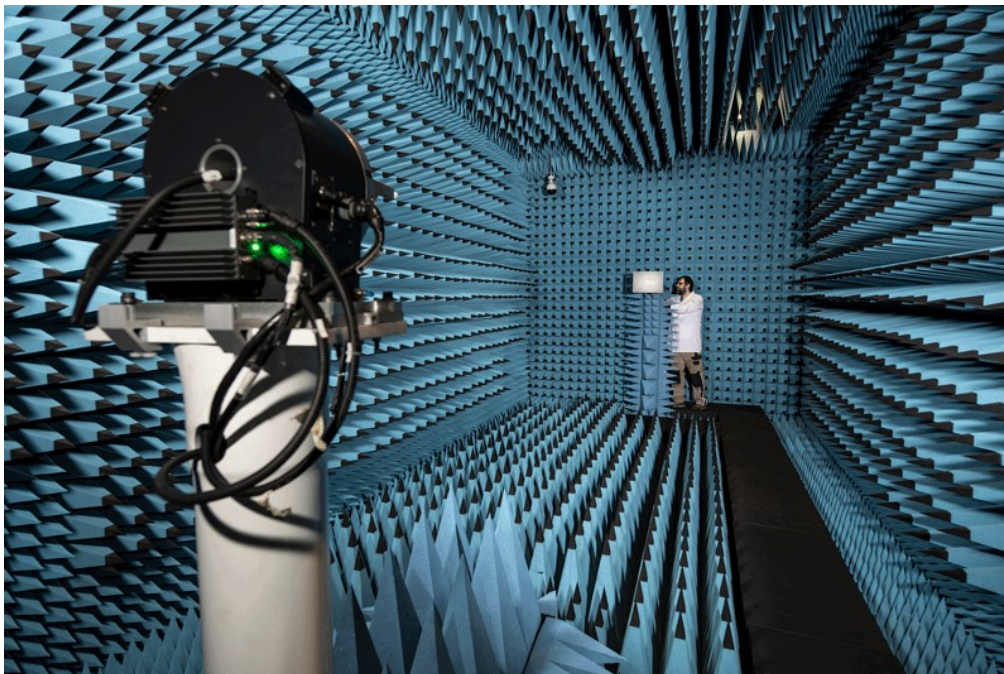


Figure 6. ECIT Anechoic chamber

The **Hydraulics Facilities** includes the **Belfast Wave Flume** basin (Figure 7) and the **Portaferry Coastal Wave Basin** (Figure 8). Both are equipped with video capture, motion tracking, load measurement and conductivity measurements. Both have adjustable tank floors for tests at various depths. They have benefitted from a £700k investment in 3D Laser Doppler Anemometry and fully submersible systems to characterize (a) water flow, (b) pressure distributions, (c) heat and (d) salinity concentration.

The **Environmental and Materials Characterisation Laboratory** provides 250m² of laboratory space equipped with an extensive range of instruments to support chemical and mineralogical analyses; whilst the **Stable Isotope Facility** specialises in analysis for environmental application.

Our **Geotechnics laboratory** contains an array of unique, bespoke, state-of-the-art apparatus and the **Rheology and Bio-based Building Materials Laboratory** contains an extensive range of equipment to test fresh properties of cement-based materials.

Unit-level environment template (REF5b)

Research is supported by extensive in-house workshops, a large mechanical production workshop and nine technicians; one of whom, Dr Mark Russell, was given the QUB Delivering Excellence Award (2018), in recognition of 20+ years of expert technical support of teaching and research.

CCE

There has been substantial strategic investment in building new state-of-the-art research laboratories for synthetic chemistry and catalysis research, with accommodation for over 50 researchers. The Queen's University Ionic Liquids Laboratory facilities and work are illustrated in Figure 9. An on-going £4M investment in research and teaching laboratory space (scheduled for completion in 2023) will significantly modernise and extend CCE's facilities. Recent added open-access equipment includes an environmental SEM facility (£400k), powder (£200k) and single crystal (£350k) X-ray diffraction equipment, a high-end confocal Raman microscope (£250k) and 400 & 600 MHz nuclear magnetic resonance spectrometer (£500k).



