Institution: University of Warwick

Unit of Assessment: B12 Engineering

1. Unit context and structure, research and impact strategy

1.1 Unit Context and Structure

The Unit comprises research by the School of Engineering (SoE) and Warwick Manufacturing Group (WMG), including closely connected research in the Department of Physics (3 FTE). The SoE and WMG are two departments of ten in the Faculty of Science, Engineering and Medicine (FSEM), chaired by the Unit's Meyer. The SoE is a General Engineering School with an undergraduate teaching and research portfolio; WMG is an industry-facing research and innovation department with significant engagement with public bodies and postgraduate training. Warwick is consistently ranked in the top ten in all major UK league tables for general engineering and 5th in *The Guardian* (2021). The Unit's research income in 2019-20 comprises 49% of the University's total, contributing to the University's ranking of 62nd in the research-dominated *QS World University Rankings 2020 (REF5a-1.1)*.

The SoE is an integrated School, in which engineering disciplines are co-located, comprising: 78 Category A staff, 20 teaching-focused staff, 36 technicians (including 3 apprentices), 33 administrative staff, 58 postdoctoral researchers and 200 postgraduate research (PGR) students. Management is organised through Discipline Streams: Civil and Environmental (C&E); Electrical and Electronic (E&E); Mechanical and Process (M&P); and Systems and Information (S&I). Research is organised through 12 groups: C&E; Ground Engineering; Structural Engineering; Water Engineering; E&E; Connected Systems; Electrical Power; Sensors & Devices; M&P; Fluid Dynamics and Multiscale Modelling; Measurement and Machines; Reaction and Materials Engineering; Sustainable Thermal Energy Technologies; S&I; Biomedical and Biological Systems; Information Engineering; Systems Modelling and Control. These contribute to progressing research in application-orientated Themes (Figure 1). Since REF2014 specific research groupings have been modified to reflect growth and evolution of capability. Compared to REF2014, the School has 15 more Category A staff, and 80 more PGR students.

WMG is the University's largest multi-disciplinary department. It comprises: 57 Category A staff, 147 engineers, 50 technicians (including 11 apprentices), 133 teaching-focused staff, 126 research-focused staff, 163 professional services staff, 111 clerical/facilities staff and 250 PGR students. Professional services staff core to research include 23 project managers and a 38 strong SME team. Research and management is organised through five Directorates: Digital Technologies; Energy; Intelligent Vehicles (IV); Materials & Manufacturing; and Organisational & Societal Transformation (OST). The structure has evolved since REF2014 to reflect growth, particularly in energy and IV research, alignment to the Industrial Strategy and, through OST, the importance of circular economy and productivity research. Cross-cutting platforms include the WMG centre High Value Manufacturing (HVM) Catapult, Institute for Digital Healthcare (IDH) and Supply Chains in Practice, which enable application across themes (Figure 1). WMG is one of seven organisations that formed the first Catapult centre, in HVM (2011); WMG's focus to enable cleaner, safer and more effective transportation. Compared to REF2014, WMG has 29 more Category A staff and 106 more PGR students.

1.2 Achievement of Strategic Goals in REF 2014

The Unit's REF 2014 submission presented a Strategic Plan that has been delivered; enabling the departments to work closely and collaboratively. The achievement of the 2014 plan is discussed below:

- *Major themes will be further enhanced* – Achieved through growth in each theme and identification of two new themes (§1.4);
- *Biomedical engineering will form closer working links with IDH and Warwick Medical School (WMS)* – Achieved *inter alia* through creation of the University's Biomedical Engineering Institute (§1.4.2);
- *Further academic posts in energy, chemical engineering and systems biology* – Achieved with new posts in energy (15), chemical engineering (5) and systems biology (2);
- *Increase industrial income to 20% of research grant income* – Achieved with an annual increase between 22 and 30% in all but 2020, when industry funding reduced 6% reflecting COVID-19 impact (*REF4b*);
- *New £3M research exchange to provide 1000m^2 to house cross faculty interdisciplinary research* – Achieved through Advanced Manufacturing and Materials Centre (AMMC) building (2016 – 1,575m^2) and Materials Engineering Centre building (MEC - 2018 – 3,050m^2) (§3.2);
- *Sustainable steel technology group will be created* – Achieved and currently comprises five academic staff and 37 research fellows/postdoctoral researchers;
- *Creation of an automotive composites research centre* – Achieved with compounding, moulding and forming facilities in the MEC;
- *In 2014, new International Institute for Nanocomposites Manufacturing will be opened* – Achieved with research infrastructure located in a new 1,040m^2 building;
- *In 2014, UK Energy Storage R&D Centre will be completed* – Achieved and significantly expanded through subsequent investment (§1.4.1);
- *Jaguar Land Rover (JLR) sponsored appointment in Advanced Propulsion* – Achieved with JLR Chair created and appointed to;
- *Academic resourcing supporting IDH will be strengthened* – Achieved and now involves eight academics across WMG and wider University;
- *New appointments in business transformation and cybersecurity* – Achieved with new academic posts in business transformation (5) and cybersecurity (3) and reinforced through creation of WMG's OST Directorate;
- *HVM Catapult, work to identify and exploit cross-sector opportunities* – Achieved *inter alia* through exploitation of electrification capability developed with the automotive sector in broader sectors;
- *Development of National Automotive Innovation Centre (NAIC) to create tailored collaborative research space* – Achieved with 33,000m^2 research environment opened in 2020 (§1.4.4).

1.3 Research & Impact Strategy

Continuing from REF2014, this has four Strategic Pillars, to:

A. Build and maintain critical mass in areas of global importance to make fundamental and applied research contributions of major international significance;
B. Nurture and develop the next generation of engineers and scientists, steeped in interdisciplinarity and innovation, and attuned to collaborating with and impacting on industry;

C. Build and maintain partnerships with industry and external stakeholders, facilitating fast routes to substantive and tangible impact;
D. Build and maintain interdisciplinary, collaborative networks and partnerships within and beyond the University and UK.

These align with and enable the institutional strategy *Excellence with Purpose* (*REF5a-2.1*) with its vision to achieve a 40% growth in STEM at Warwick, and support six of the nine institutional research themes (*REF5a-2.3*). Achievements in progressing the Strategic Pillars in Critical Mass (A) are described, by theme, in §1.4; and Next Generation of Engineers and Scientists (B) in §1.4 and §4.7. Partnerships with Industry & External Stakeholders (C) are discussed in §4.1 and Collaborative Networks (D) in §4.3.

Curiosity-led research is encouraged and enabled, supported by the University's 75-strong Research and Impact Services (R&IS) (REF5a-1.7). Networking activities, including those through the University's Global Research Priorities (GRP – *REF5a-2.9.1*), build multi- and inter-discipline relationships, and workshops and training boost skills, particularly for Early Career Researchers (ECRs). Lockerby serves on the University's GRP Steering Group *(REF5a-2.5)*.

1.4 The Application-orientated Themes

Integral to the Unit's research & impact strategy are application-orientated themes (Figure 1), these:

- Connect fundamental and applied research to industrial partners and external stakeholders, facilitating routes to impact and maximising commercialisation opportunities;
- Foster a collaborative research environment that cuts across disciplinary boundaries;
- Exploit University networks, e.g. GRPs, to facilitate interdisciplinary collaboration and wider impact and engagement.

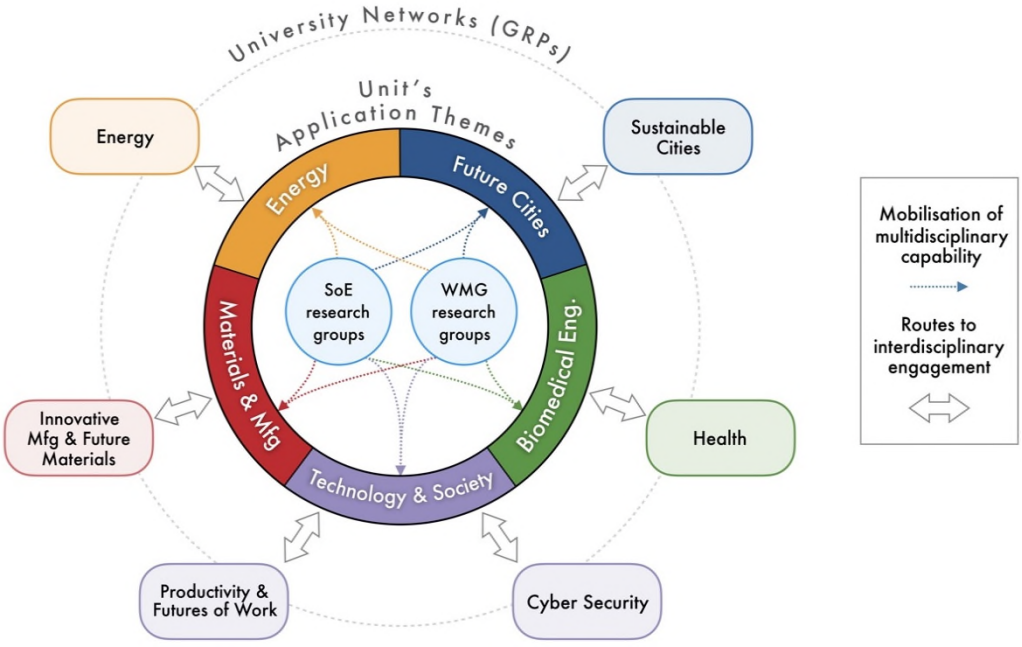

Figure 1. The Unit's themes and their connection to key University networks.

These themes enable development and delivery of major R&D projects across technology readiness levels (TRL). Monthly meetings between departmental Heads identify areas of opportunity, synergy and thematic priorities. These discussions are informed by the SoE's Management and Research Committees and by WMG's Executive, informed by its Research Executive and Advisory Boards: on Industry - Chair Richard Hill (Director Manufacturing, NatWest) and Policy – Chair Rt Hon Greg Clark MP (Chair Science and Technology Select Committee (Commons)).

In REF 2014, the Unit identified three cross-cutting research themes to facilitate interdisciplinary research – Energy, Biomedical Engineering and Sustainable Cities (now titled Future Cities). Reflecting emerging strengths and opportunities, these have been augmented by themes in Advanced Materials & Manufacturing and Technology & Society. As detailed below (§1.4.1-1.4.5), research themes have grown from strength to strength during the REF period.

