Institution: University of Aberdeen

Unit of Assessment: UoA 12 Engineering

1. Unit context and structure, research and impact strategy

Context and Structure

The School of Engineering at the University of Aberdeen is a General Engineering academic Unit with research that spans the main engineering disciplines. Within the REF period the Unit has increased substantially in size and in the scope of its research. This submission comprises 69.4 fte research academics, an increase of 77% on the REF2014 submission, with 36 fte research academics recruited within the REF period. The substantial growth was predicated by the Unit's successful REF2014 outcome and its ability to respond to government, industry, and university research initiatives. The increase in size and expansion in research capability have enabled the Unit to make substantial research contributions that address major societal challenges: environmental sustainability, the circular economy, renewable energy infrastructure and technologies, decarbonisation, carbon capture and utilisation, and energy transition. The Unit has engaged fully with the Scottish Government's OGIC (Oil and Gas Innovation Centre) and the Aberdeen Region City Deal's OGTC initiatives aimed at accelerating technology developments within the energy industry. It is home to the Leverhulme Centre for Doctoral Training (CDT) in Sustainable Production of Chemicals and Materials, and leads the National Decommissioning Centre, which was established in 2019 to develop technologies and strategies for the economic and environmentally sensitive decommissioning of redundant offshore infrastructure. Research in chemical engineering and petroleum engineering, which were new in 2014, has developed strongly within the period, while research in well-established subject areas, such as applied dynamics, fluid mechanics, power electronics and Internet engineering, has been sustained and developed, well supported by EU, UKRI and industry funding. At the same time, new areas of research are emerging, supported by recent recruitment, which will frame the Unit's research strategy for the coming period. These include a wide range of research relating to the energy transition challenge, but also robotics and bioengineering, for which new staff have brought expertise ranging from bioinspired robotics to prosthetics design.

The Unit's research is conducted within 5 main research groups, which are based on commonality of discipline and scientific approach, rather than commonality of challenge or application area: **Applied Mechanics**; **Chemical and Materials Engineering**; **Electrical and Electronic Engineering**; **Fluid Mechanics**; **Petroleum Engineering**. The group structure promotes a strong research culture, teamwork, and mutual support. Each group is led by a senior academic, has an annual research budget and organises research seminars and events that promote the work of the group. Research across groups is common, strongly promoted and supported by the general engineering structure and philosophy of the Unit, and the Unit leads major multi-disciplinary research themes across the institution (Leverhulme CDT, National Decommissioning Centre, Centre for Transport Research). Research governance within the Unit follows the institution's Handbook for Research Governance, which complies with the commitments set out in the Universities UK Concordat to Support Research Integrity. Training in research ethics and research integrity is mandatory for all researchers and PhD students, and all researchers have responsibility to report any allegation of unacceptable research conduct. Open access to research data and publications is a key part of the Unit's impact and engagement strategy (details of how open access is supported are given in Section 3).

Research Achievements and Strategy

The Unit's research activities and achievements within the REF period, and its strategic goals for the future, are described in what follows.

The **Applied Mechanics Research Group** combines two areas of established research strength in applied dynamics and solid mechanics, while expanding the research scope to include new work on structures, reliability, and optimisation. The group comprises 23.2 fte researchers, 9 of whom were appointed within the REF period and 2 of whom are ECRs. The Group's research in ***applied dynamics*** (Akisanya, Aleyassin, Pavlovskaia, Vaziri, Wiercigroch) uses a combination of modelling and experiments to study the fundamental behaviour of dynamic systems to optimise design and performance. A major area of focus is on drilling technologies, covering bit-rock interactions, rock modelling, drill-string dynamics, and application of artificial intelligence and machine learning. Initially supported by ITI Energy/Scottish Enterprise (£1.6M, 2012-2019) and industry (BG Group, £312k, 2011-2015), the research has been well supported by OGIC and various industry partners within the REF period (£680k in total, 2017-2020). It has led to optimised designs for single and multiple cutters in rotary drill bits, strategies for active and passive control of drill-string vibration, AI-based processes for well integrity assessment and new techniques for improved coring performance (e.g. 187317927[1], 187317931, 100697678, 100697792). The work led to a spin-out company in 2020 (iVDrill Ltd.) to commercialise these technologies. Other work in applied dynamics includes development of vortex-induced vibration models of marine risers using a wake oscillator approach (e.g. 69012562, 170668193). Research in ***engineering materials*** covers analytical, computational and experimental work on composites and cellular materials (Akisanya, Guz, Kashtalyan, McMeeking, Menshykov, Menshykova, Siddiq) and on metals and alloys (Kartal, McMeeking, Siddiq). Composites research supported by the Royal Society, Carnegie Trust and DFG (Deutsche Forschungsgesellschaft, Germany) has produced new analytical and numerical models for damage evolution and failure in polymer- and ceramics-matrix composites (e.g. 69118794, 144858681, 114682214, 177060158). The energy absorption and deformation of sandwiched composite plates have been analysed (e.g. 69654300) and a new peridynamics-based computational framework has been developed to predict the nonlinear transient deformation and damage behaviour of composites under shock or blast loading (72545023) (DSTL, £27k, 2014-2015). Work on the mechanics of periodic cellular materials reported in *Nature* (100698035) has yielded a new design that achieves the highest possible stiffness to weight ratio for a low-density isotropic material. The Group's research on metals and alloys is aimed at understanding and predicting material behaviour from nano- to macro-scale. Research funded by DSTL and Lloyds Register (£42k, 2014-2015) has led to a novel peridynamics-based computational model for stress corrosion cracking due to hydrogen diffusion at the microstructural scale (e.g. 72545022) and EPSRC-funded research

ZEISS Xradia X-ray Scanner with tension/compression unit

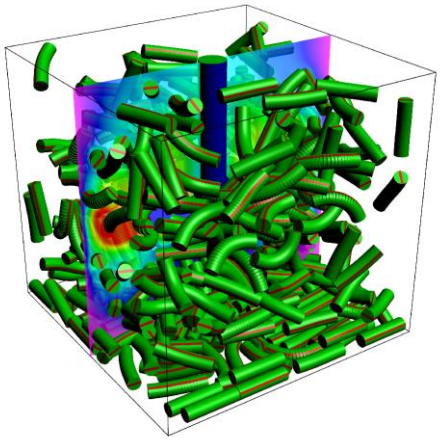
[1] These numbers are the reference numbers for the submitted outputs in REF2.

(EPSRC, £99k, 2014-2016) has resulted in a first-of-its-kind microstructure-based constitutive model that accounts for ductile damage at the scale of single crystals (97602015). Research on additive manufacture by selective laser melting funded by the EPSRC (£126k, 2018-2020), the National Structural Integrity Research Centre and The Welding Institute (NSIRC/TWI, £44k, 2016-2019) has determined the dependence of component residual stresses on manufacturing process parameters (e.g. 97498049). The 400 million strain-cycle fatigue endurance limit of the shape memory alloy nitinol has been determined, correcting erroneous results in the literature and enabling the safe and reliable use of nitinol medical implants (187983068). Industry-focused research on materials includes work on flexible composites for coiled tubing (Research Council of Norway, £40k, 2016-2017), the creep behaviour of alloys for oil well plugging (OGIC, £35k, 2016-2017) and the design of umbilical terminations for deep sea conditions (OGIC, £320k, 2017-2020), while previous research has led to the development of a reliability-based design standard and guidelines for friction grip technology used for securing concentric tubulars in oil and gas wells (Impact Case IC3). Research in ***structures and geotechnics*** (Bagheri-Sabbagh, Ivanovic, Osofero, Rui) has led to new designs for lightweight and seismic-resistance cold-formed steel (CFS) structures and moment-resisting CFS connections (e.g. 72815205), a fully coupled thermo-hydro-mechanical analysis of thermo-active geo-structures (e.g. 170756769) and advanced finite-element models for the impact of trawl gear on the seabed (e.g. 72546128) (Fisheries Innovation Scotland, FIS, £94k, 2015; EU FP7, £104k, 2012-2016). Supported by the Lloyds Register Foundation (LRF, £1.2M, 2011-2019) the Group's research in ***safety and reliability engineering*** (Omenzetter, Sriramula, Tan) extends from reliability-based optimisation of materials to human reliability analysis for safe operation of large infrastructure. The research has produced new methodologies for structural health monitoring (e.g. 105639029, 69050217), advanced reliability analyses applied to structures and systems (e.g. 138616650, 72523072) (Lloyds Register, £45k, 2014-2018; Knowledge Transfer Partnership, £179k, 2019-21) and human reliability analysis applied to large power systems (e.g. 106826151). ***Engineering optimisation*** (Dunning, Maheri, McKenna) is a new research area for the Group, predicated by the appointment of three academics with expertise in optimisation and systems analysis. New methods have been developed for topology optimisation and aeroelastic wing design (e.g. 91870108, 107164820) and for the optimised design of hybrid renewable energy systems, which has changed industry practice (e.g. 94034908, Impact Case IC1). The systems analysis research provides stakeholder-specific decision support for multi-energy systems and the uptake and integration of low carbon technologies. New methods and models have been applied to real-world case studies to enable scientifically grounded decisions, resulting in sustainable planning outcomes (e.g. 177061020, 177061012). The Group's research on ***decommissioning technologies*** (Ivanovic, Maheri, Neilson, Sriramula) includes development of an underwater laser cutting tool (OGTC-Claxton, £406k, 2019-2021), an underwater lifting system (KTP+Aubin, £146k, 2016-2018) and a test chamber for well plugging and abandonment materials (Scottish Government, £367k, 2019). Optimisation methods are being applied to cutting technologies (SRPe, and Clockwise Technologies, £166k, 2019-2022) and the decommissioning and reutilisation of offshore structures and windfarms (EU, DecomTools, £240k, 2018-2022), while reliability methods are being developed for post-decommissioning monitoring (Shell UK, £303k, 2020-2022) and the fate of structures left in place (Chevron, £186k, 2020-2024).

