Institution: University of Sheffield

Unit of Assessment: 12B - Aeronautical, Mechanical, Chemical and Manufacturing Engineering: **Chemical and Biological Engineering**

a. Overview

The Department of Chemical and Biological Engineering (CBE) is substantially larger and more successful since RAE2008: we have grown submitted staff to 30 (up 50%), PhD student entry is now 46 p.a. (up 230%), and research income (REF4b) is £13.6m (up 155%). We collaborate with over 60 non-academic and 100 academic organisations worldwide, across the process, health, environment, energy and pharmaceuticals sectors. A core strategic change has been the department's name, with replacement of "*Process*" with "*Biological*" in 2010 to reflect our view that future prosperity will involve understanding and leveraging both *chemistry* and *biology*.

Due to our increasingly interdisciplinary research, we have realigned our structure into 4 themes (allowing for both fundamental research and transfer to end-users):

I. Smart Materials*:* particle products (granules, crystals), nanotechnology, modelling
II. Life sciences interface / biological engineering*:* biological engineering, medicine interface
III. Environmental and energy engineering*:* water, energy generation and storage
IV. Bio/chemical microsystems*:* fluidic circuitry, CO_2 utilisation, green catalysis

Our collaborative work cuts across themes, using application-aware teams and research centres / institutes to ensure that our research addresses key societal challenges. We lead the Institute for Chemical Engineering at the Life Science Interface (ChELSI) and The Sheffield University Waste Incineration Centre (SUWIC). We also co-lead the Pennine Water Group (PWG) with Civil and Structural Engineering. These enable broad internal and external multidisciplinary collaboration.

b. Research strategy

1. Vision and strategy

We seek to apply our engineering strengths to problems in chemistry, biology, biomedical and materials science, through developing experimental tools coupled within a rigorous mathematical framework. We aim to address fundamental problems and those with direct stakeholder impact.

I. Smart Materials aims to explain and control particle behaviour from the nanometre scale of a nucleus, through the micrometer scale of a single crystal, to the macro scales of whole vessels. We will continue to employ biomimetic approaches, fundamental rate process modelling and experimental validation to provide underpinning understanding to be transferred to our extensive portfolio of end-users (e.g. pharmaceutical – GSK and AstraZeneca; food – Nestlé).

II. Life sciences interface / biological engineering aims to support UK bioindustry to shift from empirical screening-led to engineering design-led technologies that enable rapid prediction and control of bioproduct manufacturability. We will lead the development of industry-relevant computational / bioinformatic tools and systems-level modelling to allow us to understand complex biology and create new synthetic components and organisms that can speed complex new bioproducts to market underpinned by the establishment (see §d5) of an Advanced Biomanufacturing Centre (in partnership with our extensive enduser collaborations – e.g. Lonza, Pall, Medimmune). These tools will also aid us to expand our ability to address problems at the interface with health.

III. Environmental and energy engineering aims to ensure that water, energy and associated support infrastructure are always available at the right place, time, and quality and at the right economic and environmental cost. Our water strategy will continue to employ modern biological and engineering tools working together with stakeholders (e.g. water companies, regulators and society) to develop acceptable solution frameworks. We will continue to seek to understand and design solutions based on fundamental chemical and biological knowledge, building on our substantial work in waste-to-energy, alternative approaches to fuel (H_2; diesel; higher alcohols) production and CO_2 utilisation. Our energy storage strategy is to develop new materials / formats for aqueous electrolyte batteries to reduce costs by 50% for grid connected energy storage, allowing energy storage to be deployed for the stabilisation of electrical grids with high penetrations of renewable energy.

IV. Bio/chemical microsystems aims to measure, model and understand transport and reaction properties at small length scales and apply that knowledge in various application areas that range from microfluidic devices "scaled out" and larger devices "scaled up". This theme is also the driver for our large initiative in Carbon Capture and Utilisation (CCU) whereby we will employ catalysis,

novel separation processes, modeling and life cycle analysis to ensure that we have a future in which CO_2 will be sustainably captured and converted into valuable materials.

2. Evaluation of progress against plans described in RAE 2008

Overall progress since RAE 2008.