1.4.1. *Energy*. Impetus discussed in REF2014 has been accelerated as the topic has assumed a global priority. Enabling activities identified in 2014 have been sustained, notably the Energy GRP, which provides effective linkages with departments including Warwick Business School (WBS) and Politics. Benefits from this include the UKRI West Midlands Regional Energy System Operator - with Coventry City Council and WBS, researching generation and storage of low-carbon energy on a city-wide scale. Over 20 academic staff are contributing directly to Energy research, particularly in Power Electronics, Battery & Storage Technologies, and Clean Energy (e.g. Thermal). The Power Electronics, Applications and Technology in Energy Research Laboratory was awarded the TechWorks University Research Group of the Year (2018). Key developments, linked to our Strategic Pillars, in the REF period include:

Strategic Pillar A – Critical Mass

- £22M Energy Research Accelerator (ERA) equipment investment (§3.2);
- £14.5M UK Research Partnership Investment Fund (UKRPIF) award to create the Advanced Propulsion Research Laboratory (APRL - §3.2);
- £130M UK Battery Industrialisation Centre (UKBIC), part of the Government's Faraday Battery Challenge (§3.4);
- £4M EPSRC Faraday Institute (FI) projects in battery degradation, and multi-scale modelling and next generation electrodes as part of the FI research community;
- £5.2M EPSRC funding to establish the Interdisciplinary Centre for Storage, Transformation and Upgrading of Thermal Energy and £2M BEIS funding to develop and commercialise technology;
- £5.4M EPSRC Programme Grant funding in Low Temperature Heat Recovery and Distribution Network Technologies.

Strategic Pillar B – Next Generation Engineers and Scientists

- Regular battery summer school for the public and private sector, including tailored programmes for all FI PhDs.

1.4.2. *Biomedical Engineering*. Over 20 academic staff conduct biomedical engineering research, including digital health, devices and sensor technology, and synthetic biology. The range spans medical imaging, gait analysis, pharmacology, neural engineering, and malaria intervention. Strength in Biomedical Engineering has grown, building on the establishment in 2010 of the IDH, in collaboration with WMS. The Unit now works with over 20 NHS Trusts, including honorary appointments with the local University Hospitals Coventry & Warwickshire

(UHCW) and University Hospitals Birmingham. The Health GRP has been in place throughout the REF period. With academic co-leadership from the Unit and WMS, it provides networks linking the Unit's research to the breadth of the University, and enables partnerships. The continued growth in activity has resulted in the creation of the University's Biomedical Engineering Institute, initiated by the Unit and announced in February 2020. Key developments include:

Strategic Pillar A – Critical Mass

- £10M UKRI investment to the Warwick Centre for Integrative Synthetic Biology (with School of Life Sciences) supported by the Synthetic Biology for Growth programme;
- Leadership of €5M Horizon 2020 project, C3-Cloud, with 11 partners in seven countries, to develop personalised care plans for complex multimorbid patients;
- Application of AI to medical challenges including brain maturation (MRC); mammography screening (CRC UK) and chest x-ray (Wellcome Trust);
- Novel interventions to mitigate tropical disease transmission include: MRC, FP7, Centre for Disease Control (US), Wellcome Trust, and Bill & Melinda Gates Foundation.

Strategic Pillar B – Next Generation Engineers and Scientists

- EPSRC/BBSRC £4.8M Centre for Doctoral Training (CDT) in Synthetic Biology in partnership with Oxford and Bristol Universities;
- Marie Curie EID: Innovative Modelling for Pharmacological Advances through Collaborative Training.

1.4.3. *Advanced Materials & Manufacturing*. Over 30 academic staff research advanced materials and/or manufacturing. Research spans steels processing, engineering alloys, polymers and polymer matrix composites, nanocomposites and ceramics, electronic materials, composites for structural engineering, catalytic materials, additive layer manufacturing, multiscale materials modelling and design, and sustainable materials/manufacturing. The scope of the GRP in Innovative Manufacturing and Future Materials, with academic co-leadership from the Unit, has broadened to include enabling research, e.g. circular economy and Industry 4.0, and application priorities, e.g. space. Key developments include:

Strategic Pillar A – Critical Mass

- £100M government investment in the HVM Catapult centre in the Unit (five years from 2018) enabling materials and manufacturing technologies for future mobility;
- £14.5M EPSRC capital funding for materials research (§3.2);
- £3.4M EPSRC Programme Grant supports Micro and Nano Flows for Engineering partnership with Edinburgh University and STFC Daresbury Laboratory. This builds on the Fluid Dynamics Research Centre, founded by SoE in 1996 to coalesce researchers across the University;
- £10M EPSRC Future Manufacturing Hub in Sustainable Steels and Manufacturing with the Universities of Swansea (lead) and Sheffield;
- £10M EPSRC National Research Facility for Lab X-ray CT led by University of Manchester;
- £9M ERC Synergy grant to study fast temperature modulations in chemical reactors to improve efficiency of current technologies utilising cold plasma;
- ERC Starter grant investigating advanced simulation design of nanostructured thermoelectric materials with enhanced power factors.

Strategic Pillar B – Next Generation Engineers and Scientists

- £3.4M EPSRC CDT in Sustainable Materials and Manufacturing, with Cranfield and Exeter Universities (§2.4);
- £5.5M EPSRC CDT in Modelling of Heterogeneous Systems, combining academics in five Warwick departments, linking High Performance Computing (HPC) and software development to applications (§2.4). It builds on the Unit's Centre for Scientific Computing (now University's Scientific Computing Research Technology Platform) and Warwick Centre for Predictive Modelling (WCPM) created with an EPSRC Strategic Grant;
- Participation and PhD supervision in the Physics department led EPSRC CDT in Diamond Science and Technology (§2.4);
- Participation and PhD supervision in the EPSRC CDT in Quantitative Non-destructive Evaluation, led by Imperial College, with Bristol, Manchester, Nottingham and Strathclyde Universities (§2.4);
- Unit PhD student (Ellingford) selected to attend 8th Global Young Scientists Summit (Singapore, 2020);
- IEEE/WMG International Summer School on Industrial Agents (2020).

1.4.4. *Future Cities*. This theme is an application focus for research in C&E Engineering, Connected Systems, and IV. It has witnessed major growth, notably in future mobility technology and infrastructure. With academic co-leadership from the Unit, the Sustainable Cities GRP provides a network of 100 researchers including economics, modern languages and life sciences, enabling research and impact on economic, environmental, social and cultural sustainability. Key developments include:

Strategic Pillar A – Critical Mass

- NAIC, a 33,000 m^2 (£103M) engineering research environment opened 2020 (§3.2);
- £2.4M EPSRC/JLR - TASCC: Secure Cloud-based Distributed Control Systems for Connected Autonomous Cars;
- 5G mm Wave Test Platform for Connected and Autonomous Vehicle (CAV) applications, setting new communications speed record for vehicle-to-vehicle communication in 2018.

Strategic Pillar B – Next Generation Engineers and Scientists

- University-funded CDT in Future Mobility, to train multidisciplinary research leaders of the future to transform the mobility of people and goods (§2.4);
- Masterclass series in Communications, Connectivity and 5G for Future Intelligent Vehicles;
- Emerging research leaders include a UKRI Future Leader Fellowship holder in CAV and a Royal Academy of Engineering (RAEng) Industrial Fellow, each with labs in NAIC.

1.4.5. *Technology and Society*. Growth in the period epitomises the broadening impact and interdisciplinary research direction; centred at the interface between technology and society. Prominent areas include: wellbeing in the workplace; Industry 4.0 and supply chain strategy; security of cyber-physical systems and Internet of Things (IoT); and influencing policy and practice through design standards. This theme is at the heart of two GRPs established in the period, Cybersecurity; and Productivity and Futures of Work. Each has academic co-leadership from the Unit and support activities including expert seminars, ECR travel funding, student internships and a postgraduate hackathon. Key developments include:

Strategic Pillar A – Critical Mass

- Selection as a UKRI Academic Centre of Excellence for Cyber Security Research, following establishment of the Cyber Security Centre in 2014;
- Leading the Transport & Mobility theme of the £13.8M EPSRC PETRAS National Centre of Excellence for IoT Systems Cybersecurity;
- £8M EPSRC Future AI and Robotics Hub for Space, led by Surrey University;
- £1M EPSRC AutoTrust: Human-Cyber Design for Resilient, Useful Internet of Vehicles;
- Co-lead of £6.8M Mental Health & Productivity Pilot in the Midlands, partnering with Coventry University and West Midlands Combined Authority (WMCA), to tackle poor mental health in the workplace, piloted in 20 organisations across nine Local Enterprise Partnerships (LEPs);
- ESRC From Productivity to Prosperity – Inclusive Growth of the West Midlands, led by WBS with the Unit;
- £32M ESRC Productivity Institute to enable a step-change in quality and quantity of research to inform government policy, led by University of Manchester bringing together nine organisations – at Warwick, the Unit and WBS.

Strategic Pillar B – Next Generation Engineers and Scientists

- £2.5M RAEng Lord Bhattacharyya Engineering Education Engagement Programme linking local primary/secondary schools, FE colleges and the Unit.

1.5 Interdisciplinarity

The Unit is, of itself, interdisciplinary. Beyond its depth of engineering capability, academic staff are drawn from cognate disciplines e.g. chemistry, mathematics and physics; broader disciplines in the FSEM and from social sciences. Joint posts are in place with Mathematics, Physics and Statistics departments. Other departments, e.g. Chemistry, have made academic appointments that align with major research equipment in the Unit, e.g. in Energy.

The Unit has instigated interdisciplinary GRPs (§1.3) and embraced University initiatives including the Institute of Advanced Study *(REF5a-2.9.2)*. This advances research ideas through fellowships characterised by interdisciplinarity and innovation, including in the Unit: a WIRL COFUND Fellow investigating interconnections between medicine and religion with respect to African cultural traditions; an Early Career Fellowship examining the effectiveness of 3D printed replicas within cultural heritage; and an Associate Fellowship investigating wearable devices to monitor circadian rhythms in oncological patients. A Fellowship from the Institute for Global Sustainable Development *(REF5a-2.9.3)* explores renewable electricity systems for Bangladesh.

The Unit participates in activities including Mathematical Interdisciplinary Research at Warwick, with areas including applied control, biomedical and fluid dynamics; the Warwick Antimicrobial Interdisciplinary Centre; the Warwick Institute for the Science of Cities; and the Interdisciplinary Ethics Research Group – e.g. through the H2020 PRISMA project, developing a toolkit for companies creating innovative products and services addressing societal needs. Alongside WMS, the Unit has instigated the Clinical Challenges Forum that brings clinicians, scientists and engineers together around clinical challenges requiring interdisciplinary interventions. Unit academics are involved in many CDT across the wider University, e.g. EPSRC Mathematics for Real-World Systems (PhD supervision) and Warwick CDT in Analytical Sciences (management team and supervision of experimental analysis PhDs).

1.6 Research Integrity

The Unit recognises its obligations to uphold the integrity of academic research, and to comply with the UUK Concordat to Support Research Integrity. Two members of the Unit (Kirwan, Lockerby) serve on the University Research Committee; Kirwan chairs the Knowledge Exchange Framework Steering Committee, and Despotou serves on the Research Integrity and Ethics Committee (*REF5a-2.5*).