The Group's strategy for the coming 5 to 7 years is to sustain a strong base of fundamental research in its five main areas in order to underpin applied research that will be increasingly geared towards renewable energy systems and infrastructure and towards the engineering challenges posed by the decommissioning of offshore installations. The Group will therefore play

a significant role in the University's Energy Transition strategic research theme and play a major role supporting the recently established National Decommissioning Centre.

The **Chemical and Materials Engineering Research Group** was a new and small group (3.5fte) in REF2014. With 7 new appointments, 2 of whom are ECRs, the Group has developed substantially since that time and now comprises 10 fte research academics. The Group addresses fundamental questions concerned with energy transition, decarbonisation, the circular economy, and sustainability. There are 4 main research areas as follows. ***Carbon capture and utilisation*** research (Afzal, Fernandez-Martin, Graca, Kechagiopoulos) aligns well with the UK Government target of net-zero carbon emissions into the atmosphere by 2050. The research includes the catalytic reduction of CO_2 to methane, methane upgrading via plasma-catalytic processes, microwave-assisted carbon capture operations, and carbon-negative construction materials. Research on regeneration technologies for capturing post-combustion CO_2 has led to new understanding of their potential for portable and faster carbon capture applications, reducing the energy penalty of the capture process by increasing the regeneration kinetics at low regeneration temperatures (e.g. 72260832). Research on plasma-catalytic methane upgrading funded by EPSRC (£140k, 2018-2020), Royal Society (£20k, 2019-2020) and the UK Catalysis Hub (£86k, 2016) has led to significant new understanding of the reactivity of excited states and the relaxation of the latter via vibrational-vibrational and vibrational-translational energy transfer processes (e.g. 92763139, 69604608). Research on CO_2 methanation has led to new zeolite-based catalysts and new understanding of the optimum physicochemical properties of catalysts for CO_2 methanation and for plasma-catalysis (e.g. 170022235). The development of new carbon-negative cement additives and construction materials has been supported by industry (Omya Chemicals, £100k, 2018-2019). The work led to a spin-out company, CCM Ltd., and was the basis for CCM being one of two European teams to reach the semi-final of the global US$20M NRG COSIA Carbon XPRIZE competition. Research on ***waste valorisation*** (Dionisi, Graca, Jiang) covers waste pre-treatment, scale-up of anaerobic digestion and thermochemical conversion of lignocellulosic biomass into fuels and chemicals. Research funded by the SFC, Carnegie Trust, Anaerobic Digestion and Food Waste networks (£300k, 2015-2019) has demonstrated the feasibility of converting waste into chemicals and energy, even in the absence of pre-treatment (e.g. 111669090); conversion greater than 50% has, for example, been demonstrated for wheatgrass and vegetable waste. Thermochemical conversion of lignocellulosic biomass residues has produced new heterogeneous catalysts for glucose valorisation into chemicals and new understanding of catalyst behaviour during bio-oils co-processing in conventional refineries and during biomass catalytic deconstruction (e.g. 149366339). Research on the production of the renewables-based polyethylene furandicarboxylate (PEF) has shown that emissions and energy consumption can be reduced by up to 40% compared with the production of the fossil-based counterpart polyethylene terephthalate (PET) (e.g. 170490856). Current and new research in waste valorisation is conducted within the Group's interdisciplinary CDT in Sustainable Production of Chemicals and Materials funded by the Leverhulme Trust (£1.05M, 2018-2023), which conducts fundamental and applied research on new processes that use renewable resources and renewable energy for the production of chemicals, materials and fuels that



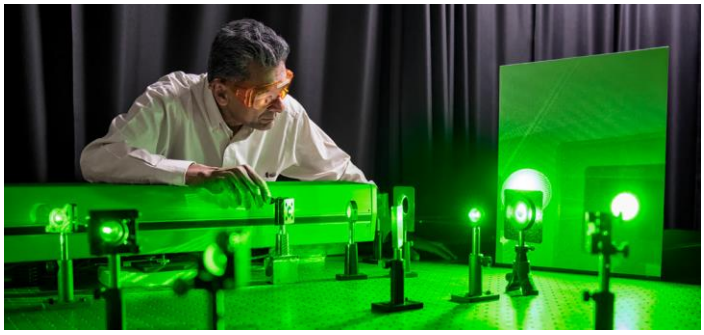
Numerical simulation of mixing tank suspension of flexible particles

are essential for everyday life. Research on ***materials for energy storage*** (Jiang, Martinez-Felipe) focuses on the development of supercapacitors and short-term and seasonal thermal energy storage systems. New photo-responsive materials have been designed, synthesised, and tested to yield new anhydrous electrolytes in fuel cells or capacitors. Using controlled living polymerisation methods, various random- and block-copolymers containing photochromic and polar groups have been synthesised, which show high conductivities at low temperatures when activated by light irradiation. Additionally, liquid crystalline dimers, oligomers and crosslinked networks that are capable of isothermal phase transitions *via* UV irradiation have been assembled by hydrogen-bonding and covalent bonds (e.g. 72520453, 72493903). Funded by the Royal Society, Royal Academic of Engineering, Royal Society of Chemistry and The Carnegie Trust (£50k, 2019-2020), the results open new possibilities for the design of materials that exhibit liquid crystalline chiral phases based on non-chiral molecules (e.g. 72493915). With applications to domestic and industrial energy utilisation, the research on thermal energy systems has led to improved design of hybrid thermochemical sorption cycles and novel composite adsorbents with enhanced heat and mass transfer and optimised thermal design. ***Process modelling and simulation*** (Campbell Bannerman, Derksen, Majumder) research covers length and time scales ranging from molecular and granular dynamics, *via* mesoscopic simulation of solid-liquid suspensions, to process-scale production of pharmaceuticals and cementitious materials. Molecular dynamics modelling of gases has discovered the possibility of "anomalous" heat transfer, which is not predictable using standard continuum mechanics models, and the research has mapped the range of conditions for which the phenomenon must occur in fluids (e.g. 143492301). Major advancements have been made in particle-resolved models of solid-liquid suspensions by extending model capability to include non-spherical and deformable particles (e.g. 114642632, 168378871, 168378821). These advanced models will be used to predict and optimise a range of processes, including biomass conversion of fibrous suspensions and battery manufacture. Population balance modelling combined with computational fluid dynamics has been used to optimise morphology and particle size distribution in the manufacture of pharmaceutical powders (e.g. 68980019). A new process-based predictive model has been developed for cement production, enabling the discovery and design of formulations for low-carbon cement (e.g. 97300481). Ongoing research in this area is motivated by the necessity to reduce CO_2 emissions from cement production (currently accounting for 10% of total human CO_2 emissions) and is funded by the Global Cement and Concrete Association (GCCA, £125k, 2019-2023) through the Nanocem project led by Aberdeen.

Carbon capture and utilisation, waste valorisation and materials for energy are vital research areas in the context of climate change, decarbonisation, sustainability and the circular economy, and will continue as primary application areas for the Group's research for the coming 5 to 7 years. The research fits well with the University's Energy Transition strategic research theme, to which the Group will make substantial contributions. The research on waste valorisation will be expanded to include the production of bioplastics from waste, which comes with challenges in terms of bioprocess and catalyst development, and the process modelling research will be increasingly geared towards the processability of the complex fluids and suspensions encountered in biomass and related conversions. Research on energy materials will focus on waste-based heat and the development of new electrolytes for photo-electrical energy conversion and supercapacitors.