In RAE2008 we planned to *employ the best people, in excellent facilities, to work on core quality of life and engineering practice problems through the interface of chemical engineering and the sciences*. Recognising the increasing multidisciplinarity and collaborative nature of our research we created four application-focussed themes to replace the formal people-focussed groups present in RAE 2008 (§a and §b1). We achieved overall growth with a concentration in biological engineering and a deeper relationship with the medical sciences, as planned. We also successfully applied our engineering strengths to problems in chemistry and materials science as we describe below, for example, for "Smart Materials". In line with our 2008 strategy, we developed experimental tools and coupled these within a rigorous mathematical framework. We have grown substantially in all activities, and exceeded our RAE 2008 strategic plans and continue to flourish as a multidisciplinary environment of research excellence. Particular key achievements are:

- ***People:*** we have increased academic staff in all themes from 20 in 2007 to 34 (returning 30) in 2013, 75% of the growth is early career staff, but also we appointed Hall to a Personal Chair to provide energy storage leadership. We have also appointed 3 new staff and 2 research fellows in the life science interface theme as well as a Business Development Manager to support commercial sector grant capture. This has been enabled by a 50% turnover growth (£8.5M in 2008 to £12.7M in 2013).
- ***Large Grants:*** highlights include a £1.2M EPSRC Platform Grant for the Pennine Water Group (unique nationally for its third renewal); a £5.7M EPSRC Programme Grant on Carbon Capture and Utilisation (4CU); and a £4.2M EPSRC energy storage grand challenge grant.
- ***Research Space:*** our growth has been accommodated by a renovation and conversion of 2750 m^2 of space, supported by an investment of over £7.2m (see also Section §d2).

Evidence of growth in all areas includes the following:

Period	Number of Grants per annum	Announced Income per annum	Journal articles per annum	PhDs awarded per annum
01/07	13.3	£2.16m	57.6	11.7
08/13	19.8	£2.72m	97.2	15.4

Our success is echoed across the Faculty of Engineering: total research income has become the 2nd highest in the UK (2011/12 HESA; THE June, 2013), with turnover increasing from £78m to £105m.

Our **research achievements since RAE 2008** all exceed our plans and are detailed by theme:

Smart Materials. *We planned in RAE 2008 to continue and grow activity on pharmaceutical, homecare and agricultural products/processes and expand towards nano-scale/structured materials (e.g. biological, colloids).* Our granulation research developed novel instrumentation and linked micro-scale measurements with multi-scale modelling. This provided granulation solutions to international industry (Nestlé; AstraZeneca; GSK; P&G and BASF) (see impact case study) and >£2.3m announced industrial funding (24% extra announced income than RAE 2008). We organised successful International Granulation Workshops (2009, 2011 and 2013; 300 attendees, > 60% industrial). We applied our knowledge orthogonally to protein aggregation, with implications for human health due to associations with many debilitating diseases including Alzheimer's and Parkinson's. In nanostructured materials research we developed diverse methods to assess spin-coating of polymer films (for polymer electronics applications) in-situ in real space, providing evidence for how phase separation and crystallisation occur during processing. We generated fundamental understanding of how self-organised nanostructure-based polymer solar cells determine their performance, thus informing future process design to enhance performance.

Life sciences interface / biological engineering. *We planned in RAE2008 to grow leading chemical engineering-driven life science research and embed knowledge, practices, and expertise in the UK*. Post-genomic analytics has been a key tool – e.g. biological mass spectrometry (MS) was used to (i) understand how the immune system of bacteria avert attacks from viruses / bacteriophage (published in e.g. *Science* and *PNAS*) in order to limit the spread of antibiotic resistance and adapt economically important bacteria for resistance against phages and genome editing; (ii) understand limiting processes in biopharmaceutical production yields in cell factories for industry (CASE awards and new BBSRC

Bioprocess Research Industry Club – BRIC - funding) so as to improve manufacturability and yields (e.g. 300% improvement in glycoprotein production); (iii) understanding roles of certain proteins in disease progression (e.g. prostate and colon cancer) to lead to early detection.

Environmental and energy engineering*. We planned in RAE2008 to develop low-to-zero emission energy, management/re-use of biomass/residue materials, deepen non-fossil fuels work (e.g. H_2) and useful utilisation of CO_2.* We developed a fundamental understanding of energy from biomass/waste (experimental and validated models) with significant benefits to related stakeholders including industry (e.g. Eco Energy Ltd, E.ON UK Ltd and Veolia Ltd) and UK local authorities. We have demonstrated pathways to higher specific energy storage technology by showing that Li-air battery capacity is related to the cathode pore structure and that we can double the specific energy capacity of supercapacitors using ether bond-containing ionic liquids. Reaching beyond RAE 2008 plans, we used advanced molecular microbiology techniques to develop more sophisticated and targeted methods to ensure drinking water remains safe to drink.