The Unit supports a culture of research integrity, ensuring that research is conducted according to appropriate ethical, legal and professional frameworks, obligations and standards. It applies the University's comprehensive ethical scrutiny process to ensure that all research involving participants, their data and/or tissue, addresses relevant ethical considerations and is subject to appropriate ethical review.

Each department has a Risk Register, embracing statutory/regulatory breach, key partnerships, state aid compliance and research quality. Business Continuity Action Plans enable the delivery of research in the light of unforeseen events. A rigorous approach is taken to health, safety and wellbeing. Management systems align with the British Standard for Occupational Health and Safety Management (18001) with the most recent audits of the Unit in 2020. Migration is underway to ISO 45001 by mid-2021. Heads of Department lead on health and safety and encourage a high notification level of near-misses, sharing learning from these with staff. WMG has led the adoption of support tools within the University, e.g. the SHE Assure system for investigating accidents and near-misses. Health & Safety and Fire Safety training is mandatory, with specific activities requiring risk, CoSHH etc. assessments (training provided). Unit staff bring their expertise to specialist University Committees, e.g. Laser Safety.

The University's Legal and Compliance Services team provides advice to Unit staff, including contracts, compliance risk, data protection and GDPR. The University's new Information Management Executive Committee includes security expertise from the Unit's Cyber Security Centre (Maple, Watson).

1.7 International Partnerships

International is one of Warwick's four strategic priorities to 2030. Unit staff are leading the development of significant research partnerships in China (Gu, Deputy PVC – China) and North America (Maple, Deputy PVC – North America). Both departments have International Committees, which are leading the strategy for international engagement. Partnerships enhance the Unit's research excellence *inter alia* through engagement with global academic expertise, access to research infrastructure, breadth of application scenarios and research impact. The University enables engagement in the Global Challenges Research Fund (GCRF) through Fellowships (£10k), Catalyst Fund (£20k) and Accelerator Fund (£50k). Through these schemes, partnerships have been initiated to address challenges faced by developing countries. Key international relationships are introduced in §4.2.

1.8 Approach to Impact

The Unit has collaborated with over 1,000 non-academic users, enabling exploitation of knowledge and impact in engineering, manufacturing, healthcare and service sectors. Collaborators range from global corporations to innovative SMEs and from government departments to health trusts. Research is structured to ensure '*excellence with impact*', working

across TRL to enable economic, environmental and societal impact. The Unit's approach is to undertake research with non-academic users and take responsibility for impact, transferring knowledge appropriately to ensure maximum exploitation. Academic staff are recruited based on academic excellence, coupled with a wish to engage with non-academic users. Full training is provided to give staff, particularly ECR, the confidence to do this (§2.3, §2.6). The University has coordinated and enabled impact through its Research Impact Advisory Group, working with Impact Directors in the Unit (*REF5a-2.6*). Aligned to this, the Unit provides dedicated support to achieve impact through approaches including:

- Collaborative research – to address stakeholder challenges through Research Council, Innovate UK (IUK) and EU awards and the HVM Catapult (§1.4.1 - §1.4.5);
- Demonstrator programmes – e.g. investment by Indian motorcycle manufacturer TVS in a Special Vehicle Projects programme to create prototypes;
- Co-location of industry partners in teams and buildings including JLR, Tata and LEAR (§4.7);
- Development of Start-Up Companies – Staff and students benefit from University support in company creation (§4.7). Facilitated by Warwick Ventures, impact is promoted by proof of concept funding, commercialisation funding, assignment of IP and licensing (*REF5a-2.8*);
- Investment in enterprise and innovation centres including the £750k WMG Growth-Hacking Accelerator Programme which matches early-stage businesses with 'minimum viable products', to develop products or services;
- Industrial chairs and secondments enable research across TRL and impact, including: JLR Chair and RAEng-Tata Steel Research Chair; together with Industrial Fellowships (§2.3);
- Facilities usage – industry access to unique or scarce R&D facilities, enabled through business development teams, websites and access via Warwick Scientific Services (§3.3);
- Knowledge Transfer Partnerships (KTP) – The Unit acts as a facilitator and key partner; examples in §4.7;
- Education programmes for industry – undergraduate and masters level degree apprenticeships. Modules developed from research, presented as stand-alone short courses, through Awards and Certificates to Masters delivered to companies (§4.7);
- Industrial Doctorates – an Engineering Doctorate (EngD) Centre has operated throughout the REF period, coupled with widespread usage of EPSRC's Industrial CASE scheme and industry funded PhD/EngD (§2.4);
- Public understanding – events for schools and other organisations, with partners including British Computer Society and the IET (§4.5).

1.9 New Underpinning Capability

Underpinning capability is shared across collaborating research groups and feeds multiple themes (§1.4, Fig.1). In the REF period, we have strategically built new capability at the interface of Engineering and Computing – to drive current and future research. These include: Data Science, Machine Learning, Artificial Intelligence, Cyber Security, Visualisation, Multiscale Simulation, and HPC; enabled through the appointment of twelve new academic staff. Warwick is a founding partner in the Alan Turing Institute (2015 – *REF5a-2.14.2*) with Kirwan a member of the Board of Trustees. Six Turing Fellows have been awarded since 2014 in Behavioural Data Science, Connected Systems, Cyber

Security, Data Embedded Networks, Data Science and IoT, together with a Turing AI Acceleration Fellowship (Montana). Other milestones include:

- £4M FI project to create a community dataset of ageing of specific battery chemistries as a research resource;
- £3.4M EPSRC Programme Grant in Computational Multiscale Fluid Dynamics, in partnership with ESA, Waters, TotalSim, JLR and Nokia Bell Labs;
- Lead partner, EPSRC £1.2M Dynamic, Real Time, On-Demand Personalisation for Scaling project to deliver a decentralised digital economy.

1.10 Forward Strategy and Future Readiness

The Strategic Pillars (§1.3) for producing ground-breaking research with far-reaching impact will continue as the foundation for future activity. The Themes (§1.4) will continue to evolve, in step with changing national and global needs and opportunities. The Unit will strengthen underpinning capability, to be responsive to those changes. This includes developing translational capability into sectors including aerospace, construction, agritech, space and logistics.

The Unit's Research & Impact Strategy is embedded within the University's strategy. It is founded on 'what we do' and 'how we do it'; driving actions and decision-making. Identified future challenges include:

- Resilient and smart manufacturing;
- Sustainable materials;
- Energy transition;
- Net zero, safe, inclusive and 'convenient' transportation;
- Connectivity, use of data and immersive tools;
- Health and productivity.

These align with regional, national and international priorities and the response to economic, sustainability and COVID-19 challenges. They will require broad collaboration, within the University and beyond.

To address economic challenges, the Unit has developed major programmes proposed within *Recharging the West Midlands – West Midlands Combined Authority Ask to the Government (2020)*:

- £65M automotive and aerospace industry R&D programme;
- £20M UK Mobility Data Institute;
- £60M Advanced Manufacturing Excellence SME programme;
- £382M Speed to Scale Region – University of Birmingham, University of Warwick and HVM Catapult Centres (MTC and WMG) focused on heat, energy, medical technology, mobility, and telecommunications connectivity and security.

The strategy aligns to key aspects of the UN Sustainable Development Goals (UN-SDGS), underpinning the Unit's lead of Warwick's COP26 engagement and involvement in the COP26 Universities Group, led by Imperial. A key future activity aims to apply electrification capability developed in the automotive sector to aerospace challenges. An example is involvement in Project Fresson, led by Cranfield Aerospace, developing an electrically powered Britten-Norman Islander aircraft to be operated by Loganair on Orkney Islands routes.

The University's Strategy *Excellence with Purpose* lays out plans to be one of the world's exceptional universities, helping to transform our region, country and world for collective good through growth in STEM disciplines. The STEM Grand Challenge *(REF5a-4.2)*, established by the University Council in 2018, aims to transform how we think about, and deliver, science, technology and engineering at Warwick, building on existing strengths, whilst adapting to opportunities from advances in data science, machine learning and automation. The Unit is at the heart of governance (Meyer (Chair) and D. Towers (Member) Programme Steering Group) and scoping of the STEM Grand Challenge, fostering new multi-disciplinary and cross-sector collaborations, to meet global challenges. Mullins leads the Fundraising and Partnerships workstream. To enable growth and tackle issues with ageing infrastructure, the building of a new Science Precinct is planned, to revolutionise discovery-led and translational research, and inspire future generations of scientists and engineers.

2. People

2.1 Staffing Strategy and Recruitment

The staffing strategy enables high-quality research and impact by recruiting, developing and retaining high-calibre academics and researchers from a wide demographic and across the world, creating a rich, diverse research culture. The Unit recognises historic barriers faced by female, black, Asian and minority ethnic (BAME) and other under-represented groups entering engineering, and is committed to ensuring that such colleagues have equal opportunities for jobs, funding and promotion.

In REF 2014, 98 Category A staff were submitted; REF 2021 has 138 Category A staff (40% increase). Research fellow numbers have increased from 120 to 184 (53%) and PGR Students from 267 to 450 (68%). The significant increase in mid-TRL collaborative R&D in WMG has led to a cohort of 147 engineers. The submission has been developed in partnership with the University's REF Submission Steering Group and is aligned with the University's REF2021 Code of Practice (*REF5a-3.5).*

The academic staffing strategy has coupled key Professorial appointments with ECR development (19% of REF submission is ECR). Succession planning and demographic analysis has ensured that a critical mass of capability has been maintained through timely recruitment. Additionally, the strategic growth projected in REF 2014 has been achieved. Departmental HR teams brief recruitment panels to ensure consistency and compliance, and staff involved in recruitment are required to undertake equality-focused training, including on unconscious bias. Approaches to ensure quality academic recruitment include search committees and use of recruitment consultants.

A focus in the REF period, aligned with departmental Athena Swan Action Plans (§2.5), has been to increase gender equality across all staff groups. Actions include:

- In WMG, use of specialist external advertisement sites to reach applicants from under-represented groups, and job descriptions revised to remove gender bias, including avoiding use of superlatives;
- SoE advertisements with the Women's Engineering Society (WES); since beginning this partnership, four academic posts have been advertised through the WES website, two women were recruited, with an increase in women applicants;
- All interview panels include a female and BAME staff member where possible.

Significant growth in local aerospace and automotive sectors have led to challenges in recruitment and retention of Engineer and Technical staff. This has been addressed through WMG's Graduate Trainee Programme (initiated in 2018, with two cohorts totalling 24 trainee engineers, the first of which have now moved into funded roles), Technician Apprenticeships, use of recruitment agencies, and appropriate market adjustments to salaries.