The **Electrical and Electronic Engineering Research Group** has expanded substantially in size and scope from the Power Systems, Communications and Optics Research Group

submitted to REF2014. The Group now comprises 16.2 fte research academics, with 8 new members since 2014, 4 of whom are ECRs. Research in digital technologies and in mechatronics and robotics have been added to the Group's well-established areas of research strength, namely, power electronics, Internet engineering and optical engineering. Under the umbrella of the Aberdeen HVDC Research Centre established in 2015, research in ***power electronics*** (Jamshidi Far, Jovcic, Li) focuses on power electronics for grid integration of large renewable power parks using DC networks and high voltage direct current (HVDC). With funding from the EC (ERC, £588k, 2011-2014; H2020, £913k, 2016-2020), EPSRC (£458k, 2013-2016), SFC and ERDF (£173k, 2011-2014) and industry partners (SSE, £75k, 2013-2016; RTE France, £264k, 2014-2016; RTE France, £114k, 2017-2020), the research has led to new DC/DC converter topologies for connecting MW-sized DC power sources, new technologies for DC circuit breakers, and new designs, models and controls for various HVDC components that underpin the development of DC transmission networks (e.g. 72649636, 145094388, 113312342, 124797756). The research enables the realisation of large-scale offshore renewable energy and is already changing the development strategies of major industry practitioners (Impact Case IC2). ***Internet engineering*** (Fairhurst, Secchi) research focusses on transport technologies and protocol design for the Internet and transport layers. Research funded by EC H2020 (RITE, £371k, 2012-2016; NEAT, £345k, 2015-2018; MAMI, £306k, 2016-2018; MONROE-PREC, £115k, 2016-2018) has led to new techniques to significantly reduce Internet latency (the Internet path delay experienced by applications), support network operations, enhance transmission robustness and overcome obstacles to evolution (e.g. 72549936, 72469819). The work underpins new standards co-authored by Fairhurst (supported by EU StandICT) and published by the Internet Engineering Task Force (IETF), which are now implemented in networking equipment, computer operating systems and other Internet-connected devices worldwide (Impact Case IC5). Research with industry (THALES, £46k, 2015-2019) and the European Space Agency's ARTES programme (MTAILS, £98k, 2019-2022; QUIC, £52k, 2019) has contributed to Internet standards that benefit the performance of broadband satellite Internet.



Optics alignment in the Laser Laboratory

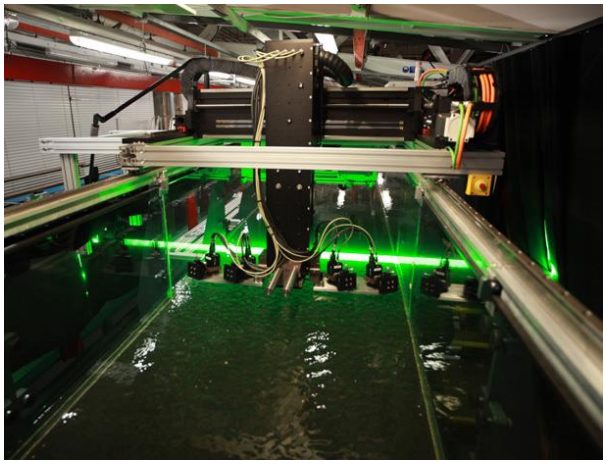
Research in ***optical engineering*** (Kaliyaperumal, Thevar) focuses on underwater holography and optical fibre transmission. With funding from DSTL (£126k, 2014-2017; £180k, 2019-2021) and the EC (H2020, €125k, 2015-2018), the group has built the world's smallest and lightest pulsed digital holographic camera, including state-of-the-art rapid image extraction and recognition, for 3D imaging of marine organisms and microplastics. Related NERC-funded research (£100K, 2018-2021) combines two optical methods to image and characterise microplastics in the water column (e.g. 170751374). Research in optical fibre transmission includes higher-order linear and nonlinear effects on coherent detection, new models of ultra-short pulses in silicon waveguides for integrated chips used to fabricate optical systems, and the use of hollow-core fibres and fibre Bragg Gratings for optical sensing (e.g. 144902692, 114687180). ***Mechatronics, robotics, and control*** (Aphale, Chadwick, Giannaccini, Meissner) includes precision positioning systems, model-free robotic manipulation, bioinspired and soft robotics, and prosthetic technologies. The research has produced several firsts in the control of nano-positioning systems, including a fully automated system identification and control tuning

scheme, and implementations of fractional-order positioning control (e.g. 69019115, 114449674, 187317211). Research on model-free robotic manipulation has reduced the time needed to set up robotic manipulators in bin-picking and machine-loading manufacturing scenarios (e.g. 170968486), while bio-inspired and soft robotics research has led to new fluid-actuated robot platforms and tactile sensors for safe human–robot interactions, object manipulation and healthcare applications (e.g. 149366259). In prosthetics, new computational models have been developed to simulate the dynamics of human hand function, enabling control of advanced hand prostheses for upper limb amputees (e.g. 170200426, 158961824). A similar modelling approach is now being used in EPSRC-funded research on technologies for spinal cord injury rehabilitation (EPSRC, £374k, 2018-2021). Research in ***digital technologies*** (Beecroft, Cottrill, Fairhurst, Nelson, Niewiadomski, Starkey, Verdicchio) was initially focused on rural digital economy (the Group played a major role in the University's RCUK-funded dot.rural Digital Economy Hub, £11.8M, 2010-2016) but has since expanded to include data mining applications, sensor networks and substantial work on (human) transport technologies. Data mining is being applied to a range of oil and gas applications funded by OGIC and industry (Expro Ltd., £133k, 2019-2020; WFS Technologies Ltd., £138k, 2020-2021) and OGTC and industry (Halliburton, £138k, 2019-2021), and a new sensor platform has been designed for environmental monitoring applications (e.g. 72437595). The transport research is undertaken through the Centre for Transport Research (CTR), which specialises in the sustainability of transport systems with emphasis on environment, society, and technology. With substantial funding from the EU (H2020 SocialCar, £287k, 2015-2018; INCLUSION, £330k, 2017-2020; CIVITAS PORTIS, £290k, 2016-2020; SMARTA, £72k, 2017-18), Innovate UK (£237k, 2016-2017), ESRC (£391k, 2014-2016) and EPSRC (£776k, 2019-2021), the Centre's achievements within the REF period include the development of a stackable, low-emission electric vehicle system for sustainable last-mile transport; analysis of the benefits from relaxing public transport operating constraints in rural areas; using social media data for enhanced communication between operators, authorities and customers; and enhanced understanding of transport barriers and solutions for vulnerable persons and communities (e.g. 67039515, 68947777, 171072605, 119862740).

The Electrical and Electronic Engineering Research Group's research in power electronics, Internet engineering, digital technologies and human transport will remain core to the Group's research for the coming period. Power electronics will focus on DC grid components and DC grid design, modelling and control for offshore renewable energy development, contributing to the University's Energy Transition strategic research theme. Working within ESA's SATnex network of research experts, Internet engineering will focus on technologies that realise low-latency and high reliability for 5G/6G cellular and broadband satellite. Following recent appointments, research in mechatronics, robotics and control will cover a range of industrial and bioengineering applications, engaging with the University's Health, Nutrition and Wellbeing strategic research theme.

The **Fluid Mechanics Research Group** has well-established research in open channel hydrodynamics, wave hydrodynamics, porous media flows, eco-hydraulics and multi-physics flows. The Group comprises 10 fte researchers, with capacity and scope enhanced by the appointment of 4 new researchers (3 of whom are ECRs) bringing new expertise in waves, eco-hydrodynamics and multi-physics. Research in ***open channel hydrodynamics*** (Cameron, Nikora, Stewart) focuses on fundamental process measurements and theoretical frameworks for hydraulic roughness, turbulence, and secondary currents. Supported by EPSRC (£526k, 2014-2018), the research has led to the development and implementation of double-averaged equations for momentum and fluid stresses (e.g. 91895379, 170734644), new insights into bed