Figure 7. Belfast Wave Flume with an operating depth up to 0.8 m and a 6-paddles Edinburgh Design Ltd Wave Maker with active wave absorption, which can produce regular and random waves up to 0.55 m high

Further open-access Departmental facilities include: three NMR spectrometers, three mass spectrometers, an additional powder XRD, ICP-OES, BET and Hg porosimetry, a CD spectrometer and a HPLC/GC chromatography, as well as standard spectrometer and computational facilities.

An in-house team provides analytical services to internal and external stakeholders using their dedicated instrument suite. 15 technicians provide support for microanalysis, glass-blowing, mechanical engineering, electronics, computer management and laboratory safety.

MAE

New investments have occurred in key growth areas within the School, including advanced manufacture and future transport related research. Of significance, the **Advanced Composites Research Group** was created in 2013 by the Royal Academy of Engineering-Bombardier Chair in Aerospace Composites (**Falzon**). It leads the field in next generation, lightweight, smart nano-enhanced composite materials, meeting the needs of future transportation by improving performance, fuel efficiency and crashworthiness. The University has invested £1M in a state-of-the-art research laboratory (Figure 10) which boasts a research autoclave rated to 14 atmospheres pressure and 425 °C for work with both thermoset and thermoplastic composites, and facilities for synthesis and processing of high specification carbon nanotubes (CNTs).



Figure 8. Portaferry Coastal Wave Basin (18 x 16 m) with an operating depth up to 0.65 m and 24-paddles Edinburgh Design Ltd Wave Maker with active wave absorption



Figure 9. QUB/Petronas Removal of mercury from natural gas streams. Left to right: Mercury removal ionic liquid containing material; pilot plant (QUB/Petronas); Queen's University Ionic Liquids Laboratory/Petronas team in front of the newly developed Hycapture-Hg™ process at Petronas.



Figure 10. Advanced Composites Research Group facilities

Beyond this, strategic investing in polymer technologies has resulted in a fourfold increase in space with the refurbishment and equipping of a new Advanced Polymers Research Laboratory at a total cost of well over £1M. Equally importantly, the university has invested in the computing capacity and skills to establish a leading capability in design and simulation. This accommodates up to 40 postgraduates, postdoctoral assistants and academics.

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

The UoA's international perspective is reflected in the extensive range of university networks and projects, as well as a number of direct one-to-one interactions. It has deliberately focused on carefully building relationships **nationally** (through collaborative research and network grants); at a **European level** (through numerous EU grant schemes and ITNs); **with the US** (through the US-Ireland funding scheme level); and **internationally**, (through various research collaboration and GCRF schemes). Our most numerous international collaborations are given in Table 7, however we have also had projects with Brazil (4), Malaysia (1), Thailand (1) and Vietnam (6).

a) Research collaborations

Major University Networks and Projects:

Examples of some major interactions and projects include:

National:

- £5M EPSRC/NCSC-funded **Research Institute in Secure Hardware and Embedded Systems (RISE)**, which aims to improve hardware security and reduce vulnerability to cyber threats. One of four, multi-university UK cyber security institutes.
- **eFutures 2.0: Addressing Future Challenges**: an EPSRC-funded national network (£484k) led by the UoA, which acts as a focal point for the electronic systems research community, engaging academia with industry. It involves the universities of Bristol, Edinburgh, Glasgow, Imperial College, Liverpool, Manchester, Newcastle and Southampton and organises targeted seminars, joint industry events, social media interactions and funding scoping exercises for multidisciplinary/industry collaborations.
- **SPIRE** is a £1M cross-border Virtual Research Graduate School with Ulster University, University of Strathclyde and Dundalk Institute of Technology, 3 research institutes and 14 businesses; and addresses how consumer-owned energy storage can resolve the problem of the variability of renewable energy output.
- **QUADRAT** is a joint NERC-funded DTI between Aberdeen Geosciences and Biological Sciences, QUB Biological Science, and engineers and geographers from the UoA's Environmental Change and Resilience cluster. It provides 25 PhD studentships to the UoA (total funding £5M).
- The UoA is a founding member of the **UK Aerospace Research Consortium (UK-ARC)** which helps organisations engage with the UK's best aerospace research capability in its leading universities. The consortium involves the universities of Bristol, Cambridge, Cranfield, Manchester, Nottingham, Sheffield, Southampton, Strathclyde and Swansea and Imperial College London.