Recruitment in SoE has included strengthening core groups and developing emerging areas, in line with EPSRC priority areas and UN-SDGS. In the former category, Civil Engineering has been strengthened with the recruitment of eight academics, including two Professors (Eddie, Hicks). Six new academics have been recruited to the internationally-leading Power Electronics group. Biomedical Engineering has been strengthened with the addition of D. Towers, C. Towers and Kulkarni, adding further expertise in optical sensing and synthetic biology. To augment Chemical and Process Engineering, SoE has recruited five academics (including Professors Rebrov, Tao, van Veen) whose work addresses challenges in catalysis and sustainable energy processes.

WMG's recruitment strategy has been to create a critical mass of expertise in areas underpinning the UK's Industrial Strategy. Many appointments have industry experience, in particular Chief, Principal, Lead and Project Engineers, enabling industrial exploitation and facilitating access for academic and research colleagues from HE backgrounds. In energy, recruitment includes: increasing fundamental capability in energy storage (Piper) and power electronics (McMahon). WMG has built critical mass in CAV; the team now consists of over 60 staff, led by four academics (Jennings, Higgins, Dianati, and Woodman). Tata Steel support leveraged a RAEng Research Chair (Davis). Health research growth is being achieved, aligning opportunities of AI (Montana) with insights into the NHS and wider landscape by a new Professor of Practice (Moore), previously Chief Executive at UHB. Expertise gaps have been filled in polymer engineering (Peijs) and complex programme management (Brookes).

2.2 Staff Development

The Unit aligns with the Concordat to Support the Career Development of Researchers and fully implements the institution's processes for development, including annual Personal Development Review (PDR) and Academic Study Leave. The University's revised academic promotion process gives clearer direction for promotion and provides a transparent matrix structure to enable consistency of application (*REF5a-3.3*). The Unit has instigated women-only sessions on academic promotions, career development, tailored support for maternity returns and support for women academics to grow research funding and their PR/external profile.

Both departments suffer from a shortage of senior level academic staff from under-represented groups, but have a wealth of talent at more junior staff and student levels, such as Fidegnon-Edoh, awarded Engineering Student of the Year at the Engineering Talent Awards 2020. Actions are underway in departmental committees to prepare these colleagues for senior academic and leadership positions. WMG has launched a Positive Action Campaign to increase recruitment of and development support for under-represented groups. SoE has embraced Academic Study Leave to enable development and impact and supported all applications. 33 staff members have been granted study leave since 2014, spread across all academic levels.

The Warwick Organisational Development Team provides training opportunities for research-active staff, e.g. career development, open-access landscape and public engagement. Leadership and management programmes range from workshops to the Warwick Leadership Programme. Recognising local needs and limited University capacity, WMG initiated a Management Programme for all line managers, with modules from WMG and external expertise. All Unit staff are required to undertake training to ensure colleagues and students are treated with fairness and equality. The University's Staff Wellbeing Support Service (*REF5a-3.4*) includes tools for psychological, emotional and physical wellbeing. A 24hr Employee Assistance Programme provides life support, legal information, bereavement support, medical information and Cognitive Behavioural Therapy.

Professors joining the Unit negotiate an appropriate package to enable rapid growth in activity. Newly appointed Assistant/Associate Professors receive a package including a PhD studentship and funding for at least one international conference p.a. They are allocated a senior academic mentor, have bi-annual review meetings with their research head, and one-to-one support in proposal development. Direct peer support is keenly supported; both departments have established Early Career Academic Forums. Godsell, WMG's Director for Academic Talent Development has instigated inaugural lectures for all new academics.

ECRs receive targeted support from research development managers and peer support when applying for EPSRC First Grant/New Investigator Awards. Seven have been awarded in the last four years (Khovanova, Collingwood, Gammon, Kermode, Zhao, Charmet, Low, and Dancer). The WMG Researcher Forum, initiated and coordinated by research staff, encourages individuals to 'take charge of' developing their capabilities to become 'world-class' researchers. It has received University support to run regular activities.

SoE's Research Committee was revised in 2017 to include a broader representation of the research community, including staff at different academic levels and disciplines. All academic administration duties and committee vacancies are advertised to ensure that all staff can apply for roles that support their development and help promotion cases (previously personnel were targeted for roles). The WMG Research Executive (replacing its Research Strategy Committee) was established in 2019, as part of a new governance structure, with all leadership posts advertised. The Research Executive is focused on a shared research vision for each directorate and cross-cutting collaborations to build collegiality and access to multi-disciplinary expertise.

2.3 Support for Researchers

The SoE's Research Office has been reshaped since 2014 to include project officers and GRP administrators and WMG established a similar office in 2015. Both work with the University's R&IS to provide guidance on preparing applications. A Notification of Intent to Submit process ensures full support through to timely submission. Expert advice is provided on strategic relevance and peer review. After a bid/no-bid decision, each proposal is optimised through a Gateway process. This includes: Business Development staff to identify and secure project partners; undertake market research and analysis; inform potential impact; undertake proof reading; and develop presentations. Mock interviews are conducted. Post award, 23 Project Managers provide support to ensure timely achievement of deliverables.

Researchers benefit from processes to stimulate and facilitate collaboration between academia, business, industry and wider research-users. Website landing pages for business inform on collaboration, facilities and resources. Business Development staff support discovery meetings, off-site visits to grow networks and develop collaborations, and training on industry engagement. Secondment between the Unit and external bodies is encouraged and facilitated.

Targeting, selection and support for Fellowship candidates is managed by Fellowship Committees, which work with internal and external networks to identify future research leaders and provide training and mentorship for candidates. In the REF period, the Unit has secured:

- EPSRC Fellowships: Early Career (Xie); Innovation (Zhao); Manufacturing (Z Li); Postdoctoral (Shah) and Supergen ECR (Loveridge);
- RAEng Fellowship (He);
- Royal Society Dorothy Hodgkin Fellowship (Antoniou);
- UKRI Future Leaders Fellowships (Sadeghi, Khastgir);
- Eight Marie Sklodowska-Curie Fellowships (Amato, Chen, Graziosi, J Li, Lin, Ping, Xie and Zhang);
- Parliamentary Academic Fellowship (Winnett).

Industrial Fellowships in the REF period are:

- RAEng: Donzella (ON Semiconductor);
- Royal Society: Alatise (Bourns), Chalmers (Johnson Tiles) and Debattista (JLR).

Together with a RAEng Visiting Professor from Tata (Clough) and Ng's recognition as ESRC Innovation Caucus Thought Leader.

Funders and collaborators are invited for strategic visits and awareness presentations, and research events facilitate dissemination from each fellowship. The University's Fellowship Celebration event in 2020 provided a platform for interdisciplinary collaboration.

The Warwick Research Archive Portal (WRAP) operated by the Library (*REF5a-2.10*) houses the University's open access research content. The Library runs training on data management and open access, which the Unit's Assistant Professors attend as part of their probation. The Unit is implementing policies around large data sets generated by CAV and battery evaluation to ensure maximum benefit to the research community without compromising commercially sensitive data. Where Data Protection Impact Assessments are required, full guidance is provided to the researcher by the University's Senior Solicitor (Assessor) prior to approval by the Head of Department (Validator). Collingwood developed a rigorous ethical approval process for student projects, culminating in implementation of a tiered approval system and in-house training, covering all engineering disciplines.

Research outcomes are promulgated through press releases, media articles, social media, and trade publications. For example, the Unit worked closely with Research England to maximise the NAIC profile, including Foundation Stone event (17/3/2015), Secretary of State BEIS (30/1/2016), University Chancellor's Dinner (11/12/2018) and formal opening by HRH The Prince of Wales (18/2/2020). These events, coupled with widespread engagement with the media and 23 Press Releases led to 247 individual references in TV, radio, print and online media; presented in 170 different outlets, reaching diverse

audiences. Numerous visits have been hosted from national and international Ministers, Government officials and industrialists.

Collaboration between Assistant Professors across different research areas are facilitated via paired meetings and workshops; e.g. Human Factors in Automotive and Remote and Personal Diagnostics for Healthcare. The Molecular and Materials-based Characterisation for Biomedical Application Symposium (2018) brought together Faculty researchers, UHCW and Baker Institute, enabled by funding from the Innovative Manufacturing and Future Materials and Health GRPs. An industry internship scheme for new PhD graduates, receives £200k funding annually from HEIF. Early Career Forums provide an opportunity to network and share best practice, alongside senior academics.

The WMG Centre HVM Catapult provides ECR opportunities, with biannual calls to apply for collaborative research funding (£25k per project) with 26 current projects in the Unit. 'Researcher in Residence' brings in external expertise from other academic institutions and vice versa (e.g. University of Nottingham and Cranfield University).

2.4 Support to Research Students

SoE's Director of Graduate Studies (DGS) and WMG's Director of Research Degrees lead teams that support research students from initial enquiry through to graduation. This includes: recruitment; pastoral care; access to relevant training content; secondment; and transferable skills development. All Unit networks, and many training sessions, are open to research students. They are encouraged to attend funder seminars to help shape plans for their future career. The Research Offices identify schemes that students can apply for and provide support to develop high-quality applications. The Students' Union Warwick Engineering Society organises events and conferences with the support of the Unit, and the Warwick University Satellite Programme (WUSAT) further enhances the student experience. Access is facilitated to the University's Student Wellness Portal, with masterclasses, self-help resources and specialist skills services.

SoE's PGR numbers increased by over 25% between 2017 and 2020 to 200; meeting the department's target of 2.5 students per FTE research academic. Following a DGS review, the structure was changed to an MPhil/PhD in 2019-20 to provide flexibility to postgraduate researchers, and to streamline the end of year review. The redesigned PGR induction programme includes talks from key sections of the University, e.g. Careers and Skills. A refreshed PGR Handbook includes information on progression and signposting for help with personal issues. SoE has a staff-student liaison committee (PG SSLC) dedicated to supporting the needs of PGRs. The PG SSLC holds a budget for organisation of events, including an annual SoE PGR Symposium, enabling students to present on their work to peers and staff. WES provides unlimited Student Supporter Memberships for female students; help with a WES affiliated Student Group; and a 'She's an Engineer' feature given to students.

WMG has 250 PGR students; 4.5 per FTE research academic. A strategic fund enables sponsorship of exceptional students in strategic areas and internally funded scholarships attract students into low recruitment areas. A split-site PhD programme with Indian Institute of Technology (IIT) in Kharagpur and Guwahati funds high-quality IIT graduates to study for a PhD with supervision in India and UK. A research internship programme identifies and attracts potential PGR students. EngD are delivered in Hong Kong with partner Hong Kong PolyU and further doctorates are funded by international organisations e.g. Indonesian Institute of Sciences

and TVS. A 2+2 EngD with SIMTECH in Singapore, funded by national funding body A-STAR, is ongoing. Strategic relationships with JLR and Tata yield significant numbers of Industrial Case awards; together with those from companies including Spirent Communications, Miba and Element. The department has increased fully funded PhDs/EngD's from companies including BAE Systems, Cummins, ELG Carbon Fibre, Thermacore, Severn Trent and EPRI. WMG runs Summer Schools for industry and researchers/students at other academic institutions, and holds an annual PhD conference, and a multi-University Tata Steel Conference.