friction and hydraulic resistance for rough beds (e.g. 170873053, 170734638), the discovery and characterisation of very large-scale motions (VLSMs) in open channel flows that are critically important for mixing, hydraulic resistance and sediment transport (e.g. 170815554, 91895328), and new understanding of the role of turbulent velocity and pressure fluctuations on sediment particle entrainment (e.g. 170815618, 170815613, 72336193) and of the effects of bed topography on secondary currents in channels (e.g. 170873063). The research is founded on advanced measurement capability that includes a unique field stereoscopic Particle Image Velocimetry (PIV) system and the world's first robotic multi-camera PIV, both of which were designed and developed by the Group within the REF period. The research on secondary currents and turbulence over rough boundaries has recently received further substantial external funding (EPSRC, 2020-2024, £735k). Research in ***wave hydrodynamics*** (Michele, O'Donoghue, van der A,) focuses on breaking-wave and bottom-boundary-layer hydro- and sediment dynamics, wave interaction with energy converters and theoretical modelling of hydroacoustic waves. Direct numerical simulation (DNS) combined with detailed experimental measurements has led to new insights and detailed datasets for turbulence in accelerating and oscillatory flows over smooth and rough boundaries (e.g. 129554522, 114728615, 69194492). EPSRC-funded (£606k, 2012-2016) research has yielded a comprehensive description of hydrodynamics, turbulence and sediment transport processes under large breaking waves and a unique experimental dataset for the development and validation of numerical models for cross-shore wave processes (e.g. 97020960, 72336437, 174192315, 108136717). Research on wave energy converters using theoretical approaches to predict structure response and power extraction for various structure types and configurations, has shown the importance of nonlinear resonances and structure curvature on power absorption (e.g. 171912765, 171912753), while theoretical modelling of hydroacoustic waves in the ocean has demonstrated the effects of sound speed vertical profile on the speed of the wave-train envelope, with significant implications for tsunami early warning systems (e.g. 171912757). ***Porous media flow*** research (Pokrajac) focuses on mass and momentum transport in porous media and mass and momentum exchange at fluid-porous media interfaces, with application to fluvial beds (British Council, £100k, 2016-2018), coastal beaches (EPSRC, £214k, 2012-2016), groundwater and rock flows. The research has resulted in new insights into the effects of subsurface turbulence on the forces acting on sediment grains close to the fluid-porous interface (e.g. 148675299), advanced up-scaling approaches applied to multiphase flow in porous media (e.g. 186802735), and development of spatial averaging to address the scale mismatch between surface and subsurface flows (e.g. 72228506). The group's research in ***eco-hydraulics and flow-biota interactions*** (Cameron, Nikora, Stewart, van der A) has seen substantial expansion within the REF period, mainly predicated by the Group's participation in two EC-funded MC ITN grants (HYTECH: Hydrodynamic transport in ecologically critical heterogeneous interfaces, €597k, 2013-2016, and RIBES: River flow regulation, fish behaviour and status, €300k, 2020-2023), but motivated also by interest in nature-based resilient solutions to climate change impacts (EC, Hydralab+, £78k,

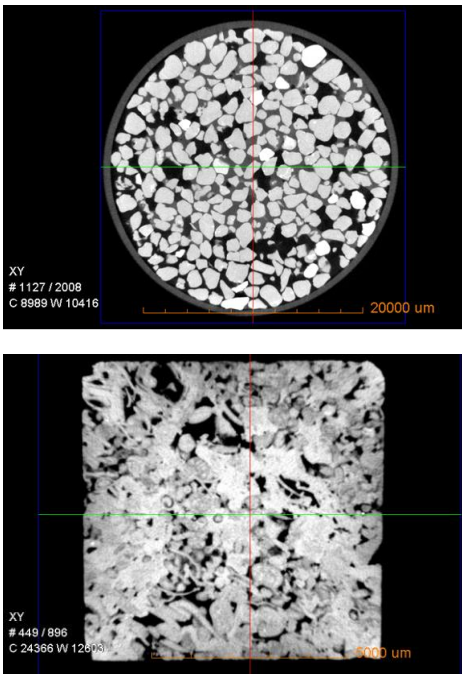


Robotic multi-camera PIV system in the Aberdeen Open Channel Facility

2015-2019). The research has produced conceptual and mathematical models for flow-plant interactions in unidirectional and oscillatory flows, supported by high-precision laboratory and field measurements (e.g. 144881543). The capability of the Group's field stereoscopic particle image velocimetry system is currently being developed to support this work further (NERC, £289k, 2019-2020). Research on ***multi-physics flows*** (Gomes, Hicks, Zhan) includes the development of computational tools for multi-fluid flow dynamics, transport processes in biological and physiological systems, and the fluid mechanics of liquid-solid impacts with applications to tank sloshing, gas cushioning and droplet gas entrainment. Achievements include an open-source computational model with dynamic anisotropic mesh adaptivity for multiphase flow in porous media (e.g. 114731605) and new techniques for localised drug delivery for brain tumour therapy (e.g. 149070295, 170672005). The work on liquid-solid impacts has discovered previously unknown droplet touchdown mechanisms in low ambient pressure environments (e.g. 114731885), yielded new insights into the effects of surface porosity on gas entrainment during droplet impact (e.g. 69461112) and demonstrated the importance of phase change on sloshing-induced LNG-solid impacts (e.g. 171365536).

Fundamental research on free-surface flows, wave hydrodynamics and multi-physics flows will continue to be the primary focus of the Group for the next 5 to 7 years, expanding its application to renewable energy infrastructure, nature-based solutions, hydro-epidemiological processes and bio-engineering, areas that align well with the University's Energy Transition and Environment and Biodiversity strategic research themes. A large-scale RCUK programme grant application on the transport and dispersion of pathogens during floods is under development with UCL. The application is an outcome from the EPSRC UK Fluids Network Special Interest Group (SIG) 'Hydrodynamics of Open-Channel Flows', which the Group established in 2019 and now leads with colleagues from UCL.

The **Petroleum Engineering Research Group** is a new research group formed in 2015 in response to Scottish Government and industry demand for research that supports the development of new technologies aimed at maximising economic recovery from marginal hydrocarbon fields. The Group comprises 10 fte researchers, 8 of whom (1 ECR) were appointed since REF2014. Research across the Group has been supported by a £1M grant from the Scottish Government's Oil and Gas Academy Scotland (OGAS) for research equipment. The research has two main themes as follows. ***Hydrocarbon production technologies*** research (Akanji, Hamidi, Jadhawar, Rafati, Sharifi) uses a combination of modelling and experiments to develop technologies for cleaner and enhanced recovery of hydrocarbons. Research within the REF period has been funded by OGTC (£360k, 2018-2021), OGIC (£35k, 2019), British Council (£159k, 2019-2021), industry (Sonangol EP, £174k, 2015-2018), The Royal Society, and through PhD studentships funded by the Nigerian PTDF (£400k, 2016-2018) and TETFund (£69k, 2018-2021). With application to ultrasonics-based enhanced oil recovery (EOR), the research has yielded new understanding of the effects of ultrasound on the emulsification and demulsification of oil and surfactant solutions (e.g. 63683451); for CO_2 gas injection-based EOR, important new insights have been gained on the dependence of foam stability on the interaction between hydrocarbon solids and aqueous foam (e.g. 70449467). Motivated by the need to move from oil-based drilling fluids to cleaner, water-based fluids, the performance of water-based fluid impregnated with aluminium oxide and silica nanomaterials has been investigated under high-pressure, high-temperature conditions (e.g. 110721591). Modelling work includes a novel fracture upscaling method to represent the complex fracture systems within hydraulically fractured reservoirs (e.g. 183242026) and an AI-based method for selecting the most appropriate EOR technology depending on reservoir characteristics (e.g. 102289923). The



MicroCT images of packed sand grains (top, 25mm diameter image) and rock (bottom, 7.5mm image)

Group's research on ***multi-phase flow in porous media*** (Syed, Tanino, Vinogradov, Wu, Zhou) addresses fundamental aspects of oil, gas, and water flow through porous rock, from pore scale to reservoir scale. Experimental research using centrifuge, core-flooding, microfluidics, scanning electron microscope (SEM) and x-ray microcomputed tomography (micro-CT) facilities has been supported by NERC (£35k, 2016-2017), industry (COREX, £41k, 2015-2020; Anasuria, £24k, 2017; Total E&P, £10k, 2019), EPSRC (£21k, 2016-2018), the Royal Society and PTDF (£50k, 2019-2022). It has yielded new data on the gas-water permeability of various coals (e.g. 72467617), the relationship between capillary pressure and oil relative permeability in limestone for various wettability states (e.g. 148675319), and new understanding of the effects of grain roughness on the capillary trapping of air within porous media, with potential implications for CO_2 storage, groundwater remediation and hydrocarbon recovery (e.g. 171331998). The research has demonstrated, for the first time, a correlation between oil recovery and the zeta potential at the mineral-water and oil-water interfaces during controlled salinity water flooding (CSW), with significant implications for predicting the effectiveness of CSW for EOR (e.g. 73043609). New measurement and modelling techniques have been developed, including: a stochastic algorithm for pore network generation, which has been validated against SEM data (e.g. 187317804); a new method for recreating mineralogical heterogeneities in micromodels used in microfluidics (e.g. 72229849), which were previously limited to mineralogically homogeneous systems; and a new, mathematically well-defined approach to determining in-situ contact angles from micro-CT images of immiscible fluids in rocks (e.g. 170340936). At reservoir scale, the effectiveness of self-potential (SP) measurements in monitoring saline intrusion has been demonstrated (e.g. 187318074), and a new numerical model has been developed to simulate flow in a confined fractured aquifer containing a network of discrete or connected fractures (e.g. 170340997).