Unit-level environment template (REF5b)

- **SALINA** is a £1.5M QUB-led, EPSRC project with Imperial College London, Golder Associates, Ministry of Defense and Southern Water looking to develop early warning systems to protect coastal aquifers from saline intrusion.

	Number of Awards	Total Value
Germany	35	£8,556,820
Ireland	31	£13,779,201
USA	27	£5,425,140
France	17	£4,561,244
China	14	£1,114,012

Table 7. Top five countries for UoA12 collaboration

EU:

- The aforementioned €9.3M **Bryden** Centre for Advanced Marine & Bio-Energy Research into biomass and marine-based renewable energy sources, funded under the INTERREG VA Programme.
- **ICONIC**, a €3.8M Marie Curie ITN, co-ordinated by the UoA is focused on improving the crashworthiness of composite transportation structures. It is led by QUB with partners: Bombardier (UK), CRF (IT), DLR (DE), University of Limerick (IE), University of Patras (GR), RISE/SICOMP (SE), Politecnico di Torino (IT), University of Ulster (UK).
- **REMEDiate** is €3.7M, Marie Curie ITN focused on technologies to help accelerate the remediation of contaminated sites. It includes microbiologists, geochemists, numerical modellers, environmental scientists and engineers from Belfast City Council, the British Geological Survey, Copenhagen, Cranfield, Dublin City University, Duisburg Essen and partners, the Geological Survey of Ireland, the Geological Survey of Northern Ireland, Northern Ireland Environment Agency RSK, Shell Global Solutions, and Torino.
- **UniServer** was a €4.8M, Horizon 2020 project led by the UoA that facilitated the evolution of the Internet via an infrastructure where data is gathered in the Cloud to a distributed and localized manner. It brings together experts from the world's leading processor and software industry, ARM, Applied-Micro and IBM and application developers: Meritorius Sparsity and Worldsensing.
- The **RE4** EU-H2020 project (€5.1M) involved the reuse and recycling of materials and structures in energy efficient buildings and involved Acciona, CDE Global, Cetma (Italy), Fenix, Research Institutes of Sweden (Sweden), and others. The project recently won the Hans Sauer Award 2020 for research.
- **BIOIMPLANT** is a €3.3M, Marie Curie ITN focused on developing improved bioabsorbable materials for medical implant applications and involving National University of Ireland Galway, RWTH Aachen, IMDEA: Madrid Institute of Advanced Studies, Boston Scientific Ltd in Ireland, Vascular Flow Technologies Ltd., Meotec GmbH and ITA TextilTechnologieTransfer GmbH.
- **ALTPACK** is a €1.1M, European Institute of Innovation and Technology funded project "Consumer and Manufacturing Driven Alternative Packaging Solutions from Agri-Food Waste Streams" partnered with the Fraunhofer IVV Institute for Process Engineering and Packaging, ABP Food Group, Waitrose Partnership Supply Group.
- **OPRECOMP** is a €5.1M, 4-year EU2020 Program Future and Emerging Technologies (FET) proactive project which aims to build an innovative, reliable foundation for computing based on transprecision analytics. It is led by IBM Research GmbH, (Switzerland) and involves CEA (France) and ETH Zurich (Switzerland), among others.
- **LifWEC** is a €3.4M H2020 project led by QUB (£622k) alongside, Aalborg University, University College Cork, Technical University of Hamburg, Maynooth University, University of Strathclyde and industrial partners INNOSEA, LHEEA Centrale Nantes, Julia Chozas

Unit-level environment template (REF5b)

Consulting and WavEC. It aims to develop a novel wave energy converter.

- **Eirocrete** is a €1M QUB-led, Industry Academia Partnership Project (IAPP) with Azichem Ltd, Banagher Concrete, and Politecnico Di Milano, with the aim of developing sustainable, lower carbon, pre-cast concrete infrastructure.
- **APPFlow** is a €900k, Marie Skłodowska-Curie Innovative Training Network on Flow Chemistry involved in investigating active pharmaceutical ingredients using continuous flow technologies. It is a collaboration with Almac (UK) and Arran (Ireland).
- **PowerKite** was a €5.1M QUB-led Horizon 2020 project to enhance the structural and power performance of the power take-off for the Deep Green tidal energy technology. It involves AC&E Ltd, Chalmers University of Technology, Engie Lab, Midroc Project Management, Minesto AB, Moorlink Solutions AB, SSPA Sweden and UW-Elast AB.