The departments focus on PGR progress monitoring and quality assurance procedures with a view to securing high completion rates, quality student experiences and future careers. The University's Doctoral College (*REF5a-3.10*) and the Unit provide support to students and supervisors. For students, this includes a tailored programme with online coaching and development sessions; a researcher development newsletter; e-learning resources; and research integrity, ethics and methods training. Funding is available for PGR-led conferences, meetings and seminars; together with training in public engagement.

University Guidelines on the Supervision and Monitoring of Research Degree Students identify the student, supervisor and Department/University responsibilities. In accordance with the University's monitoring policy, all students must have a minimum of one meeting per month with their Supervisor; recorded on the Tabula system. At least 50% of the meetings should be face-to-face if logistically possible. Monitoring points for PGR are reviewed monthly by the departments' Research Degree Offices and missed monitoring points are reported every three months to the Doctoral College. PGRs have two opportunities to upgrade; if they fail their first evaluation, they can re-submit. If this is unsatisfactory, a senior departmental panel will discuss possible steps forward. In the few cases that cannot be resolved, MPhil is offered as an exit option.

The Unit benefits from the EPSRC Doctoral Training Partnership (DTP) administered by the University, which applies some studentships strategically, e.g. to create or augment CDT, with others (typically thirteen p.a.) available for Unit allocation. The departments operate transparent processes for DTP allocation, including: new starter packages, requests for research students aligned to major project applications, alignment with departmental research strategy, supervision load of supervisor, and availability of an appropriate student. The Unit welcomes external awards; e.g. 2020 Worshipful Company of Engineers Leete Award.

The Unit leads, or significantly contributes to, a number of doctoral research centres. Kirwan is Director of the EPSRC CDT in Sustainable Materials and Manufacturing (with Cranfield and Exeter), which runs until 2022. The 56 EngD students to date have been offered the opportunity to engage in the i2i Programme at Cranfield. This takes Ideas to Innovation and focuses on skills development, creative and critical thinking, decision-making and clear communication. Academic and Industrial mentors provide insights via interactive workshops. CDT students are co-located with the Director and Coordinator to receive mentoring and support from the wider research group.

The EPSRC CDT in Modelling of Heterogeneous Systems (Brommer, Figiel, Kermode (co-director), Lockerby, Neophytou and Mousavi-Nezhad plus 15 staff in cognate physical sciences departments) commenced in 2019. It supports fifty PhD students to tackle societal challenges from nanoscale devices and new catalysts, to smart fluids and energy from fusion. The cohort experience bespoke training, which includes transferable computing skills. Students from engineering and physical sciences are trained to apply mathematical skills flexibly and model

complex systems to help businesses address key challenges. 15 industrial partners provide access to real-world problems, and an understanding of business pressures. 13 international partners provide cohorts with exchange opportunities.

The Warwick-funded CDT to Advance the Deployment of Future Mobility Technologies is a Unit-wide collaboration, led by Jennings and Mawby. It trains cohorts of 10 students who choose research across two streams: Wide Bandgap Power Electronics and CAV, whilst working with leading companies and organisations. The Unit is a strong participant in externally-led CDT. The EPSRC Diamond Science and Technology CDT (Dancer, Gammon, Kermode and Mawby) involves nine partner universities and 30 industrial companies, creating opportunities for research students and exploiting new research in real-world situations. The EPSRC CDT in Quantitative Non-destructive Evaluation (Dixon, Edwards, Bilson, and Hutchins) links with 25 companies via the UK Research Centre in NDE and the Centre for Industrial Ultrasonics. The Centre for Complexity Science (Stocks) and the Warwick Institute for Sustainable Cities CDT (Laory) both offer structured PhD programmes. SoE has secured H2020 MSCA Innovative Training Networks; £1M for IMPACT (Chappell); £800k for WinGRID (Zhao).

In 2015, JLR announced its Lifelong Learning Academy, in partnership with WMG, which coordinates the technical and vocational curriculum for company staff. The department benefits from a PhD pipeline (in part linked to EPSRC-JLR programmes) together with a JLR-funded EngD programme. 51 studentships have been sponsored by JLR in the REF period.

Students outside of structured programmes, including FI and ERA postgraduate student groupings, are supported by their supervisors, and benefit from academic and technical expertise within their group. Research students have an annual symposium where they are invited to present to faculty members and external visitors. The Unit promotes undergraduate student research, with initiatives including: research intercalated year; group projects with industry sponsors *inter alia* Warwick Moto, Warwick Racing and Warwick Sub; funded summer projects (one per academic in WMG); and funded and facilitated internships into local SMEs. In 2022, the University will host the British Conference of Undergraduate Research (BCUR) and its international parent conference (ICUR).

PGR students nominate members of governance bodies including: Student Staff Liaison Committees; Health and Safety Committees; SoE Equality & Diversity Committee and WMG Welfare & Communications Group. This representation augments other feedback opportunities including the postgraduate student survey. Many PGRs have undertaken training to show visitors around facilities, undertake lab demonstration duties and conduct outreach activities with local schools; enabling them to broaden their engagement and experience, further embed in the departments and provide employment.

2.5 Equality, Diversity and Inclusion Policy

Social inclusion is a key element in the University Strategy, with 2030 target to be best in class for approach to equality, diversity and inclusion. Performance is analysed through social inclusion metrics at University/Department levels; together with publication of data on gender and ethnicity pay gaps. Initiatives include a Wellbeing Strategy, Working Groups on Research Culture, a Race Equality Charter Survey and LGBTUA+ Taskforce *(REF5a-3.4)*. SoE and WMG are committed to equal opportunities and inclusivity and the Heads have engaged in a series of conversations with a Panel led by Professor Kandola on race, gender, disability, sexual

orientation and inclusive leadership, extending to webinars on racism at work, including micro-incivilities and active bystanders. Collingwood is chair of the University's Gender Task Force.

The SoE Equality & Diversity Committee and WMG Welfare & Communications Group focus on staff and student well-being; aligned to the UUK Stepchange Framework for mentally healthy universities. Activities to promote collegiality, a sense of belonging, information sharing and ideas generation include: dignity contacts; mental health and mindfulness workshops; all-staff social events; newsletters to celebrate success; induction programmes; lunchtime seminars; book clubs and charity events. WMG has established a representative task team to develop further proposals, and SoE has trained 'mental health first-aiders'. Goodship is a University Dignity Advisor. SoE and WMG have both established Green Champions groups to promote environmental issues and promote healthy lifestyles. WMG has provided menopause awareness sessions and appointed menopause "buddies".

The Unit has made significant inroads into enabling access; Andrews chairs the Warwick Staff Disability Forum and formed the WMG Staff Disability Group. All buildings have lift access to all floors; in the Engineering building a new external lift enables access to first floor entrance and in IDL, a new ground floor door gives level lift access. Access reviews are held regularly with the University's advisor. The new Engineering extension features lift/chair-lift facilities on gradient changes and group loop induction. Powered doors are in place in key access points to buildings, with disabled parking bays outside. Buildings feature disabled toilets and recent refurbishments include multi-gender facilities and touchless taps. Evacuation chairs have been installed coupled with user training. After assessments with Accessibility Officer/Welfare, changes have been made to offices, including sit/stand desks, specialised chairs and SAD lights. Other facilities include nappy changing spaces and expressing rooms for nursing mothers.

The University has a strong commitment to Athena SWAN and holds an Institutional Silver Award *(REF5a-3.4)*. Kremmyda is Deputy Chair of the University's Institutional Athena SWAN SAT and chairs Athena SWAN Panels for the Equality Challenge Unit. SoE achieved the Silver Award in 2019, reflecting its advances in diversity, building on the Bronze Award (2013). The department's Athena SWAN team (40%/60% male/female), includes undergraduate students through to Head of School. The SoE Senior Management Team is 40% female; the Senior Management Committee 44%; a third of committees are chaired by women. The department is an Educational Partner of the WES (Kremmyda was a Trustee to 2019) and receives significant benefits including many for students (§2.4).

WMG has held the Athena SWAN Bronze Award since 2013. Innovations include Star Awards (to celebrate staff achievements and impact), Conference Support Fund, a Family Room and Women of WMG group. WMG's Athena SWAN team has a 25%/75% male/female split, with at least one representative from each staff group and student representation. Four of the seven members of the department's Executive are female, including the Executive Chair. The WMG Assembly brings together its Executive; Chairs of Athena Swan, Disability Interest Group and Senior Staff Forum; Director of Academic Talent Development; elected representatives of staff and students in all areas and levels. WMG is a member of WISE (Women in Science and Engineering) to help energise staff in the participation, contribution and success of women in STEM.

The Unit is committed to ensuring the wellbeing of staff and students and to provide equal opportunities; key policies include:

- Support for returners after periods of leave (e.g. ill health, caring responsibilities);
- Flexible working to support individuals balancing external commitments; determined with line managers and supervisors. During COVID-19 this flexibility has been significantly extended;
- Enabling shared parental leave;
- Focus groups to consider matters including bullying and harassment, generating action plans;
- Detailed action plans produced from Warwick staff surveys (Pulse), with targets set for improvement;
- Increased communication, discussion and feedback opportunities during COVID-19 to support wellbeing.

The Unit is delighted to be hosting the 18th International Conference of Women Engineers and Scientists, chaired by Kremmyda. The original date of September 2020 has been postponed by a year due to COVID-19.

The Unit's REF Team, led by the Heads of Departments, has developed the submission with full regard for protected characteristics. The University's analysis of this submission by protected characteristic, identifies equality in the number of Category A staff submitted and average number of outputs per FTE by gender and BAME.

2.6 Incentives to Staff to Develop Impact

Research impact is a key element in the assessment criteria in staff PDR, merit awards, senior staff performance reviews and the selection of staff to propose for promotion. Bespoke training is provided and applied as a route to impact, e.g. WMG in Westminster (research to underpin policy) and WMG Talks (TEDx sessions). HVM Catapult and IDH facilitate access to end users and a programme of collaborative events in the Unit. Matched funding is offered to staff that can obtain part funding from industry, healthcare trusts etc. to support new PhD students.

WMG's SME Programme supports student internships into regional SMEs. A £1M programme supported by Coventry & Warwickshire (C&W) LEP supported Unit academics to work with local SMEs to enable opportunities from advanced materials. UKRI Impact Accelerator Awards (Chappell, Covington, Godsell, Jennings, Kermode, Murphy, Tao, Wen and Williams) and the HEIF Warwick Impact Fund are used to accelerate and widen the reach and significance of key impacts (*REF5a-2.7*).