Fundamental science, artificial intelligence and new technologies applied to cleaner energy production and enhanced oil and gas recovery will continue as primary research areas for the Group for the next 5 years. Recently awarded grants for research on environmentally friendly oil-field chemicals and on applications of nano-particles and ultrasonics, and a new project that uses AI to integrate digital rock physics and Big Data to optimise oil recovery (CNOOC, £175k, 2020-2022), are already stimulating research in these areas. The Group's research will contribute to the University's Energy Transition strategic research theme, especially through work on decarbonising oil and gas production, carbon storage, and development of processes and technologies for blue hydrogen production.

2. People

Staffing strategy

A notable feature of the Unit's submission is the number of new researchers since 2014, with 36 fte research focused academic appointments within the REF period. This has increased the Unit's size by approximately 75% and increased the Unit's REF submission by 77% relative to

REF2014. Academic appointments are research led - besides the 36 fte research appointments, only 1 teaching focused appointment was made within the REF period - and are strategically made to sustain and further develop areas of existing research strength, develop new research areas, and increase capacity for interdisciplinary research.

Early in the REF period, the focus was on developing research capacity and expertise in Petroleum Engineering and in Chemical and Materials Engineering, motivated by government initiatives and industry demand for academic research in these areas. Within the period, six research academics were recruited to Chemical and Materials Engineering (Afzal, Fernandez-Martin, Graca, Kechagiopoulos, Majumder, Martinez-Felipe) and nine to Petroleum Engineering (Akanji, Hamidi, Jadhawar, Rafati, Sharifi, Syed, Vinogradov, Wu, Zhou). Recent appointments support the Unit's new research in robotics and bioengineering (Chadwick, Giannaccini, Meissner, Zhan) and the University's strategic research theme in Energy Transition (McKenna, Rui, Jiang), with senior appointments made to take leading roles in these areas (McKenna, Chair in Energy Transition; Chadwick, Reader in Bioengineering). At the same time, other appointments have been made to support areas of established research strength in applied dynamics (Vaziri), power engineering (Li, Jamshidi-Far), Internet engineering (Secchi) and fluid mechanics (Michele, Stewart).

Staff development

Of the 36 research-led appointments, 29 were recruited to their first academic position within the REF period, 12 of whom are ECRs by the REF2021 definition. The Unit supports new academics to establish their research as quickly as possible by allocating low teaching loads and giving priority in the allocation of School funded PhD studentships and School funds for new research equipment. Within the period, 44 fully funded PhD studentships, 5 partly funded PhD studentships and £406k equipment funding were allocated to new academics. In addition, the Unit provides fully funded PhD studentships to support successful EPSRC First Grant or New Investigator Award applications: 2 such applications were successful within the REF period (Kartal, Kechagiopoulos). All colleagues recruited to their first academic position are assigned a senior colleague as mentor and benefit from support from within their research group. With this support, 4 academics recruited within the REF period have already been promoted from Lecturer to Senior Lecturer (Hamidi, Kartal, Kechagiopoulos, Osofero).

The Unit encourages and supports all academics through the research group structure, the research group budget, School and research group seminar series, an annual research away day and peer review of research grant proposals by senior academics. It operates a Research Enhancement Scheme (approximately £40k per annum), to which individual researchers or team of researchers apply for funds to support their research, and a Research Visit Scheme, which funds research visits to top engineering universities worldwide. Within the REF period, 12 such visits were funded at a total cost of approximately £50k (Akisanya to NTU, Singapore; Aphale to Shanghai Jiao Tong; Derksen to Princeton and to Tsinghua; Kashtalyan to Santa Barbara; Maheri to NTU, Singapore; Majumder to Purdue; Menshykov to McGill; Osofero to Zhejiang; Pokrajac to EPFL, Lausanne; Vinogradov to Monash; Wang to NUS, Singapore). The Unit also operates a 50-50 PhD scheme, whereby matched funding is provided for PhD studentships for which 50% industry funding has been secured by the academic (5 funded within the REF period) and has fully funded 3 PhD studentships for collaborative research with Curtin University, Australia. School support has been augmented by institutional support through the Principal's Interdisciplinary Fund and the Principal's Excellence Fund, which supported 23 of the Unit's

researchers and PGR students within the period to conduct pilot research studies and attend conferences and networking meetings.

Postdoctoral researchers are encouraged to apply to the University's Research Futures Fund to support cross-disciplinary networking, professional development and industry engagement, and the institution is working towards full implementation of the new Researcher Development Concordat, which allocates postdoctoral researchers ten days' professional development time per annum. The Unit has a track record of successfully developing the careers of its postdoctoral researchers: five academics appointed within the REF period were previously postdoctoral researchers with the Unit (Jamshidi-Far, Secchi, Stewart, van der A, Vaziri), as were eleven other academics included in this submission (Aleyaasin, Ivanovic, Kashtalyan, Menshykov, Menshykova, Neilson, Pavlovskaia, Starkey, Thevar, Verdicchio, Wiercigroch). Research-led promotions provide further evidence of successful staff development within the REF period: in addition to the four promotions of new staff to Senior Lecturer already mentioned, there were a further seven promotions to Senior Lecturer (Aphale, Campbell Bannerman, Dionisi, Sriramula, Starkey, Tanino, Thevar), two to Reader (Dionisi, Menshykov) and five to Professor (Akisanya, Ivanovic, Kashtalyan, Neilson, Pokrajac).

The Unit encourages researchers to take on institutional roles that further their understanding of higher education policy issues and develop their leadership skills. Neilson was the University's Dean for Industrial Engagement and Knowledge Exchange (2014 - 2109) and is Director of the National Decommissioning Centre since 2019. Guz, Ivanovic and Akisanya are members of the University's Equality, Diversity, and Inclusion Committee. Kashtalyan chairs the University's Ethics Board for Physical Sciences and Engineering, overseeing research integrity standards and governance, including the biennial School governance and ethics health assessment process. As School Director of Research, Pokrajac is a member of the University's Research Policy Committee, which oversees research strategy, policy, and performance. These institutional roles enable researchers to work with senior University colleagues on supporting and enabling research good practice, performance, and impact.

Research students

PhD students within the Unit are a mix of home and international students funded by the School of Engineering, EPSRC DTG, Carnegie Trust, industry, charities (e.g. Lloyds Register Foundation) and various overseas government organisations. Staff appointed within the first half of the REF period have been energetic in recruiting PhD students and supervising them to successful completion. This has led to a 78% increase in the number of PhDs awarded per annum over the period (14.25 fte in 2013-14, 25.35 fte in 2019-20).

PhD students are supervised by at least two supervisors, one of whom is designated the Main Supervisor. Supervisor training is provided by the University's Postgraduate Research School and is mandatory for all PhD student supervisors. Students are also allocated a Mentor, separate from the supervisory team, who takes an interest in the student's overall progress and well-being and provides an additional level of student support. PhD student progress is assessed in the first year of study at month 7 and in the second year at month 19, involving a written progress report and oral examination by two assessors, who are not part of the supervisory team. PhD students are allocated office space, a desktop computer and £1k to support their research. The Unit has a dedicated Postgraduate Research Student-Staff Liaison Committee and PhD students themselves organise an annual 1-day PGR Symposium at which senior students present on their research and early-year students present posters; PhD students also present their work within the various seminar series organised by the research groups.

The University's Postgraduate Research School provides training to PhD students in a range of generic skills, including tutoring and demonstrating, research methods, writing and publishing, presenting, digital know-how, time management and well-being, impact, and enterprise. Courses on research ethics, data management, equality and diversity, and health and safety are mandatory. PhD students complete a Training and Development Plan at the outset of their PhD and 6-monthly Progress Review forms issued by the PGR School include reflection on the student's progress against their plan.

Equality and diversity

The Unit is internationally diverse with 85% of submitted researchers and approximately 70% of PhD students originating from outside the UK. 38.8% of submitted staff have declared a BMEO background, which is significantly higher than the University or sector baselines (14% for University, 15.4% across HE sector, HESA 2018/19). 62% of submitted researchers are aged between 35 and 49; 45.1% are at Lecturer level. The Unit is conscious of the importance of supporting such a diverse community of researchers - many of whom are early-career and came to Aberdeen from institutions outside the UK - through the various School and University support mechanisms previously described.

In common with most UK Engineering units, women representation is low: 15% of submitted academics and approximately 15% of PhD students are women. Increasing women representation is an ongoing challenge. There is however evidence that women are well supported within the Unit: three of the five professorial promotions within the REF period were women, the Unit's Director of Research and its Director of Internationalisation are both women (Pokrajac and Ivanovic respectively) and Pavlovskaia is one of the Unit's five Academic Line Managers, while also holding the University position of Dean of Postgraduate Taught Studies in Sciences, Engineering and Health Care (2016-2019). CWTS Leiden Rankings (2020) place Engineering & Physical Sciences at the University of Aberdeen 11th in the UK for percentage of papers authored by female researchers (based on papers published between 2015-2018). A full analysis of the Unit's record of admitting and supporting women research students and recruiting and supporting women academic staff is contained in the Unit's successful 2018 Athena SWAN Bronze Award submission, which also contains a detailed action plan aimed at increasing women representation at all levels and improving the working environment for all staff by embedding Athena SWAN principles within the Unit's policies and operations.