Bio/chemical microsystems*. We planned in RAE2008 to deepen and develop computational and theoretical approaches for fluidic flow and reactions with a key aim of exploiting transport properties.* The underpinning science of microbubbles, and its exploitation, has been a key activity. This has cut across all four themes, with impacts made in transport phenomena in cardiovascular science, improved CO_2 exchange via airlift bioreactors for algal biofuels; and reduced bubble size for aerated wastewater treatment. We have also developed microplasma reactors to generate hydrogen at very low power, very low voltage, and atmospheric pressure. This work has garnered a number of prizes (see §e.3.V) and been spun out into Perlemax Limited.

c. People:

1. Staffing and recruitment strategy and staff development

Our ***staffing strategy*** was to *grow* significantly across our themes via targeted appointments and *to deepen our commitment* to apply our world leading engineering research capabilities to problems in chemistry, biology, materials and biomedical science. We now incorporate 34 FTE, of which 30 FTE are submitted for REF 2014. 12 Cat A staff were appointed during the assessment period, with 2 Cat A staff retiring or departing to positions elsewhere (promotions). Our ***recruitment strategy*** focused on primarily attracting leading early career researchers to Lectureships, bringing creativity, vitality and renewal to established research themes, and developing this talent as future discipline leaders. Of our new appointments, 5 were at Lecturer level (plus 2 were RAs awarded research fellowships and 1 was promoted into a research fellowship). All appointments have succeeded in attracting significant external research funding (e.g. Vaidyanathan built a network of Indian collaborators on algal biomass utilisation, leading to a BBSRC/Indian DBT grant - 2013-6, £1.2m). The strengthening of the four themes is summarised as follows:

- ***Smart Materials****:* Smith, Ebbens and Zhou brought in expertise in particle interactions, soft materials and biological-colloids.
- ***Life sciences interface / biological engineering:*** Wong, Falconer, Dobson and Evans brought in expertise in protein engineering, biophysics, systems biology and analytical analysis. This team is now the second largest academic biological engineering team in the UK.
- ***Environmental and energy engineering:*** Lisbona, Jensen and Pandhal brought in expertise in energy storage/safety environmental and ecological engineering coupled with environmental post-genomics. Water research was strengthened by recruiting through open advertisement Biggs (then a Reader in CBE) to a Professorial position to lead on water applications. We also invested in new leadership of energy storage, recruiting Hall, a world recognised authority, to a Professorial position.
- ***Bio/chemical microsystems:*** MacGregor has brought in expertise in catalysis.

Our ***financial plans*** indicate that we will recruit at least 1-2 additional academic staff p.a. to 2018, targeted against our strategic initiatives outlined in §b1, and we aspire to attract and retain internationally leading staff.

Our ***staff development strategy*** is to promote a culture of research excellence, vitality and sustainability through a supportive framework of staff review, workload management, reward and promotion. Our Executive Committee (Exec) is chaired by the Head of Department (HoD) and governs overarching research strategy, engaging in scrutiny of new appointments and research investments (infrastructure and facilities planning and allocation), theme research strategies, horizon scanning and

foresight activities. Exec instituted the following actions to promote vitality and sustainability of research in the REF period:

- A series of funded away-days (at least 3 for each of our four themes) to stimulate research proposals within and between our four research themes and engage in research foresight and strategy development; one of these led to the successful 4CU EPSRC Programme Grant.
- A Research Pipeline, managed by Exec, to stimulate, prepare and support research proposals, leading to 301 applications and 125 successful outcomes; our success rate with EPSRC applications reached as high as 93% pa in the REF period (41% average).
- A Departmental Strategic Reserve Fund was created, through provision of a CBE operating surplus (currently £1.1m), enabling matched funding of, or sustainable investment in Research Fellowships; start-ups; studentships; equipment upgrade / purchase; networking opportunities.
- Arrangements to return 10-15% of income overheads to PIs on grants, enabling staff to pump prime new research and receive recognition of success.
- Implementation of Red Lining Weeks (2 p.a.) in which teaching and administration activity is suspended, providing staff with an opportunity to focus on research outputs and proposal writing.

We promote a research culture with our staff via research seminars (~18 p.a., 33% external speakers), refurbishment of space for discussion, display of acclaimed outputs, seminars and research meetings (e.g. ChELSI Conference 2012; Solar Energy 2012), allocation of time within our Workload Allocation Model to engage with learned societies, reviewing, and research community activities. We also benefit from Faculty investment of £6.4m in cross-faculty research support, including ten Business Development Managers and associated staff in the Faculty of Engineering Research & Innovation Hub.