Impact Working Groups, including departmental Impact Directors, meet regularly to develop activities, highlight incentives and hold regular presentation/discussion events with staff. Comprehensive efforts are made to expose researchers to different pathways to impact and build their profile across diverse communities, e.g. calls for evidence in response to Parliamentary inquiries or contributions to POST notes and Library briefings.

3. Income, infrastructure and facilities

3.1 Research Income

Achievement of the Unit's REF2014 Strategic Goals (§1.2) has led to sustained year-on-year growth (26%, 24%, 16%, 16% and 23%) in research income; from £25.1M in 2013-14 to £65.5M in 2018-19. A 1% fall in research income in 2019-20, to £64.7M, reflected the impact of COVID-19 (*REF4b*). Strategic academic appointments and capital investments aligned to the UK Industrial Strategy have enabled a 29% increase in funding from UK Government programmes. Competitively awarded research funding highlights of the REF period are presented in §1.4.

3.2 New Infrastructure and Equipment

Major enhancements to infrastructure and equipment align with REF 2014 Strategic Goals and complement Industrial Strategy priorities. Four new Unit buildings, totalling 40,000m^2, have been constructed during the REF period:

- NAIC, within the Professor Lord Bhattacharyya Building (opened 2020). A critical mass of research capability in an inspiring 33,000m^2 building, designed to encourage cross-fertilisation of ideas (currently shortlisted in RIBA West Midlands Regional Awards). Its focus is the creation of future vehicle technologies and mobility solutions through partnership with JLR and Tata Motors European Technical Centre. Co-location enables collaborative research across the automotive supply chain and a clear route to impact. The £103M building was supported through a UKRPIF grant of £15M, £85M industry investment and a £3M University investment;
- WMG Degree Apprenticeship Centre (2019 – 2,500m^2) funded through a £10M investment from C&W LEP. It enables delivery of training programmes up to Level 8 (EngD) with an initial capacity for 1,000 students. Degree Apprentices are focussed on high-value manufacturing and digital technologies, and employed by companies including: Amazon, GE Aviation, JLR, Royal Mail and Thales, directly enabling impacts from Unit research;
- AMMC (2016 – 1,575m^2) and MEC (3,050m^2) buildings were funded through a strategic EPSRC award (£14.5M) and University investment (£3M). The buildings house the Advanced Steels Research Centre (ASRC) and the Automotive Composites Research Centre established during the REF period.

The Unit has bid successfully for capital funding from external bodies and the University to purchase strategic equipment to underpin its application-orientated themes. Investments in the REF period include:

Energy.

- £22M ERA investment in community research facilities for electrochemical materials, battery scale-up, battery characterisation and thermal analysis (element of £60M Midlands Engine (IUK) investment to Midlands Innovation (MI) consortium – *REF5a-4.3.2*);
- £14.5M UKRPIF award to create the APRL, with co-funder JLR, providing research and characterisation facilities for hybrid and electric propulsion.

Biomedical Engineering.

- £3M University investment to form a physical centre for WCPM and the Warwick Biomedical Engineering Institute.

Advanced Materials & Manufacturing.

- £1.2M EPSRC Strategic Equipment Award to enable rapid processing, characterisation and modelling of metals;

- £1.15M EPSRC Strategic Equipment Award for a High Speed, High Throughput, X-ray Computed Tomography scanner;
- £5M University investment in Engineering Build Space including 3D printing, metal additive manufacturing system and laser and water jet cutters.

Future Cities.

- EPSRC funded (£3.2M) 3XD Simulator, augmented with additional £600k from EPSRC created the world's first immersive, simulated environment for smart and connected vehicles.

3.3 Organisational and Operational Infrastructure

Major investments in buildings/equipment from EPSRC, Research England and IUK are managed by Steering Groups, which report realisation of impacts to funding bodies. Usage of Unit research facilities by other researchers and students at Warwick, other universities and industry is encouraged. Facilities are promoted via Warwick Scientific Services (*REF5a-4.3.1*) and the departments' equipment database. As part of Research England's TALENT programme, technicians in the eight MI universities have launched an equipment sharing initiative that incorporates Unit equipment *(REF5a-4.3.2)*.

The University's GRPs (§1.3) enable research clusters and the Unit is a participant in many research centres, in University and multi-university, and in national and international research networks some of which are introduced in §4.3.

The University's Research Technology Platforms (RTPs – *REF5a-4.3*) provide access to a network of cutting-edge equipment and enable interdisciplinary collaboration, particularly for the Unit in Advanced Bioengineering, Electron Microscopy, Polymer Characterisation, Scientific Computing, Spectroscopy and X-ray Diffraction. The Unit's CT scanning capability, grown during the REF period, become an RTP in February 2021. The announcement (October 2020) of a partnership between BT and the University to install the UK's first dedicated public 5G network for a connected campus, enables collaborative research with the Unit including: Europe's first connected autonomous mobility demonstration over a public 5G network; and 5G monitoring of health and wellness through normal daily activities.

Staff apply for and receive allocations on major national and international facilities – ESRF, International Space Station, ISIS Neutron and Muon Source, XMaS and ILL (*REF4c*). Users include *inter alia:* Collingwood chaired the Diamond Light Source Synchrotron User Committee and served as UK representative for the European Synchrotron Users Organisation; Hughes, recruited from the ILL undertaking materials characterisation using X-ray and neutron facilities; Schiller using the Australian Synchrotron through collaboration with Monash University.

Operating across 11 buildings on the campus, the Unit has a dedicated facilities team supporting built infrastructure, new build and refurbishments. This team was critical during COVID-19 with the need to safely close down and re-open (with limited capacity) research laboratories. Working with the University's Sustainability Team, the Unit is reducing energy consumption and increasing the number of PV arrays. Energy research facilities feed electricity generated to the University's 11kV grid.

The Unit provides IT support staff for specialist hardware and software beyond that provided by the University's IT Services, and benefits from access to Linux desktops and

HPC through the Scientific Computing RTP *(REF5a-4.3)*. The Unit provides technical support to equipment, staff and students, with 86 technicians, including Technician Apprenticeship Schemes with 14 current apprentices and a comprehensive training programme in line with 'The Technician Commitment' *(REF5a-3.3)*. The Unit has recruited an increasing number of technician apprentices since 2014; many are undertaking Unit-funded study (HND/Degree), and/or have secured roles overseeing facilities. All apprentices successfully appointed to permanent roles have progressed to more senior roles within 18 months. The Unit is part of the BEIS 'trailblazers' who group together to influence the syllabi of colleges.

WMG is a member of the Warwickshire College Group Advisory Board focused on skills development in mechanical, high voltage electricity, robotics, hydraulics, fluidics, and health and safety; creating a local pipeline of skilled individuals for the Unit. The Unit has championed the Higher Education (HE) Technicians Summit, sharing best practice amongst HE technical staff, with 700 technicians attending the 2019 Summit (Birmingham). At the event, a new Lifetime Achievement Award was presented in honour of Lord Bhattacharyya – 'a very passionate champion of the work of technicians'.

3.4 Application of Infrastructure to Impact Activities

In 2018 a consortium of Coventry City Council, C&W LEP and the Unit won a national competition (Faraday Battery Challenge – APC/IUK) to establish UKBIC to enable the scale-up and commercialisation of advanced technologies central to the development and manufacture of batteries, initially for the automotive sector but with wider application. With additional funding from WMCA, the £130M facility, creating 100 jobs and opening in Coventry in 2021, provides the missing link between promising battery technology and successful mass production. It can be accessed by any organisation with existing or new battery technology – if that technology will bring 'green jobs' and prosperity to the UK. The Unit has worked closely with the City Council/C&W LEP to turn the vision to reality with staff secondment, expertise provision, recruitment support and involvement in governance of the company limited by guarantee created to build and operate UKBIC for the community.

Equipment investments e.g. ERA have enabled development and validation of battery cells, modules and packs with companies including JLR, McLaren, Nissan and Rolls-Royce. Strategic collaboration with the Unit, led to Tata Steel establishing a new R&D Centre on the University Science Park in 2015. The collaboration includes equipment sharing, with a co-located suite of Gleeble Thermal-Mechanical Simulators providing a unique national resource; Tata Steel usage of the Unit's microscopy facilities and the Unit's usage of Tata Steel's coating and corrosion facilities. Other equipment donations include Continental, National Instruments and Spirent.

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

4.1 Partnerships with Industry and External Stakeholders

The Unit has over 90 collaborations with universities in the UK and overseas; many multidisciplinary in nature. They range from strategic partnerships, e.g. EPSRC Prosperity Partnerships, to GCRF collaborations with Low and Middle Income countries. The Unit has strategic collaborations with industrial partners via direct contract research and IUK and APC collaborative R&D. Examples of partnerships with industry and external stakeholders (Strategic Pillar C) include:

Energy.

- £5.7M EPSRC Prosperity Partnership with JLR and King's College London (KCL) to address core challenges inhibiting electrification;
- APC – in response to IUK tender, the Unit bid successfully to host the new government/industry centre on campus. Greenwood leads the APC Electrical Energy Storage Network;
- Multiple APC/IUK collaborative R&D projects, totalling £25M to the Unit with vehicle manufactures: Alexander Denis; Ariel; Aston Martin; BMW; Honda; JCB; JLR; McLaren; Nissan; Potenza; Triumph, Williams and Volvo with 36 suppliers and six universities;
- IUK project i-CoBat, led by M&I Materials with WMG, won The Engineer 'Collaborate to Innovate Award', 2021.

Biomedical Engineering.

- Warwick-Wellcome Trust Translational Partnership *(REF5a-2.7)* – Translation and Innovation Grant in Nocturnal Hypoglycaemia Detection, with UHCW;
- IDH developed the Tommy's National Reproductive Health Biobank and supported its data management. Commended in the 2020 UK Biobank of the Year competition (UKCRC Tissue Directory).

Advanced Materials & Manufacturing.

- £10M p.a. research, skills and innovation programme funded by TVS Motor;
- £2.4M EPSRC Prosperity Partnership with Tata Steel and Swansea University focused on rapid alloy and product development for the strip steel industry;
- £4M IUK funding to develop lightweight vehicle and powertrain structures, part of the £18.7M Tucana project led by JLR with their supply chain;
- Forensic Centre for Digital Scanning and 3D printing, supported by West Midlands Police to develop techniques to generate evidence to support the criminal justice system;
- Collaboration with ReNew ELP in Teesside in £4.4M IUK project to build the world's first commercial-scale plastic recycling plant using Cat-HTR™ technology. The initial plant will recycle 80,000 tonnes of waste plastic p.a.

Future Cities.