USA:

- During the period, the UoA has engaged in over 15 **US-Ireland tri-nation collaborations**, pulling in over £4M. Each project is limited to £300k (non-FEC) and topics include: metamaterials, coastal flood management, multi-hop and millimetre-wave communications, composite materials, wind turbines, electrical generation, advanced manufacturing, bridge health monitoring, electronic devices and location-based services.
 - US universities: Alabama at Birmingham, Central Florida, Georgia Tech., Minnesota, New York, North Carolina State University, Purdue, Rice, University of Texas at Dallas, Utah, and Virginia Tech.
 - Irish universities: University College Cork, Trinity College Dublin, and University College Dublin.

International:

- **UK China Universities Consortium on Engineering Education and Research** is an initiative led by the UoA, with nine other UK Russell Group universities, and is in partnership with China's Excellence League universities. It was signed in the presence of the Chinese Vice Premier and UK Secretary of State; and is engaged in multi-disciplinary engineering research in energy, intelligent manufacturing, and knowledge transfer to industry.
- **UK-Jiangsu 20+20 World Class University Consortium** is jointly spearheaded by the British Council, Universities UK, and the Jiangsu Province (2nd in terms of GDP out of China's 23 provinces) as part of the Chinese government's 'World-Class Universities and First-Class Disciplines' initiative. The UoA was a founding member. The consortium facilitates collaborative, world-leading research in advanced manufacturing, environmental engineering and healthcare. It is supported by research studentships in both countries.
- **LowCoPreCon** is a £1.2M, Newton-Ungku Omar Coordination with the University of Malaya and Monash University Malaysia and industrial partners, Creagh Concrete, Macrete, Sunway Paving Solutions, and Ikhmas Jaya Group. It researches geopolymer concretes manufactured using novel low impact alkali activators, and the construction and environmental and socio-economic assessment of demonstration projects [in Malaysia] that use precast geopolymer concretes.
- **iGIVE** was a £1.3M EPSRC/NSFC project that created Intelligent Grid Interfaced Vehicle Eco-charging for more reliable, more flexible and more efficient smart grid solutions. It involves the Harbin Institute of Technology and State Grid Electric Power Research Institute in China.
- CSIT has strengthened its links with Korea's National AI Research Institute, **ETRI**, through a new MoU, 4 collaborative projects, workshops, exchange visits and 12-month secondments of ETRI engineers to CSIT. One £1.6M project (2016-18) involved ETRI, SecureIC (France), ICTK (S.Korea), Korea University, Purdue University (US) and CSIT. Links have been broadened to other S.Korean institutions, Kookmin University, Hanyang University and NSR (National Security Research Institute - equivalent to the UK's NCSC).
- **ECSASDPE** is a €1.6M European and Chinese partnership for Stacked Aero-Structure Drilling Process and Equipment, involving an extensive staff and student exchange between the UoA, University of Warwick, Tsinghua, Tianjin and Shanghai Jiao Tong universities.

Unit-level environment template (REF5b)

There are **several other collaborations** including: a £3M, UK-India project on valorisation of waste (Innovate UK, BBSRC, DBT); the establishment of three joint laboratories in manufacturing with Tianjin University, Chongqing University and Nanjing University of Aeronautics and Astronautics (funding from NSFC and EU ECSASDPE); a project with UniMaP and University Malaya (funded through a Newton fund Institutional Links project); a project with Tianjin Polytechnic (EPSRC first grant) and, with Shanghai Jiao Tong University (China), Ton Duc Thang University (Vietnam) and University of Peradeniya, a DfE GCRF grant.

In addition to the collaborations highlighted above, the UoA has a range of other substantive collaborations with the following institutions: American University of Beirut (Lebanon), Austrian Institute of Technology (Austria), Caltech, (USA), Duke University (USA), Duy Tan University (Vietnam), Leibniz Universitaet Hannov (Germany), Linkoping (Sweden), National Taiwan University of Science and Technology (Taiwan), Princeton (USA), RWTH Aachen (Germany), Stanford (USA), University of California in Berkeley (USA), University of Granada (Spain), University of Kraków (Poland), University of Turin (Italy), ZRS Architekten (Germany).