All new appointments are supported through investing our (CBE) resource in provision of high quality space, funded PhD studentships, cash start-up (£10-£100k: e.g. £50k for Jensen for environmental engineering) and other start-up requirements, which exceeded £340k (cash for early career staff) plus we core funded 8 PhD studentships over the REF period. Newly appointed early career staff engage in a ***probation process***, to launch them on a leadership path. Through engagement with a personal mentor and cohort based training, an understanding of the expectations of academic excellence in research, teaching, management and professional partnership is developed. We support our staff to meet ambitious but realistic targets for research outputs (9 papers over 3 years), grant capture (£250k over 3 yrs) and impact delivery, whilst also managing teaching (25% of a 'normal' established academic load in year 1; 50% year 2 and 100% year 3) and administration (0% in year 1; light in year 2, 'normal' typically by year 3) loads. As evidence of success, staff who were probationary in the period, have earned >£2.43m of apportioned income (e.g. Elder (£397k), Dunbar (£275k) and Vaidyanathan (£271k)). ***Established academic staff appointees*** receive substantial support based on a strategic business case – typically this is large-scale infrastructure creation/improvement (see §d.2). Established staff also can bid for departmentally funded PhD studentships and are beneficiaries of overhead investment (§b.3).

Through the annual ***Staff Review and Development System*** (SRDS), we support all staff in career development and planning of academic goals, with a focus on ambitious research. Success is measured by formal review against key performance indicators designed to manage staff progression and build a track record for promotion. A formal ***workload allocation model*** is used to moderate duties across CBE, recognising individual strengths and career ambitions, and providing research leaders with reduced teaching loads to focus on strategic initiatives (e.g. James to develop plans for an Advanced Biomanufacturing Centre announced October 2013); secondments or sabbatical. We reward success in academic practice, with emphasis on research excellence, through ***promotion*** to senior grades by evaluation against clear but demanding criteria, including research metrics. In this period, 3 staff were promoted to Senior Lecturer / Reader and 3 staff were appointed/promoted to Chairs. Cultivating academic ***leadership*** is a cornerstone of our staffing strategy and we advance aspiring staff through The Sheffield Leader programme, a challenging 9 day development programme, designed to accelerate realisation of leadership potential (Biggs and Zimmerman).

Research staff have equal access to mentoring, annual review (SRDS) development and management opportunities. As a result, in the Careers in Research Online Survey (2012) 86% of our RAs agreed / agreed strongly that they are encouraged to take part in personal and career development (sector average 73%). Furthermore, Sheffield achieved the European Commission HR Excellence in Research award (2012). This signifies that we have a high quality research environment

for ECRs aligned with the UK Concordat for the Career Development of Researcher's 7 Principles.

All senior staff have an SRDS objective to develop their researchers towards grant application writing – especially fellowships. Evidence of our supportive structure includes:

- RAs recruited as lecturers in open competition: Jensen and Noirel
- RA promoted onto an open-ended Research Fellow contract: Evans
- RAs upgraded onto our 'Fellowship to Lectureship' scheme: Ebbens and Pandhal (see below)

Fellowships, exchanges and visits. We encourage all staff to collaborate widely and apply for fellowships and secondments to support this. Pandhal (NERC Fellow) and Ebbens (EPSRC Career Acceleration Fellow) will automatically be considered for open-ended Lectureships at the end of the fellowship. We have hosted and sent staff on funded discipline hops (e.g. Wellcome Trust: CBE staff to cardiovascular science and Dental School staff to CBE). We have one staff member with an RAEng Industrial Secondment (microbubbles) and one funded via an EPSRC KTA account for 12 months to work with bioindustry. We also have a healthy number of visiting scholars and visiting professors (e.g. Palzer, Nestlé; Litster, Purdue, USA; Reardon, Colorado State University, USA).

Equality and diversity. We are committed to equality of opportunity in all activities, and promote the University's *Excellence through Inclusion Strategy* and its *Female Academics' Progression Action Plan*. Our Opportunities Committee (chaired by the HoD) considers data on gender equality relating to student admissions and performance, as well as staff recruitment and progression, in preparation for a 2013 Athena Swan Bronze application. Our supportive approach to staff development has proven successful in attracting candidates from a diverse range of backgrounds, and 7/12 staff appointments were international. We are strongly committed to supporting our staff by enabling working parents and carers access to flexible hours and part-time contracts where requested. We apply light teaching loads (0 for at least a semester) and research support (e.g. £15k coupled to 0 teaching load for the returning semester) for female academics returning from maternity leave.

2. Research students

As PhD students are the lifeblood of our research-led department, we have focussed on recruiting and developing the best students from the UK and overseas.