- £25M investment to Unit-led Midlands Future Mobility (MFM), for a CAV testbed with a 300km route from the University. Partners include: AVL, Costain, Mira, Coventry University, Transport for West Midlands and Vodafone;
- £11M IUK programme bringing Highways England to MFM;
- €35M EC L3 Pilot – Piloting Automated Driving on European Roads, led by Volkswagen, with 36 European partners including BMW, Daimler, Fiat, Ford, JLR, Honda, PSA, Renault, Toyota and Volvo;
- Leading research in Very Light Rail (VLR): lightweight, energy efficient rail vehicles with low manufacturing and operational costs, to increase mobility in cities. From early involvement in Revolution VLR, the Unit is central to the delivery of:
    - VLR National Innovation Centre, a £28M centre at the site of the former Dudley rail station, to be used for prototype trials;
    - Coventry VLR – a low-cost city tram solution with funding from Coventry City Council for research innovations (vehicle - £5.5M and low cost track - £1.4M). The woven composite vehicle frame won Gold at the JEC World 2020 Innovation

Awards. A £114M Coventry VLR development proposal has been presented in the *West Midlands Investment Case to Government (2020)*.

Technology and Society.

- Release of the Unit's `Industry 4 Readiness Assessment Tool';
- Launch of the Supply Chain Innovation Hub in 2019, a collaboration with GEFCO to help create the automotive battery supply chain.

4.2 International Partnerships

During the REF period, the Unit has consolidated and grown international partnerships. The Unit typically hosts 20 international visiting academics p.a. some supported through RAEng Distinguished Visiting Fellowships, e.g. Brooks (Swinburne University of Technology) and Zhang (University of Science and Technology Beijing). It has embraced the Monash-Warwick Alliance (*REF5a-2.12.1*), including a joint Professor of Polymer Materials.

In China, major relationships include Harbin Institute of Technology, Hong Kong PolyU, Shanghai Jiao Tong University (SJTU) and Tsinghua University. The SJTU-Warwick Joint Seed Fund has enabled new collaborations, broadening from the ongoing series of UK China Symposium on Polymer Nanocomposites organised by the Unit and SJTU. WMG is a founder partner (1995) in the International Strategic Technology Alliance – collaborating with 25 research-intensive Chinese universities.

In Europe, the Unit has strong engagement with partners in European universities and industry, including through the ERC, H2020 and Marie Sklodowska-Curie projects discussed in §1.4.

In India, the Unit has longstanding relationships with companies, e.g. Bharat Forge, Confederation of Indian Industry, Tata and TVS; and universities, e.g. IIT Kharagpur (International Advisor to the IIT Centre of Excellence in Advanced Manufacturing Technology and current UKIERI-DST Safety of AI-based Systems project). An RAEng Industrial-Academia Partnership Programme enables collaboration with the National Institute of Technology Raipur. The Unit has Co-I involvement in three of the four work packages in the Joint UK-India Clean Energy Centre, which brings together 10 UK and 13 Indian institutions.

In North America, relationships include Argonne National Lab (including staff secondment); Boston University (BBSRC/NSF/BIO project); Lawrence Livermore National Lab; NIST; University of Minnesota (CBET-EPSRC US-UK collaborative scheme) and US EPA. These are underpinned by intelligence gathering and networking. Collingwood was featured in the UKRI *Impact of UK-US Research Collaboration (2018)* publication highlighting research into potential impact of metals in the brain in Alzheimer's disease, undertaken with the Advanced Light Source in Berkeley, University of Texas, and University of Florida.

4.3 Collaborative Networks

The Unit instigates and engages in collaborative networks (Strategic Pillar D). Examples are introduced below:

Energy.

- EPSRC's £7.3M Centre for Power Electronics, a 12-university collaboration across five research themes. The Unit leads Reliability & Health Monitoring and Switch Optimisation themes;

- FI, UK's independent institute for electrochemical energy storage science and technology (Greenwood, Founding Member of Expert Panel);
- Partner in EPSRC Supergen: Energy Storage Hub, Storage Network Plus and Offshore Renewable Energy Hub.

Biomedical Engineering.

- Partner in £30M Health Data Research (HDR) UK programme, to transform health through data science, building on radiology research with WMS, funded by Wellcome Trust and Tommy's Miscarriage Centre;
- Partner in €20M GATEKEEPER project, creating a European digital solution framework for healthcare providers and businesses;
- Founding member of the Quantitative Systems Pharmacology Network, hosting events and workshops.

Advanced Materials & Manufacturing.

- EPSRC UK Metamaterials Network, Chair of Special Interest Group (ceramics);
- Unit-led Sustainable Production Innovation Network brings together businesses across sectors to discuss solutions and challenges surrounding sustainability;
- £1.05M UKRI Circular Economy Network+ in Transportation Systems; Unit-led with 20 UK/European universities and companies, delivering circular economy approaches for material stocks and flows.

Future Cities.

- Humanitarian engineering Erasmus+ developing risk management strategies with partners in Bangladesh and Indonesia;
- ConVEx project involving government, academic, private sector and local authority organisations to create an open platform for commercial exchange of data to accelerate new mobility products and services.

Technology and Society.

- UKRI Transforming Construction Network+, creating a new community and body of knowledge. Led by UCL, with the Unit and Imperial;
- EPSRC Commitment to Privacy and Trust in IoT Research Hub – a small number of universities working coherently across disciplines, at Warwick - the Unit and departments including Computer Science;
- EPSRC Robotics & Autonomous Systems Network, led by Imperial College.

4.4 Contributions to Research Base

In 2016, H.M. The Queen awarded WMG the Regius Professorship in Manufacturing; held, until his passing, by Professor Lord Bhattacharyya (FRS, FREng). In July 2019, the Secretary of State, BEIS announced an annual RAEng Bhattacharyya Award for sustained collaboration between universities and industry. Gardner, Hutchins and Johnson have been elected as FREng; the former received the 2018 Royal Society Mullard Award. Davis was awarded the Institute of Materials, Minerals and Mining Hadfield Medal and Prize 2019. Lucas achieved the WES Prize (2019) for work promoting equality in STEM. Kremmyda is a Director of the International Network of Women Engineers and Scientists. Maple is an elected Board member of the Engineering Professors Council.

Staff are members and fellows of many Professional Bodies. Current Fellows include:

- American: Ceramic Society (2); Physical Society (1);
- British: Geological Society (3); Institute of Non-Destructive Testing (1); Tunnelling Society (1);
- Institutes of: Electrical and Electronics Engineers (6); Engineering & Technology (9); Materials, Minerals and Mining (4); Mathematics & its Applications (2); Mechanical Engineering (6); Nanotechnology (1); Physics (6); Physics & Engineering of Medicine (1) and Structural Engineers (1);
- International: Academy of Production Research (1); Society of Rock Mechanics (1);
- Materials Research Society;
- Royal: Microscopial Society (1); Society of Chemistry (3); Society of Medicine (2).

Godsell is cabinet member of UK Roundtable of Council of Supply Chain Professionals and a member of the Manufacturing Steering Committee of IMechE; Khastgir is a member of IMechE Council and Chair of IMech International Young Member Committee. The Unit hosts regional meetings and provides an interview location for some of the above organisations.

A quarter of Unit academics are members of the EPSRC Peer Review College and serve as referees and panel members. Wider peer review includes UKRI, H2020 (expert evaluators), MRC, Royal Society and UKIERI. Staff serve as reviewers, editorial board members and associate editors for journals; Editors in Chief include: Arvanitis (Digital Health); Dianati (Field Chief Editor Frontiers in Future Transportation); Dixon (Nondestructive Testing & Evaluation); James (IET Healthcare Technology Letters); McNally (Functional Composite Materials) and Peijs (Nanocomposites). The Unit has hosted many events: seminars and guest lectures by collaborators and visiting academics; network events (e.g. EPSRC Early Career Forum) and events for professionals in industry and government (e.g. Whitehall and Industry Group). Hosted international conferences include: European Conference on Silicon Carbide and Related Materials (2018); European Operations Management Association 2020 (with WBS); IEEE International Conference on Industrial Informatics (2020) and UK International Society for Porous Media Conference (2017).

4.5 Contributions to Society

Under the leadership of Lord Bhattacharyya, WMG became a major enabler of strategic growth in the West Midlands. This culminated with the launch of the West Midlands Industrial Strategy at Warwick (May 2019), which was dedicated to Bhattacharyya – 'a constant champion of the West Midlands and a key figure in its industrial renaissance'. This contribution has continued under James (member of WMCA COVID-19 Economic Recovery Group and West Midlands India Partnership). The Unit's regional engagement includes:

- Co-Director West Midlands Academic Health Sciences Network (Arvanitis);
- WMCA Digital Strategy Advisory Group (Kirwan);
- WMCA Electrification Task Force and author in *Midlands Manufacturing Resilience Report* (Greenwood);
- Partner in the Industrial Strategy Challenge Fund (ISCF) Decarbonisation of Industrial Clusters – Repowering the Black Country project (Godsell);
- Business case for VLR investment in Coventry (Hughes);
- C&W Energy Innovation Zone (Mullins).

Staff play a role in shaping national policy, e.g.:

- APC Advisory Board (Greenwood);
- Automotive Council Technology Group (Greenwood);
- EPSRC Manufacturing the Future ECR Forum (Low, Charmet);
- EPSRC Strategic Advisory Teams (Greenwood, Kirwan);
- ISCF Driving the Electric Revolution Advisory Group (Godsell);
- ISCF Manufacturing Made Smarter Advisory Board and Expert Group (Godsell);
- UK Industrial Strategy (Bhattacharyya).

Broader national and international policy impact includes:

- *Automotive Battery Chemical Supply Chain Report (2019)* – authored by the Unit and published by APC;
- Projects to identify potential to create national supply chains for emerging technologies, e.g. power electronics;
- Involvement in creating the European Parliament Interest Group on Biomedical Engineering. An early result is the Biomedical Engineering Profession listing in European Skills, Competences and Occupation database;
- Briefing to World Health Organisation and European Parliament on impact assessments for application of innovative medical devices;
- Advice on digital forensics to the Home Office Forensic Science Regulator;
- Responses to Government consultations, Parliamentary inquiries and APPGs, oral and written evidence to Select Committees and contributions to POST notes;
- Road-mapping exercises led by BEIS Manufacturing Advisory Group;
- Workshops for Government officials, e.g. Office of Lightweight Electric Vehicles on CAV.

National and international standards enable the introduction of innovative products in frameworks that protect consumers and the environment. Examples of the Unit's role in new standards in autonomous vehicles, civil engineering, electric vehicles, and fire safety are discussed in the Impact Case Studies (*REF3*). Unit staff designed and piloted a health-technology assessment tool (MAFEIP), which changed the way the EC selects digital health research projects (the tool is compulsory for all relevant Horizon Europe proposals).