The Unit follows the University's Equality and Diversity Policy in respect of all aspects of recruitment, promotion, development opportunities and disciplinary procedures, and all staff and PhD students undergo mandatory Equality and Diversity Training. Academics are also encouraged to attend unconscious bias training and there are a range of University groups available to support staff, such as the senior female network group, LGBT staff network group and the disability network group. The Head of the Unit (Guz) and the Unit's Coordinator for Equality and Diversity (Ivanovic) are members of the University's Equality, Diversity and Inclusion Committee, which oversees and progresses the advancement of equality, diversity and inclusion across the University. Akisanya is a member of the University's Race Equality Strategy Group, whose work culminated in the University signing the Advance HE's Race Equality Charter in 2020.

3. Income, infrastructure and facilities

Income

The Unit's average external research grant income is £3.5M per annum, equating to £51.2k per annum per fte submitted. Annual research income increased by almost 50% over the REF

period (£3.06M in 2013-14, £4.47M in 2019-20), increasing sharply within the last 2 years of the period as new staff established their research and successfully applied for external funding.

Increased funding from industry and government agencies is a feature of the Unit's funding portfolio: 70% of the total industry and government income was generated in the second half of the REF period, and the trajectory of industry funding remains upward. Industry funding is stimulated by University Knowledge Exchange grants, Scottish Funding Council Innovation vouchers and Knowledge Exchange Partnership grants (within the period, the Unit was awarded 21 SFC innovation vouchers and 11 researchers shared a total of £125k to support innovation, impact and commercialisation.) EU funding remains an important source of income, particularly for the Electrical and Electronic Engineering (power electronics, Internet engineering and digital technologies) and the Fluid Mechanics Research Groups. The Unit will continue to target EU funding by engaging fully with Horizon Europe.

Infrastructure and facilities

Within the REF period there has been substantial investment (£2.3M total) in facilities and equipment to support the Unit's research across the 5 research groups.

Experimental research in **Applied Mechanics** is supported by materials testing, dynamics, structures, and geotechnics laboratories. New purchases (£95k total) within the REF period include a Vallen Systeme Acoustic Emission system for structure condition monitoring, new equipment for dynamic testing of structures, a 10 kN testing machine for natural fibre material characterisation and a 300 kN, 250 mm stroke actuator for large scale structural testing. Two micro X-ray computed tomography (CT) scanners are used to study material microstructure: within the REF period a new XT H 225ST Nikon CT scanner (3 µm spatial resolution, 225 kV maximum source) was purchased (NERC, £350k) to complement the existing ZEISS Xradia 410 Versa machine (0.9 µm spatial resolution, 150 kV maximum source). To study damage in materials under load, a DEBEN CT5000 tensile and compression stage with 3- and 4-point bending jaws and 5kN capacity is placed directly into the ZEISS Xradia X-ray machine. The micro-CT facilities are also used by researchers in fluid mechanics to measure pore space geometry for input to numerical models of flow through porous media, by petroleum engineering researchers to determine formation damage and the petrophysical properties of reservoir rocks, and for research on combining artificial intelligence with digital rock imaging to optimise hydrocarbon recovery. The Unit boasts unique, high-specification facilities for its drilling technologies research, comprising two resonance enhanced drilling (RED) rigs, a drill-string dynamics rig, and a rock mechanics laboratory. The drilling rigs are capable of both resonance-enhanced and conventional drilling with controllable weight-on-bit (WOB), angular velocity, frequency and amplitude of dynamic oscillation. The drill-string rig is unique worldwide and reproduces the nonlinear and dangerous string motions that can occur during drilling. It provides controllable rotational speed and WOB, and provides measurements of angular velocities, lateral motions, torque-on-bit and rate of penetration. The rock mechanics laboratory was established within the REF period and is dedicated to experiments in which the detailed forces between a single cutter and rock formation are measured to give data for the validation and development of predictive models. The total investment in the drilling technologies research labs within the REF period was approximately £200k.

New research facilities in **Chemical and Materials Engineering** have been established with a total investment of £437k within the REF period. The new facilities include an anaerobic digestion facility with up to ten laboratory-scale reactors to support waste valorisation research (£60k), a suite of hardware for measuring the performance of proton exchange membrane, direct

methanol and solid oxide fuel cells for a wide range of temperatures and atmospheric conditions (£59k), and a flexiWAVE microwave synthesis reactor for research on CO_2 capture (£28k). A new chemical reaction engineering facility comprising fully automated high temperature, high pressure, fixed bed reactors for the study of heterogeneous catalytic and plasma-catalytic reactions has been established (£140k). The facility is equipped with multiple gas chromatography units, one optical emission spectrometer and multiple electrical diagnostics, and is being used for research on natural gas (methane) upgrading and hydrogen production from biomass. A pilot facility was established (£150k) to demonstrate the "carbon capture machine" (CCM) process in which aqueous solution of sodium hydroxide and aqueous solution of calcium chloride are combined with captured CO_2 to produce precipitated calcium carbonate as product and sodium chloride aqueous solution as by-product. (CCM was 1 of 2 European teams to reach the semi-final of the global US$20M NRG COSIA Carbon XPRIZE competition.) Other investment within the REF period includes a reconfiguration of laboratory space (£300k) and installation of six extractor hoods (£600k) to accommodate the expansion in research.

The **Electrical and Electronic Engineering Research Group** is home to substantial experimental facilities for its research in power electronics, Internet engineering and optical engineering. The Aberdeen HVDC Research Centre laboratory includes a 900V DC grid test rig with five 30 kW AC/DC converters. The rig incorporates two 30 kW DC/DC converters and a 30 kW DC Hub connecting with a smaller DC grid at 200 V. This test rig has capability for live DC fault testing and includes open-source DC grid protection relay. As part of the recent EU project PROMOTioN, a state-of-the-art 5 kV - 2 kA DC Circuit Breaker test rig and multiple DC circuit breaker demonstrators were built. The Centre also has RTDS (Real Time Digital Simulator), which enables simulation of complex power systems in real time and is available at only one other University in Scotland. Total investment in the HVDC laboratory within the REF period was approximately £350k (including the RTDS at £230k). Internet Engineering facilities include a dedicated research networking data centre, with enterprise-grade routers, support tools and platforms for the execution of networking experiments, collection of results, and analysis of Internet measurement data. Within the REF period the research infrastructure was upgraded to 10 Gb/s and a computing cluster was added to support virtualised networking and facilities for simulation (£60k). An industry equipment donation added network storage for collecting and archiving measurement data. The laboratory also hosts satellite and mobile testbed facilities, the latter via the MONROE *Platform*. Research in optical engineering is supported by laser research laboratories equipped with four vibration isolation optical tables, nine high power lasers (class 4), twenty lower power lasers, two high resolution spectrometers, four high resolution CMOS cameras and a wide range of optomechanical equipment. New investment in laser equipment within the REF period amounted to £70k. Following new appointments in robotics, mechatronics and control, the Unit is investing in a dedicated laboratory for research in this area. Existing equipment includes a mechanical robot arm, a 2-degree-of-freedom industrial manipulator, nano-positioning systems, various sensors and a swarm of mobile robots; several robotic manipulators and haptic interfaces are currently being procured.

Experimental research in **Fluid Mechanics** is conducted within the Fluid Mechanics Laboratory, which houses the Aberdeen Open Channel Facility (AOCF), two 12-m open channel flumes, a 20-m long random wave flume and the Aberdeen Oscillatory Flow Tunnel (AOFT). Other facilities include a porous media flow rig and a new tilting lock-exchange facility to study stratified shear flows. The laboratory is equipped with laser Doppler and acoustic Doppler instruments for fluid velocity measurements and state-of-the-art particle image velocimetry (PIV) systems. The Aberdeen Open Channel Facility (AOCF) is the primary research facility for research on flow

turbulence, secondary currents, sediment dynamics, mixing, and hydraulic resistance in open channel flows. The facility is an 18-m long, 1.18-m wide recirculating flume, equipped with an instrument carriage that traverses its length, and instrumentation for precision measurement of flow velocities, water surface fluctuations, flow rates and bed surfaces. The highlight is a robotic multi-camera PIV system, designed and built in-house, which can be operated remotely in multiple modes. Within the REF period, the AOCF was upgraded with new pumping and control systems, a reconfigured flow entry and flow exit, and the addition of the robotic multi-camera PIV, at a cost of £250k funded by the University, EPSRC and EU research projects. The AOFT is a 16-m long water tunnel in which oscillatory flows with periods up to 10 s and velocity amplitudes up to 1.5 m/s are generated. One of the few facilities of its kind in the world, the facility gives exceptional capability to study wave-seabed interactions and wave-sediment processes at full-scale under laboratory conditions. AOFT investment within the REF period includes *inter alia* an ultrasonic 2-component velocity profiler, high-speed camera, and precision load cells, funded by the University, EPSRC and Lloyds Register Foundation (£65k total).