Recruitment. To recruit the best students, we implemented a rapid selection and offer process with a Postgraduate Admissions Tutor and full time clerical support. We fund a range of advertisements and targeted strategic scholarships that are reviewed by our Scholarships Selection Committee. Although academic staff generate the research funding to employ PhD students, this is supplemented by full- or part-funded studentships, with ring fenced priority given to new academic staff. Since RAE 2008, in addition to RCUK and University/Faculty Scholarships, we used £600k of core budget to fund PhDs. As a result of this effort, the annual PhD student intake rose from 20 in 2008 to 46 in 2012/3, which will lead to year-on-year increases in the number of doctoral degrees awarded per staff FTE.

Training, development, facilities and support. 86% (up from 71% in RAE2008) of our PhD students submit within 4 years. This has been enabled by our support mechanisms:

- We have a formal ***supervision and monitoring*** process for all PhD students and they meet their supervisors at least monthly. Our progression milestones are at 6 (research proposal), 12 (confirmation dissertation and viva voce exam), 18 (conference paper), 24 (CBE poster day), 30 (CBE seminar) and 36 (submission expected) months. Those who still have not submitted by 42 months are required to prepare an action plan and discuss it with the HoD.
- All PhD students receive an integrated induction, a designated desk and computer, technical support and travel funds (e.g. we paid for all PhDs to attend the 2013 IChemE Research Conference).
- Sheffield's Doctoral Development Programme (DDP) provides all PhD students with bespoke skills and competency-based training and research ethics awareness, equipping them with transferrable skills to extend their employability. In addition, Sheffield's Think Ahead scheme provides a collaborative, research-led framework for professional development.
- CBE run a Research Methods taught module codifying research philosophy, best practise and planning.
- CBE's PhD students feel valued and respected as part of an inclusive environment, with regular social occasions (e.g. monthly coffee and cakes – aka "Fat Friday" - for all staff and PhD students).

d. Income, infrastructure and facilities

1. Research infrastructure investment plans

The creation of the faculty structure in 2008 enabled a programme of significant growth of and investment in Engineering. Over the next 5 years, improving our infrastructure will be a central aspect of our strategic plans. This forms part of a University-wide £250m capital plan, with £154m committed to the Faculty of Engineering for the period from 2010 to 2015.

The **Engineering Graduate School Building** (£21m) will open in Dec 2013, providing 5,355 m^2 of laboratory and office space for interdisciplinary research groups and teaching space for postgraduate taught and postgraduate research students. The building will house PhD student and academic offices from CBE (150 m^2), and postgraduate research students from across the Faculty will use the building's resources. The **New Engineering Teaching Building** (£81m) will create by 2016 a purpose built teaching space occupying 19,500m^2. This relocation of teaching laboratories will free up 240m^2 space in CBE to accommodate new research labs, academics and research staff.

CBE is also undertaking a £500k programme of upgrading space (175m^2 of biophysics, microscopy, insect cell culture and water labs) and PhD student offices (55m^2 of new space).

2. Research infrastructure investment in CBE since RAE 2008.

The University has invested £7.2m in CBE infrastructure resulting in 2750 m^2 of new, high quality space since 2008. A major component of this was a £5.2m investment from the University for the improvement of >1500 m^2 of CBE space (laboratory, offices and communal) to support the *Life science interface* theme. The ChELSI facilities underpin the research programmes of 12 members of academic staff directly. Other improvements include:

- *Environment*: An investment of £225k in water infrastructure in CBE includes, unique to the UK, 2m diameter annular flume for analysis of sewer processes to be housed in an environmentally controlled laboratory. The University has wholly funded this collaborative facility with Civil and Structural Engineering. Also, a 50m^2 water lab supports molecular microbiology work.
- CBE has state-of-the-art, recently commissioned, labs for particle products (143m^2) including the Nestlé labs for food processing.
- *Smart materials:* We converted teaching space into bespoke nanotechnology labs (£150k) and refurbished research space (40m^2) to support early career staff and an EPSRC fellow.
- *Microsystems*: For microbubble and plasma microreactors, bespoke facilities in the Kroto Research Institute (KRI) were provided and Garden Street Labs (£215k, 62m^2) were renovated.

3. Investment in research facilities.

Since 2008, core CBE funds of £800k has been used for equipment and related expenditure, and we plan a further core budget expenditure of £300k p.a.to 2018. Investments this period include:

- ***Smart Materials****:* Our world-class granulation facilities comprise >£1m range of bench scale and laboratory scale equipment for wet and dry granulation. There has been particular investment in facilities for sophisticated particle scale measurements (e.g. single drop-powder interaction measurement at very short time scales). Underpinning our nanotechnology growth, we purchased specialist facilities for submicron imaging of nanoparticles and nanobubbles, electron microscopy and cameras and microscopes for fluorescence imaging and high-speed stroboscopic imaging.
- ***Life sciences interface / biological engineering:*** £1.4m worth of analytical equipment (e.g. tandem MS) and equipment for protein biophysical characterisation have been added to our state-of-the-art analytical facilities and mammalian and bacterial biotechnology facilities.
- ***Environmental and energy engineering:*** SUWIC have well equipped facilities (small to pilot scale combustion, gasification and pyrolysis experimental rigs) and analytical tools (e.g. suite of MS tools, including inductively coupled plasma) that have benefited from additional £105k investment in analytics (e.g. GC, AAS, TGA). Environmental engineering has benefitted from investment in modern molecular microbiology and analytical facilities (e.g. incubators and Fourier transform infrared).
- ***Bio/chemical microsystems*** has seen substantial investment in numerous (ml to 2.2m^3 scale) reactors for microbubble work and plasma work. Investment in analytical tools has also been made in particular for catalysis (e.g. GC-MS and reactors, £100k).

4. Provision and operation of specialist infrastructure and facilities

- ***ChELSI*** is distinctive for chemical engineering departments in the UK providing specialist facilities for high-end biological mass spectrometry (£1.4m investment this REF period): 4 x tandem mass

spectrometers coupled to nanoflow HPLCs. We have completely refurbished our old and redundant combustion labs and three floors of our building (£5.2m investment) to house this prestigious Institute.

- ***Granulation***: We have the largest and best-equipped academic granulation laboratories internationally, underpinned by refurbishment (73m^2), new lab space (esp for food: Nestlé lab 70m^2) and ca. £1m in industrial grants and studentships in recent years. It is unique, due to the diversity of equipment from lab-scale to pilot scale (high shear mixer; fluidised bed; twin screw; roller compactor; spry dryer) coupled with modern analytical and analysis tools (e.g. AFM).
- ***Energy/Environment***: We have pilot-scale pilot scale facilities at our Harpur Hill Laboratories (1240m^2) allowing for high temperature experiments, combustion work, and a remote field station for fires and explosions (e.g molten metal biomass gasifier, USS gasifier). It is staffed by two technicians.

5. Research Award Portfolio and Plans.

We have a healthy funding portfolio as evidenced in REF4b: 76% UK public funders (e.g. EPSRC, BBSRC, NERC, Royal Society), 7% government bodies, 8% EU and 9% industry (the latter for our particles and therapeutic protein research). We have a high EPSRC success rate (41% average; 86% in 2013) and EU (42%) demonstrating the excellence of our applications. Key RCUK awards are:

- Biopharmaceuticals work – (i) 2 recent BBSRC Bioprocess Research Industry Club grants (£956k) to work on therapeutic proteins (Wright and James; 2013-2016); (ii) 14 PhD students with biopharmaceutical industry support (inc links to RCUK supported studentships, inc DTGs)
- An EPSRC Programme Grant to Allen (£4.56m) to work on Carbon Capture and Utilisation
- Four EPSRC Supergen grants (£1.35m) involving Sheffield to work on biomass and energy
- A 2013 EPSRC £4.2m energy storage grand challenge infrastructure & H_2 integration grant.

We are proud of our links to industry for our particles research (see impact case study), where 21 PhD students were supported by industry (e.g. Nestlé, BASF, AstraZeneca, Proctor and Gamble and GSK).

Our ***future funding plans*** are tailored to deliver strategic and targeted staff and capability growth across our four research themes. We aim to grow overall research income significantly as our early career staff "mature" and become strong research leaders due to our probation process and supportive research environment. Building on current high success rates, we plan to increase the number of applications per staff member, without compromising quality. We recognise and welcome the paradigm shift in EU funding strategy in Horizon 2020, coupling research to innovation and market, with a strong focus on industry sectors such as nanotechnology, biotechnology and manufacturing to solve societal challenges. We will utilise the newly-appointed Faculty EU funding specialist to assist us in targeting substantial growth of our EU portfolio in the next period.

Our focused Impact Strategy provides a platform to grow and expand our commercial research income, through more effective strategic engagement with end users (see Business Development Manager: §b.2). Our mission will be to develop selected high value end-user partnerships. A particular example where we will invest heavily (ca. £100k p.a. from core on support staff and materials for at least 3 years) is biomanufacturing – we will set-up a cross university Advanced Biomanufacturing Centre (ABC) led by James, because the UK bioscience sector is rapidly growing, with a community of 942 companies and £5.5bn of turnover. Biopharmaceuticals invest more in R&D than any other sector in the UK, representing over 30% of total R&D spend.