The UoA have contributed to the wider research base by engaging in a range of activities with professional bodies, research councils and other funding bodies. In addition, staff have contributed widely as journal editors, as conferences organizers and by delivering major invited talks.

Fellows of Engineering and Science Professional bodies includes: Royal Academy of Engineering: RAEng Fellows (**Whittaker, Fusco, O'Neill**); Irish Academy of Engineers: Fellows (**Fusco, O'Neill**); Royal Irish Academy: (**Fusco, O'Neill**); Royal Society: Short Industry Fellowship (**Varghese**); Royal Society of Chemistry (**Chen**); Royal Aeronautical Society (**Falzon, Johnson**); Royal Society of Edinburgh (**Johnson**); British Computing Society (**Johnson, Nikolopoulos**); Fellows of Engineering and Science Professional Bodies including: IEEE (**Fusco**); ICE (**Sivakumar, Whittaker**); AIAA (**Kontis**); IChemE (**Ranade**); IET (**Fusco, Woods, Nikolopoulos**); IMechE (**Kontis, Lucas, Murphy, Price**); RAeS (**Kontis**); IEI (**Taylor**); IMMM (**Sha, Chen**); INA (**Whittaker**); FIMarEST (**Karimirad**); CIHT (**Hughes**); American Concrete Institute FACI (**Sonebi**); RILEM (**Sonebi**); FMICT (**Sonebi**).

Research Council membership:

- **UKRI**: Science, Engineering and Technology Board (**Taylor**), UK Energy Programme Scientific Advisory Committee (**Robertson**), SAT on Manufacturing the Future (**Price**, Chair), SAT on Information and Communication Technology (**Woods, Johnson**), Research Infrastructure (**Nikolopoulos**).
- **EU**: REA Funding review Panel for Individual Marie Curie Actions programme (**Manyar**); European Science Foundation College of Review Panel Members (**Robertson**);

Prizes and personal fellowships:

Over the period, staff have been awarded 26 prizes and awards. Key examples include:

- UK Royal Academy of Engineering Silver Medal (**O'Neill**, 2014);
- Royal Society Wolfson Research Merit Award (**Nikolopoulos**, 2015);
- Royal Irish Academy Gold Medal for Engineering Sciences (**Fusco**, 2019);
- Royal Academy of Engineering – Bombardier Chair in Aerospace Composites (**Falzon**, 2013-2017);
- Distinguished Member of the ACM -Association for Computing Machinery (**Nikolopoulos**, 2018);
- Newton Prize, RAEng Chair (**Duong**, 2017);
- Leverhulme Trust Research Leadership Award (**Yurduseven**, 2020).

Plenary and keynote lectures (selection):

Several hundred staff in the UoA have engaged in a wide range of invited talks at universities and industry over the REF period. In all, 12 plenaries and keynote lectures have also been delivered. Examples include:

Unit-level environment template (REF5b)

- 2nd International Conference on Ionic Liquids in Separation & Purification (**Atkins**, 2014); International Conference at Advanced Fibres and Polymer Materials (**Chen**, 2019);
- 7th International Conference on Smart Materials and Nanotechnology in Engineering, China (**Falzon**, 2019);
- 2nd International Conference on Emerging Trends in Engineering, Sciences and Technology (**Naeem**, 2017);
- Royal Irish Academy Discourse, Royal Irish Academy, Dublin (**O'Neill**, 2018);
- UK Royal Academy of Engineering AGM (**O'Neill**, 2014);
- Asia Pacific Catalysis Conference (**Ranade**, 2017);
- 5th European Conference on Environmental Applications of Advanced Oxidation Processes, Czech Republic (**Robertson**, 2017);

Conference Chairs (selection): International Conference on Ionic Liquids in Separation & Purification (**Atkins**); Asilomar IEEE Conference on Signals, Systems, and Computer (**Woods**); CFD Symposium at World Congress of Chemical Engineering (**Ranade**); International Conference On Manufacturing Research (**Price**); EU-US Frontiers of Engineering Symposium, Seattle, USA (**Falzon**); International Conference on Body Area Networks (**Cotton**); IEEE International Conference on Computing, Management and Telecommunications (**Duong**); Intelligent Computing for Sustainable Energy and Environment (**McLoone**); IEEE International Conference on Cluster Computing (**Nikolopoulos**); International Conference on Advanced Composite in Construction (**Taylor**); International Conference on Bio-Based Building Materials (**Sonebi**); International Conference on Unsaturated Soils (**Sivakumar**); International geoENV2018 Conference (**Ofterdinger**)