New **Petroleum Engineering** laboratories have been established within the REF period to support this new research group. With £655k investment, the facilities include four core-flood rigs; two lab-on-a-chip stations with micromodels for dynamic visualisation of pore-scale multiphase flow; a unique multi-purpose EOR test facility that allows easy switching between different EOR technologies; an ultrasonics facility for investigating ultrasound-based technology applied to various downhole issues such as scale removal, formation damage reduction and condensate banking stimulation; a high pressure, high temperature (HPHT) triaxial cell with beamline measurements for 3D images of evolving fractures; and a facility for HPHT anaerobic cultivation of microbes that produce biosurfactants, which reduce interfacial tension for EOR purposes.

In addition to the above, a further £4.8M is being invested in facilities to support NDC related research. This includes a 15-kW laser and a real-time, real physics marine simulator for trialling offshore operations in virtual environments. It also includes a substantial contribution (£440k) to the £750k total investment over the REF period in enhancing the institution's high performance computing facility (Maxwell), which now comprises 1240 CPU cores, 12 TB of RAM, several specialist nodes (one with 3TB of memory), and more than 1 Petabyte of tiered storage, including 15TB of very high-performance storage.

The Unit's research is supported by 17 fte technicians based in the Unit's research laboratories and workshops.

University Support for Research

The University's Research and Innovation office (R&I) provides dedicated support for research costing, contracts, engagement with industry, research commercialisation and advice on research governance and policy. Through its Grants Academy Programme, R&I provides pump-priming funds for new research ideas, and advice and training on identifying research opportunities, applying for external funding, public engagement and achieving impact. For example, within the assessment period, pump-priming funds were awarded to Fernandez-Martin, Dionisi and Martinez-Felipe to explore the production of bioenergy and smart materials from palm tree waste in Malaysia, which resulted in a £225k International Collaboration Award in 2017, and impact-related funding was provided to Nelson, Fairhurst, Jovcic and Maheri to help realise the impact of their research on intelligent mobility, internet standards, HVDC technologies, and optimisation of hybrid renewable energy systems respectively (supporting the development of Impact Cases IC6, IC5, IC2, IC1). R&I also supports researchers with patent

filing and intellectual property. Four patent families from the Unit were approved within the assessment period (three relating to DC convertor design and one on nano-control of robotic movement) and two spin-out companies were created: Carbon Capture Machine (UK) Ltd, concerned with converting carbon dioxide into carbonates for use in cements and other products, and iVDrill Ltd, concerned with commercialising the various drilling technologies developed from the Unit's research in applied dynamics.

Open Research

The Unit meets its open access obligations with support from the Scholarly Communications Unit based in the University Library. In REF 2014, 26% of the Unit's journal articles were publicly accessible from the point of publication; open access compliance is now (2020) 79% across all journal articles and exceeds 90% for journal articles that are based on funded research. Open data is supported by the University's data management policy, which encourages and provides training in the use of data management plans, and by the University Library who ensure the correct metadata is present and appropriate copyright licences are selected. The Unit complies with EPSRC's and other funders' open data mandate. Fourteen datasets from the Unit are currently publicly available from the University's repository, which supports direct uploads as well as DOIs or web links that connect to other repositories, such as Figshare and Mendeley. The Unit's research facilities are available to academic and industry users through https://equipment.data.ac.uk/ and https://abdn.pure.elsevier.com/en/equipments/.

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

The Unit recognises that excellent engineering research is conducted collaboratively. For this reason, the Unit encourages internal collaboration through research group activities and external collaboration by inviting external speakers to speak at the School Seminar Series (18 within the REF period) and Distinguished Lecture Series (10 within the period), and funding research visits to top institutions worldwide via its Research Visit Scheme. All submitted researchers are engaged in collaborative research in various ways, evidence of which is seen in the Unit's collaborative funding and in its outputs: data from Web of Science shows that, for the period 2014 to 2020, 64% of the Unit's total outputs have at least one international co-author. The Unit's collaborations and partnerships vary in scale from a few academics collaborating on a specific research problem to large-scale projects involving many partners addressing a major research challenge. The former are too numerous to detail here, but notable examples include: Derksen's research on the fluid dynamics of mixing with Princeton University (114642632); Kashtalyan's work with the University of Seville on composites modelling (144858681); McMeeking's collaboration with the University of Virginia on cellular materials, which led to a *Nature* paper (100698035); Pokrajac's collaboration with the Technical University of Milan on sediment transport modelling (164251112); Sriramula's collaboration with Oxford on multi-scale stochastic mechanics applied to composites (138616650); and Zhan's work with the National University of Singapore and Johns Hopkins School of Medicine on the design of drug delivery systems for brain cancer treatment (170672408). Collaborations of this kind contribute significantly to the overall vitality of research within the Unit and can lead to substantial externally funded research projects. Examples include Nikora's research on bed friction in rough-bed free-surface flows with Cardiff University (EPSRC, £526k, 2014-2018) and on secondary currents with UCL, Glasgow and Southampton Universities (EPSRC, £735k, 2020-2024), O'Donoghue and van der A's work on breaking and irregular wave hydrodynamics with the Universities of Liverpool and Twente (EPSRC, £606k, 2012-2016) and Jovcic's work on DC

networks with Strathclyde, Shanghai Jiao Tong University and Huazhong University of Science and Technology (EPSRC, £735k, 2013-2016).

The Unit's larger-scale collaborations mainly occur within EU research projects, doctoral training centres and industry focused research programmes. The Unit collaborates extensively with European researchers through EU partnerships and projects (16 within the REF period), typically involving multi-disciplinary teams from several universities, research institutes, industry, and stakeholder partners. Highlight collaborative projects of this type include the International Training Networks (EU-MC-ITN) HYTECH (Hydrodynamic transport in ecologically critical heterogeneous interfaces, 2013-2016) and RIBES (River flow regulation, fish behaviour and status, 2020-2023), and PROMOTioN (2016-2020), which is H2020's largest energy research project with 33 partners addressing the technical, legal, regulatory, economic and financial barriers to the implementation of a HVDC transmission network in the North Sea. Other examples include HYDRALAB+ Adapting to Climate Change (2015-2019), involving a network of 24 institutes developing improved hydraulic modelling approaches to address climate change scenarios, and DecomTools (2018-2022) involving 12 partners developing new technologies to reduce the costs and environmental impact of decommissioning offshore wind energy infrastructure. The Unit also participates in the 22-partner European Satellite Network of Experts (SatNEx) funded by the European Space Agency (ESA), which explores new research directions for satellite telecom networks for possible inclusion in ESA's R&D programme.

The Unit has developed a strong partnership with the Scottish Government's OGTC and OGIC centres, with 16 OGTC/OGIC-industry research projects with a total value of £3.6M within the REF period. Launched in 2019, the National Decommissioning Centre (NDC) is a partnership between OGTC and the University of Aberdeen, with OGTC contributing £12.7M towards operational and infrastructure costs and the University contributing £5M through provision of buildings, staff time and fee waivers. An additional £4.8M was secured through the Scottish Government's Decommissioning Challenge Fund for facilities to support NDC research. Several NDC-funded PhD projects are underway and two major industry-funded research projects have recently been awarded (Chevron, £186k, 2020-2024; Shell, £303k, 2020-2022). RTE (Réseau de Transport d'Électricité), the largest transmission system operator in EU, is an important industry partner for the Unit's research in power electronics and has funded and collaborated on three major research projects related to DC transmission systems. The Unit also partners with industry through Knowledge Transfer Partnerships (5 KTPs within the period) and the provision of several CPD courses for upskilling professional engineers working in decommissioning and energy transition. Neilson was a member of the Steering Group for the North East of Scotland KTP Centre (2017–2019).

The Unit is alert to opportunities for collaboration and partnerships with other disciplines within the University of Aberdeen. The Unit's Chemical and Materials Engineering Research Group leads the cross disciplinary Leverhulme Centre for Doctoral Training in Sustainable Production of Chemicals and Materials (£1.05M, 2018-2023). This is a collaboration between the Unit and the University's Schools of Biological Sciences, Social Sciences, Medicine, and Natural and Computing Sciences, aimed at providing doctoral training and research in new technologies for the sustainable production of chemicals and materials from organic waste and renewable resources. The Unit's Centre for Transport Research leads cross-disciplinary research involving engineers, geographers, psychologists, sociologists, economists and computing scientists - as well as partnerships with European researchers, government policymakers and industry - on the *sustainability of transport systems with emphasis on environment, society and technology.*

Contributions to the research base

The Unit contributes substantially to the research base through journal editorial work, membership of research funding panels, organising conferences, and delivering keynote lectures.