We will maintain a focus on securing large grants to support research theme sustainability (building on our track record: e.g. 4CU and ChELSI), whilst supporting research vitality and diversity via medium scale funding. We will place special focus on supporting early career staff in First Grant and Fellowship applications (e.g. tailored sabbatical type arrangements, mentoring and business plan support through our BDM). We will continue to support large grant applications by matched funding (e.g. investment in PhD studentships, with £1.2m from core budgets forecast to 2018).

6. Knowledge transfer and professional services

We strongly encourage working with end users to achieve maximum research impact. This is undertaken via a number of mechanisms with a total announced income of £1.69m: consultancy (£138.2k) KTP (£391k), KTA (£72k) and direct research sponsorship (£1.078m).

e. Collaboration or contribution to the discipline or research base

1. Collaborative & Interdisciplinary research.

Our collaborative and interdisciplinary research, evidenced with over 550 joint ISI publications, is conducted with approximately 100 partner universities (one quarter of which are UK-based, the

remainder international) and over 60 non-academic organisations. Research across our four themes and across a range of application areas has fostered and enhanced this interdisciplinary collaboration. Exemplars demonstrating the scale and reach of collaborative and interdisciplinary research are:

- The ChELSI Institute is an interdisciplinary institute integrating chemical engineers and life scientists to advance understanding of biological systems for health and industrial exploitation. With ca. £4.3m of EPSRC (to December 2012; EP/E036252/1) support, the research strategy generated over 220 journal papers, 23 industry collaborations, 40 academic collaborations, >£5m in announced grants, and 27 PhD student completions. In addition, ChELSI hosted two international conferences.
- Biggs is a co-director of the Pennine Water Group (PWG). The PWG is a 3 times EPSRC funded Platform Grant centre (EP/I029346/1, £1.2m) for research dedicated to water and wastewater. PWG is the largest urban water research group in the UK spanning across Chemical, Civil and Mechanical Engineering as well as Social Sciences and containing over 50 active researchers.
- The newly started £4.56m 4CU - A Coordinated, Comprehensive approach to Carbon Capture and Utilisation - EPSRC Programme Grant (EP/K001329/1) comprises 12 Academics, 11 PDRAs and 9 PhDs students from the University of Manchester, UCL, Queens University Belfast and University of Sheffield. This is a key pillar of our energy and environmental research for the next period.

2. How research collaborations have informed research activities

We have aligned our research strategy with national, regional and European priorities. Research programmes have been shaped to map onto *RCUK/TSB thematic priority areas* in sustainable processing, industrial biotechnology, healthcare, food security, and sustainable energy. We are heavily engaged in EU research *priorities* including sustainability, renewable energy generation and water.

Major CBE/joint initiatives (e.g. ChELSI, PWG, 4CU, EPSRC Supergens) benefit from external (international) advisory boards (EABs), comprised of internationally leading engineering and end-users, to assist in shaping strategic research aims and maximise translation. Direct end user collaboration has influenced our research strategy / activities by identifying, growing and exploiting opportunities for mutual benefit. Examples of *end-users* shaping our research are:

- Our successful relationship with the biopharmaceutical sector has broadly shaped our biological engineering research thinking. We focus on providing our partners with disruptive new tools and ways of working that can be implemented to reduce time and costs spent in the creation of synthetic biomanufacturing systems - from biofuels to biopharmaceuticals. This has led to BBSRC BRIC grants and industry funded studentships (9 PhD graduates employed in the sector as a result).
- Long-term relationships with diverse industry partners with particle-based products (e.g. Nestlé, Lausanne Switzerland; BASF Germany; ARAMCO Saudi Arabia; AZ Sweden; Procter & Gamble) have helped shape our research priorities in particle processes, especially granulation and crystallisation. This has led to generic fundamental understanding and design rules.
- Our long-term collaborations with regional councils (e.g. Sheffield) and industry (e.g. E.ON) have informed our research strategies on heat and energy supply for society. For example, this led to geographic information systems modelling of existing district energy networks. Results are being used by the Sheffield Local Authority to design a two-fold increase in scale of the heating network.
- Since publicity from the Royal Society Innovation Award on energy efficient microbubbles in 2010, >100 industrial enquiries about novel uses led to feasibility studies with 29 company collaborations; 12 as student sponsorships. These scoping studies identified fundamental engineering science research targets, with possible paradigm shifts in productivity of gas-liquid systems. Patents filed in 2012 are the subject of KE/KTP proposals to TSB, KTP, and BBSRC schemes, aimed at exploiting simultaneous reactive separations in bioprocessing, and underpins the 4CU programme grant.