Partnerships with NHS Trusts and regional networks deliver patient outcomes, training for clinicians and practitioners, and efficiencies to Trusts (UHCW, UHB, Leicester, George Elliot, South Warwickshire, Birmingham Children's & Women's NHS Foundation Trust) and Clinical Commissioning Groups. Innovations include sensors for the diagnosis/monitoring of colon cancer, tuberculosis, liver disease, reproductive medicine, chronic diseases, age-related conditions, and metabolic diseases. Additional strategic partnerships include the Oxford University Natural History Museum and British Museum focused on developing engaging exhibitions via new technologies.

Research has far-reaching societal relevance through projects in cybersecurity; health and mental health; humanitarian engineering; mobility; productivity; sustainability and waste minimisation. Broader areas include Ng's research changing perspectives on data ownership (*Value and Worth: Creating New Markets in the Digital Economy, Cambridge University Press*). Societal impact is showcased on websites, digital platforms, and through social media campaigns, e.g. for International Women in Engineering Day. The University is a principal partner supporting Coventry City of Culture 2021 (*REF5a-4.3.4*). As part of this, Chalmers is creating multi-sensory virtual environments with the Herbert Gallery, enabling visitors to

experience the sights, sounds and smells of three industries of Coventry's medieval past (dyeing, weaving and tanning).

Staff and students participate in outreach activities to enable public understanding and inspire the younger generation. Academics speak, demonstrate and debate at events including the Cheltenham Science Festival, Hay Festival and Big Bang Fair. The British Association of Science Festival (Warwick - 2019) had a record attendance of 16,900. With University sponsorship, and logistical and organisational support from the Unit, it highlighted several Unit staff members. SoE and WMG Outreach Teams undertake regular activities for young people with local schools and professional bodies. Initiatives in the REF period have included:

- *Hereward College* - helping students with physical disabilities to create 3D-printed personalised objects to help their daily lives;
- *Imagineering* – Warwick Mobile Robotics, Warwick Sub, and Engineering without Borders highlighted;
- *MozFest* – Tiles for Tales workshop, storytelling with collaborative computing;
- *Royal Institution Masterclasses* – 3D printing, autonomous vehicles and crash structures;
- *Smallpeice Trust* – Mathematics for Engineers and hosting Girls into Engineering courses;
- *Sutton Trust* – Summer Schools and *ThinkHigher* STEM Enterprise Challenge;
- Activities with local schools with pupils from a widening participation background include:
    - For pupils – Day in the life of a battery engineer; understanding supply chains; creative programming and control;
    - For teachers – CPD in manufacturing and automation; Turtlestitch to teach computing and mathematics; Tinkercad to teach design and technology;
- Hackathons, the use of poetry to explain supply chains of chocolate and an Engineering Family Day for members of the public.

In 2016, the Unit's Technology Volunteers presented their outreach innovations to peers at the Scratch@MIT Festival.

4.6 Response to COVID-19

The Unit's response to COVID-19 is testament to the agility and future readiness of its strategy, which adapted quickly to an unprecedented change to global needs. Contributions to local, national and international efforts to address COVID-19 have included:

- Donation of 75,000 gloves and other PPE to UHCW and secondment of IDH staff to support delivery of UHCW crisis plan;
- Mobilisation of logistics expertise to support Scottish Government and NHS Scotland;
- Additive layer manufacturing of visors in Unit's laboratories;
- Support to Ventilator Challenge UK (positive pressure devices), including creation and operation of a Quality Control facility for manufacturing in a DHL warehouse and prototyping the Exovent (negative pressure) device;
- Technical support to the MAN Group to prototype and scale up production of 20,000 face visors for the NHS;
- Continuity of forensics analysis to West Midlands Police; processing evidence from 16 homicide cases during initial 'lockdown';
- Analysis of mortality rates reported to HDR UK COVID-19 response team and included in their SAGE update;

- Research which identified that the UK public wished the COVID-19 contact-tracing app to be controlled by the NHS;
- IUK funded research, including the Health and Safety Executive, into anti-microbial poles for public transport;
- Analysis with Blue Yonder of how retailers and supply chains responded to COVID-19;
- Global virtual hackathon tackling COVID-19 impacts;
- The Outreach Team created STEM challenges for 7-14 year olds to undertake at home using household materials and facilitated by PGR students;
- In collaboration with KCL and St Francis University College in Tanzania, IDH designed a training programme to equip medical staff in leadership roles with knowledge and skills to integrate remote consulting into practice;
- Participation in the €13M EC ODIN project, which identifies 11 hospital critical challenges, where hospitals were unprepared for COVID-19, which can be addressed through robotics, IoT and AI. The interventions will be piloted in hospitals in Berlin, Lodz, Madrid, Paris, Rome and Utrecht.

4.7 Contributions to the Economy

The Unit has a significant track record in developing technologies into market-ready propositions via patents and spin-outs. 77 patent searches were made in the REF period, leading to seven granted patents to Chalmers, Debattista, Dianati, Mawby and Myronov. Impact Case Studies (*REF3*) discuss spin-outs: Cambridge CMOS sensors (Gardner, Covington) and Warwick Acoustics (Billson). Additional spin-outs in the period include:

- Dataswift – formed from EPSRC research at seven universities with CEO (Ng), received £1.6M seed funding to develop platform that enables personal data accounts for sensitive information;
- Sorex Sensors - further exploiting 'electronic nose' technology, established at Warwick in the 1990s, with applications in airborne particulate monitoring and gas detection (Cole);
- Stoli Catalysts – €1.2M H2020 SME Stage 2 grant to design, build and test small-scale pilot plant for medicines, vitamins and food supplements (Rebrov).

Broader commercialisation includes: mPatch mobile device for fitness monitoring using microfluidic hydrogel patches (Charmet); impact evaluation of Sweatcoin technology on physical activity behavior (Elliott); and C3-Cloud digital infrastructure identified as 'tech ready' by the European Innovation Radar (Arvanitis). McNally, working with Senergy Innovations, has developed the first nanomaterial enabled all polymer solar thermal cell, and is now working with industry partners on high volume manufacturing.

WMG's expertise and research infrastructure have made it a beacon for growth and inward investment in deprived local areas. Industry partners (including JLR, Tata Motors UK, Tata Steel and R&D intensive Tier One suppliers e.g. AVL, Bosch, ZF) have co-located on the Warwick campus and Science Park and work collaboratively with the Unit. In July 2020, Lotus announced the creation of a specialist advanced technology centre and new headquarters for the company's engineering consultancy. The new facility on the University's Wellesbourne Campus, established in partnership with WMG, includes offices, workshops and laboratory space for (initially) 130 engineers.

Events for industry including Physical Sciences Industry Day, WCPM UQ&M Study Group, and Aerospace Electrification: Accelerating the Opportunity (with Aerospace Technologies Institute), provide networking and collaborative opportunities. In the automotive sector alone,

collaborations are in place with 25 vehicle manufacturers and 222 supply chain companies. New knowledge is transferred across and between sectors. For example, Harrison led a £1.9M EPSRC programme in Knowledge Driven Configurable Manufacturing (concluded 2018). It has expanded into higher TRL research with industry in multiple sectors including: smart seating (LEAR), factory automation (Atlas Copco and SKF) and future landing gear (IUK consortia). Ceglarek's research in Remote Laser Welding won the JLR Innovista Award in 2018 for the most innovative project in piloted technologies category.

The WMG centre HVM Catapult (CEO, Greenwood) works with companies from multiple sectors - automotive and aerospace to energy and pharmaceutical. Its HVM Reach Programme has 25 innovation experts, providing multi-disciplinary support to help SMEs and larger businesses address technology challenges, exploit new market opportunities and gain competitive advantage. The WMG centre enables collaboration with other HVM Catapult centres and other Catapult Centres including Connected Places and Satellite Applications.

Enabling national and regional productivity is an imperative for the Unit. Activities include Ready for Electrification supply chain events and Smart Factory Innovation Hub Testbeds (ISCF Made Smarter). Dedicated programmes enable SME growth, with tailored support for: Late Adopters (basic technology, e.g. workshops); Mainstream SMEs (advanced technology, e.g. demonstrators and guilds); and Leading Edge SMEs (strategic thinking, e.g. KTP and doctoral projects). KTP in the REF period include: Astec, Carwood, Centurion Safety Products, First Utility; Frost EV Systems, Geoffrey Osbourne, Grainger & Worrall, Masons, Ove Arup, Raleigh Coatings, R53 Engineering, Siemens, Simpact Engineering and W H Tildesley.

In September 2020, the Unit secured a £6M extension to its European Regional Development Fund programme to support small manufacturing companies in the East and West Midlands. Since 2018, the Fund has helped over 100 companies develop 71 new products/processes from automation and productivity planning to zero emission technologies. These include: Genius Facades achieving a 15% increase in productivity through factory floor digitisation; Power Panels Electrical winning £3M of contracts in the niche vehicle sector; Char.gy securing a Transport for London contract to install 1,150 on street EV charging points; and Pashley Cycles - where work on alloy selection and supplier engagement contributed to winning London and Edinburgh Cycle Hire schemes, securing 50 jobs in Stratford-upon-Avon.

Education programmes delivered to industry improve the skills base to enable economic growth, these include:

- Degree Apprenticeships (§3.2) – including Applied Engineering; Civil and Infrastructure Engineering; Digital Healthcare Science; and Digital & Technology Solutions degrees to address chronic skills shortages. Research England Catalyst funding (£2.8M) developed processes to ease entry to HE for new participants and return to study for existing staff. The Dyson Degree, developed, taught and assessed by WMG, was launched in 2017 and delivered to 150 apprentices at the Dyson Institute. A Unit apprentice from Royal Mail was Highly Commended at the National Apprenticeship Awards (2020);
- Technical Accreditation Scheme (TAS) - with WMG as lead academic partner. During 2014, over 1400 individual JLR employees undertook one or more TAS modules. The JLR Learning and Development Centre identified a return on investment of 159%. Similar programmes continue; October 2020 saw the first fully online (due to COVID-19), delivery of *Introduction to Hybrid and Electric Vehicle* course for Bentley Motors employees;

- WMG Academy for Young Engineers - A business-focussed, business-led University Technical College opened in Coventry in 2014 and a second opened in Solihull in 2016. Working with organisations including Arup, Balfour Beatty, Bosch, Cummins, Meggitt, National Grid and Rolls-Royce, these academies focus on high-quality, relevant education in STEM subjects for over 1000 students (14-19 years). Unit engagement includes governance; expertise; student mentorship and relationship building.
- Programmes with Lloyds Banking Group and Allied Irish Bank have taught manufacturing awareness to bank managers, enabling the banks to target support to businesses.

Almost 600 company staff are enrolled in part-time postgraduate programmes, and over 900 in part-time undergraduate programmes.