Guz, Kashtalyan, Nikora and Wiercigroch are (or have been within the REF period) Editor-in-Chief of Applied Composite Letters (since 2019), Applied Composite Materials (since 2020), IAHR Journal of Hydraulic Research (2011-2016) and the International Journal of Mechanical Sciences, respectively. Associate Editor positions are held by Derksen (Canadian Journal of Chemical Engineering, 2014-2021; Chemical Engineering Research and Design, since 2015), Jovcic (IEEE Transactions on Power Delivery, since 2015; IEEE Power Engineering Letters, since 2015; IEEE Access, since 2019), Nikora (IAHR, Journal of Hydraulic Research, since 2017), Pavlovskaia (Subject editor, Journal of Sound and Vibration, since 2019) and Pokrajac (AGU Water Resources Research, since 2011; AGU Hydrological processes, since 2013). Nelson is Series Editor for Routledge's Transport and Mobility and Transport and Society book series.

In addition, Unit staff sit on the Editorial Boards of numerous journals including, *inter alia*, Acta Geophysica, Acta Mechanica Sinica, Biomechanics and Modelling in Mechanobiology, Coastal Engineering, Extreme Mechanics Letters, ICE Geotechnical Engineering, International Applied Mechanics, International Journal of Satellite Communications and Networking, International Journal of Solids and Structures, Journal of Oil, Gas and Petrochemical Sciences, Journal of the Mechanical Behaviour of Biomedical Materials, Mechanics of Composite Materials, Process Safety and Environmental Protection, Ships & Offshore Structures.

Membership of research funding panels within the REF period include Chadwick (National Scientific Committee of the Inspire Foundation, since 2019), Derksen (Assessment panel, PETROMAKS 2, The Research Council of Norway, 2017 and 2018; Review panel, Clusters of Excellence, DFG, Germany, 2018), Guz (Horizon 2020 RTD-TRANSPORT-MG-2014 Expert Panel, FP7-AAT-2012-RTD-L0-batch 4 Evaluation Expert Panel), Jovcic (EPSRC Assessment Panel Chair, 2015; Horizon 2020 H2020-LC-GD-2020-1 expert panel), Kartal (Royal Society International Exchange Committee 2017-2022, Commonwealth Science Conference Grants Committee 2016-2019), Nikora (Evaluation Panel 7, Engineering Sciences and Technologies - Civil and Geological Engineering, Portuguese Funding Research Council, 2018-2019), O'Donoghue (Assessment Committee, The New Delta Research Programme, NWO, The Netherlands, 2015), and Wiercigroch (Royal Society of Edinburgh, Travel and Scholarship Committee 2017-2020, RSE Fellowship Committee: Section B3 Engineering, 2019-2022).

Researchers from the Unit were on the steering or advisory committees for numerous conferences within the REF period and co-organised or co-chaired the following major conferences: Recent Advances in Nonlinear Mechanics, 2014, Harbin, China (Wiercigroch); IEEE Oceans '17, 2017, Aberdeen (Thevar); 4th UK InterPore Annual Meeting, 2018, Aberdeen (Zhou); Recent Advances in Nonlinear Mechanics, 2019, Lodz, Poland (Wiercigroch); International Conference on Engineering Vibrations, ICoEV 2020, Aberdeen (Pavlovskaia, Wiercigroch).

Unit staff presented over 50 opening, plenary or keynote lectures at major international conferences within the period, the most prestigious of these include: Keynote, 7th International Conference on Fluvial Hydraulics - River Flow 2014, Switzerland, 2014 (Nikora); Keynote, Euromech Colloquium 562 on Stability and Control of Nonlinear Vibrating Systems, Italy, 2015 (Wiercigroch); Keynote, 14th Workshop on Two-Phase Flow Predictions, Germany, 2015

(Derksen); Keynote, CANCAM, Canadian Conference on Applied Mechanics, Canada, 2015 (McMeeking); Keynote, Gordon Conference on Adhesion, USA, 2015 (McMeeking); Keynote, 11th International ERCOFTAC Symposium on Engineering Turbulence Modelling and Measurements (ETMM-2016), Italy, 2016 (Nikora); Opening, 45th Summer School of Russian Academy of Sciences on Advanced Problems in Mechanics, Russia, 2017 (Wiercigroch); Plenary, 3rd International Conference on Numerical Methods in Multiphase Flows, Japan, 2017 (Derksen); Plenary, 14th International Conference on Vibration Engineering and Technology Machinery, Portugal, 2018 (Wiercigroch); Keynote, Symposium on Fatigue and Fracture in Memory of Paul Paris, Society of Engineering Science Meeting, USA, 2019 (McMeeking); Plenary, 38th IAHR World Congress, Panama, 2019 (Nikora).

Outstanding contributions by the Unit to research and the research base have been recognised by prestigious fellowships and major international awards. McMeeking (elected in 2014), Nikora and Wiercigroch are Fellows of the Royal Society of Edinburgh (FRSE). McMeeking and Nikora (elected in 2019) are Fellows of the Royal Academy of Engineering (FREng), and McMeeking is also a Member of the US National Academy of Engineering. Jovcic (since 2021) and Watson (since 2019, now retired) are IEEE Fellows. Jovcic is also an IEEE Power and Energy Society (PES) Distinguished Lecturer. Within the REF period, McMeeking was awarded the 2014 Timoshenko Medal of the American Society of Mechanical Engineers for "outstanding distinguished contributions in applied mechanics" (the Timoshenko Medal is considered to be the highest international honour in solid mechanics) and the 2014 William Prager Medal of the Society of Engineering Science for "achievements in solid mechanics". Nikora was awarded the American Society of Civil Engineers (ASCE) Hans Albert Einstein Award (2017) for "outstanding theoretical and experimental contributions to the engineering profession in the field of cohesive sediment transport, turbulence structure, and alluvial river mechanics" and the IAHR 7th M. Selim Yalin Lifetime Achievement Award (2019) for "experimental, theoretical or numerical research that has resulted in significant and enduring contributions to the understanding of the physics of phenomena and/or processes in hydraulic science or engineering".

Contributions to economy and society

The Unit's contributions to economy and society range from the design of engineering components that enhance the competitiveness of UK industry, to taking a leading role in addressing new challenges of profound national societal and economic importance. An example of the former is the Unit's research on a novel friction-grip technology for oil and gas casing hangers that led to the technology being used in nearly one-third of the approximately 120,000 hangers used in oil and gas operations worldwide. The stand-out example of the latter is the Unit's role in establishing and leading (Neilson) the National Decommissioning Centre, bringing industry and academic expertise together to address the engineering, environmental, economic and legal challenges associated with decommissioning or reusing the estimated 100 offshore platforms and 5700 km of subsea pipeline that will become redundant on the UK Continental Shelf (UKCS) over the coming decade. Action 3 of the Government Response to the Call for Evidence on "strengthening the UK's offshore oil and gas decommissioning industry" (2020) calls on the Decommissioning Task Force, OGTC and the NDC to develop a plan with regulators and industry for developing new technology and solutions for decommissioning, aimed at achieving the regulator's (Oil and Gas Authority) 35% target reduction on the estimated starting-point cost to the taxpayer of £59bn.

The energy sector's shift from fossil-based sources of energy to renewable sources has profound economic, environmental, and societal impact. Energy transition related research

features strongly in the activities and strategies of each of the Unit's research groups. Contributions with notable impact already achieved include HVDC technologies that are changing industry's approach to the design of offshore renewable power transmission to enable large-scale expansion of offshore wind energy, and new tools for optimising the design of hybrid renewable energy systems, which have been used for renewable energy systems in the UK, Malaysia, Jordan and Turkey, and for mobile water systems in sub-Saharan Africa and India. Guz is a member of the Energy Board of Opportunity North East (ONE), a private sector catalyst aimed at driving transformational change in north east Scotland's economy in response to energy transition, and is also a board member of the Scotland-wide Energy Technology Partnership, which brings together industry and academic expertise for energy-related research.

The Unit's Internet engineering research has contributed new analyses, protocols, algorithms and architectural design to Internet Standards published by the Internet Engineering Task Force (IETF) and published 11 specifications in the Requests for Comments (RFC) series. These documents underpin Internet operation globally and are embedded within technology products that support the economy and society in numerous ways. An example application is Intelligent Mobility (IM), whereby data and technologies are used to connect people, places, and products across all transport modalities, and which is expected to have a global market worth £900 billion by 2025 (Transport Systems Catapult). The Unit's Centre for Transport Research is a recognised thought-leader in IM, particularly focused on applying technologies for more efficient, equitable and sustainable practices to complete end-to-end journeys, and developing shared mobility models to enhance transport services for under-served populations in peri-urban and rural environments. This research has contributed to increased government and industry interest in Mobility-as-a-Service (MaaS), with the travelling public and wider society being the ultimate beneficiaries.