b) Economy

During this period, the UoA has continued its strong focus on economically-driven impact as evidenced by the extremely high number of spin out companies and by major achievements in KTP projects. A key component of the Faculty's activities, ECIT, is the anchor tenant for Catalyst (the NI Science Park) which now accommodates over 150 companies. ECIT has had a major influence on acceleration of SME ecosystems in the area of cybersecurity, both in the Belfast Region (with >1700 jobs over last 10 years, resulting in NI becoming the number one region worldwide for USA FDI in cyber security); and by knowledge transfer to numerous digital technology, defence and security primes, e.g. Analog Devices, IBM, Intel, ARM, Thales, QinetiQ, BAE, Bosch; and by acting as a key delivery partner of the £13.5M UK Government funded London Office for Rapid Cyber Security Advancement alongside Plexal and Deloitte. ECIT provide academics and engineering support to cohorts of start-ups at Plexal, the innovation campus based at London's Olympic Park.

Economic interactions range from KTP projects through to major collaborations and commercialisation activities. A number of specific examples of impact for the economy include:

- Commercialisation of advanced scheduling software and engines through the spin-off EventMAP Ltd., (**McCullum, McMullan**) who apply their technology with the universities of Cambridge and Oxford, Aecom, BAE Systems, Channel 4, KBR, and Kings College Hospital Trust.
- Data analytics solutions from the spin-off Analytics Engines Ltd., (**Woods**) have been applied to investigative journalism (RTÉ), illegal dumping (Dublin City Council), financial fraud (Coriolis Technologies) and bioinformatics acceleration (Almac), and the heritage sector (The National Gallery, London).
- Unique stretch blow moulding technology commercialized through Blow Moulding Technologies (**Menary**) has been used by Coca Cola, Pepsi, Unilever, Kraft, Procter and Gamble and Nestlé, resulting in the creation of innovative, lightweight bottle designs, and introduction of new bio-based materials into bottle packaging, saving millions of pounds and reducing greenhouse gas emissions.
- Novel algorithms for accelerating network security processing and high-speed IP flow classification (**Sezer**) has been used by for Netronome's in their next generation of flow

Unit-level environment template (REF5b)

processors, leading to an increased turnover of over £80M per annum and resulting in an exemplar University/Industry research partnership in which they have invested \$2M.

- Numerous research projects with Acheston and Clover, Banagher Concrete (RoI), BanahUK, Bullivant, Creagh, FP McCann, Macrete, Moore Concrete, Quinn Building Products, and Tracey Concrete (**Taylor, Nanukuttan, Sonebi, McPolin and Soutsos**), have targeted resource efficiency, performance prediction, rheology and textures in concrete technology, which has allowed these companies to sustain their position as market leaders (close to 50% of the precast concrete supply for UK is provided by companies based in the region).
- Face recognition software developed in the University (**Robertson**) and commercialised through AnyVision has resulted in the first commercial deployment face recognition software in Europe's third largest airport, Schipol, with 200,000+ people passing through every day.
- Commercialisation of a hardware accelerated regex processor (RXP) based on the university research (**Sezer**) has been licensed to major security solution providers, including Cisco, Looking Glass, Trent Micro, Silicom, Valtix, and through TitanIC to Mellanox and Cavium/Marvell, who together supply ~50% of the Cloud Network Interface Controllers.
- Research into massive MIMO (**Matthaiou**) has had transformative, global engineering and commercial impact. It has changed the research agenda within Nokia Bell Labs and Ericsson, resulting in significant investment into R&D programmes by these two leading 5G telecoms vendors, and resulted in commercial gains through new technological product developments.
- Collaborative project with ETRI on monitoring and deriving telemetry features for Malware threats (**Sezer**), leading to a joint outcome which was successfully licensed to Anhlab, one of Korea's largest security companies.
- Thermal fatigue modelling, start-up cycle optimisation and runner optimization research has led to significant £1M annual savings per year (in terms of raw materials and energy usage) for Ryobi UK.
- A series of tidal energy projects have brought research to realisation through collaborations with industrial partners: CNR-INM (formerly INSEAN), Italy, Ocean Flow Energy and ORE Catapult, UK, Schottel Hydro, and Sustainable Marine Energy. Continuation of the MARINET 1 and MARINET 2 projects, supporting a European trans-national access network to wave and tidal testing facilities, saw five commercial companies test and develop their technology in the UoA's wave tank facilities and at its tidal energy test site.

The UoA has extensive links and major grants with a wide range of industrial partners, ensuring wide applicability of our research and often creating an enhanced research base within these companies. The companies have included Airbus UK, Allstate, Analog Devices, Aptar, Astra Zeneca, BAE Systems (UK), BP, Catena, Citi, Dell-EMC (Ireland), Eastman Chemicals, Eli-Lilly, ExxonMobil, Petronas, Schell, Chevron, European Space Agency, Ferrari, Ford, GSK, Huawei (China), IBM (UK), Infineon Technologies, Infosys (UK), Intel, Invista, Johnson Matthey, Merck, National Instrument, Nokia Bell labs (USA), Pacific Northwest National Lab (USA), Proctor & Gamble, RAL Space, Rolls Royce, Solvay, Sumitomo Electric Europe, Tata Steel, Tica Denmark, Toyota, UK Centre for Earth Observation, UNESCO, UN Office for Disaster Risk Reduction, Umicore, Unilever, Xilinx. These collaborations have been crucial in identifying challenging scientific problems that have the potential to lead to commercial outputs. Efforts here have resulted in more than 15 patents.

c) Society

A key focus of the UoA's contribution in addressing societal issues is a direct output from the research in the core areas as identified below:

Connectivity and cybersecurity:

- Membership of AI Council (**O'Neill**) an independent expert committee created to help boost growth of AI in the UK, promote its adoption and ethical use in businesses and organisations across the country.

Unit-level environment template (REF5b)

- Creation of the annual Cyber Security Summit (**O'Neill, Sezer**) in Belfast, brings together the international research community alongside industry leaders, government policy makers, start-ups and SMEs from around the world;
- CSIT's co-authoring of the Department for Digital, Culture, Media & Sport's 2020 report on Cyber Security Sectoral Analysis, which provides an update on the status of the sector at the midpoint of the Government's Cyber Security Strategy.

Smart, sustainable and resilient infrastructure:

- The development of a catastrophe-tolerant, communications network (**Trung**) has provided seamless connectivity for relief authorities and workers. It has been incorporated by Vietnam Disaster Management Authority into their national disaster response plans and has played a vital role in the evacuation and rescue of 5,000 people in DaNang city.
- Lack of effective bridge monitoring has led to a £6.7bn backlog of bridge maintenance works. **Taylor** has led to the world's first, fibre optic Bridge Weigh-in-Motion system to extend bridge life which is now operational on the A1 in Northern Ireland.
- **Flynn**'s peatland hydrological model has directly underpinned the Irish Government's policy for the conservation and restoration of bogs; and its application successfully prevented the imposition of annual EUR 9 Million in fines.
- Millions currently living in the US and UK with a hip or knee replacement are now tested with methods developed at QUB (**Buchanan**). Beyond economic benefits, this has impacted on quality of life, with longer lasting hip and knee joints and a reduced need for revision surgery, resulting in an estimated annual savings of £1.4 Billion.
- The vWa project (**Ranade**) is focused on valorising waste from sugar cane industries in India by transforming these into transportation fuels, reducing 115MT of biomass waste and generating employment in rural India.

In addition, other UoA contributions include: Dr Myra **Lydon's** appearances as one of ICEs Invisible Superheroes as 'Dr Sensora' in Belfast City airport, and in a BBC programme on Civil Engineering; a TV feature on Louise **Kregting's** marine renewables in the BBC 'Our Coast' Series 1:3 and BBC 'Tides' programmes; board membership of the UK's leading independent Campaign for Science and Engineering (**Price**) providing a voice at government level to influence policy making; Chair of the IET Engineering Policy Group for Northern Ireland (**Woods**) which acts as a two-way link between the engineering profession and Government; engagement in international standards and bodies, e.g. RILEM Technical and American Concrete Institute Committees (**Sonebi**); the Ireland Environmental Protection Agency (**Ofterdinger and Flynn**); the International Atomic Energy Agency (**Elliot**).