3. Leadership in the academic community

All staff are active in leadership activities at a national level on a regular and on-going basis. Many staff are active internationally, setting research agendas and defining the grand challenges for the future. Summary figures and examples indicating the breadth and depth of our leadership include:

I. Participation in advisory, funding, professional, learned or standard setting bodies. 16 staff were members of 20 international advisory, funding or standards bodies, including:

- 7 staff as members of 10 RCUK advisory and funding boards: e.g. Wright - ESPRC Strategic Advisory Team (SAT) for Engineering and M3E; BBSRC Standing Committees C and BRIC; EPSRC Engineering CDT Panel B Chair (2013); Biggs - EPSRC Cross-disciplinary SAT and BBSRC BRIC; Allen - EPSRC SAT Engineering; recent President of The Engineering Professor's Council; Howse -

Chair of the Soft Matter Panel, Diamond Light Source; Salman - Chair of the Agglomeration Working Party of the European Federation of Chemical Engineering.

- 7 staff were members of commercial, industrial, or government advisory boards: e.g. Hounslow - Reviewer and panel member for the "Excellence Initiative for German Universities" of the German Federal and State Governments (administered by the Deutsche Forschungsgemeinschaft); Wright – RCUK and Foreign and Commonwealth Office missions and workshops for UK-international research relationships for Malaysia, Japan, Denmark, China.
- Many staff hold leadership roles on (inter)national advisory groups: e.g. Wright – Advisory Board EU ERASysBio – Systems Biology; Hall - Core and Management Committee for Energy Storage for the European Energy Research Alliance; Management Committee EU COST MP1004 (high performance energy storage systems); Styring - European Task Force for Artificial Photosynthesis; International Energy Agency Working Groups (High Temperature Hydrogen Production Processes).
- 22 Staff are Members (13) or Fellows (11) of 15 different institutes. There has been a 100% increase in numbers of Fellows of the IChemE (from 4 to 8) since RAE 2008.
- Royal Academy of Engineering Fellows now number 3 (vs 2 in RAE 2008): e.g. Hounslow elected to a RAEng Fellowship in 2011.

II. Conference organisation and programme chairs. We supported the delivery of 32 national and international conferences, symposia and other meetings, as members of organising committees or advisory boards: e.g. Biggs and Jensen - 7th Int'l Water Association: Sewer Processes and Networks Conf (Sheffield, 2013); Salman - International Granulation Workshop and Course – lead (Sheffield, 2009; Lausanne, 2011; Sheffield, 2013; >300 delegates); Priestman - 11th International Conference on Fluid Control, Measurements, and Visualisation (Taiwan, 2011); Wright, Biggs, Dobson, Evans, Jensen – ChELSI International Conference (Sheffield, 2012; > 100 delegates).

III. Invited and keynote lectures. Our staff delivered 173 invited lectures and presentations, including 58 plenary or keynote addresses, at conferences and meetings. For example:

- Styring - International Conference on CO_2 Utilisation, Washington DC, USA, 2013 (plenary);
- James - Informa Cell Line Development & Engineering, Munich, Germany, 2011 (double keynote)
- Biggs - Society for General Microbiology, Spring Conf., Dublin, Ireland, 2012 (keynote)
- Wright - Thai Institute of ChemEng and Applied Chemistry Conference, Thailand, 2012 (plenary);
- Zimmerman - 4th Algae World Europe, Munich, Germany, 2012 (plenary);
- Salman - 10th International Symposium on Agglomeration, Kobe, Japan, 2013 (plenary)
- Hall - 3rd China International Energy Storage Conference, Beijing, China 2013 (plenary).

IV. Externally funded fellowships. Full details for two new awards are given in §c.1. Biggs held an EPSRC Advanced Research Fellowship (07-12); Styring, EPSRC Senior Media Fellow (06-09).

V. Awards, prizes and honours. 3 staff were awarded 6 major prizes. E.g. Styring: Nova Institute Innovation Award, October 2012 (Germany); Zimmerman: Royal Society Innovation Award, 2010; CleanTech Open UK 2010 winner and International Finalist 2010; 2009 IChemE Moulton Medal.

VI. Peer review activities. 7 staff are members of EPSRC peer review colleges. Our staff act as peer reviewers for EPSRC (e.g. Allen, Biggs, Styring, Sharifi, Wright), BBSRC (e.g. James, Biggs, Wright), MRC (e.g. James), STFC (e.g. Howse). Many staff also act as peer reviewers for international funders, e.g. Singapore Research Board (Edyvean); FCT Portugal (Styring); NWO Netherlands (e.g. Styring and Wright); BMBF Germany (Wright); Austrian Centre for Industrial Biotechnology (James).

VII. Journal editorships, editorial boards etc. 8 staff are associate editors or sit on editorial boards for 18 journals: e.g. Salman, Editor, Powder Technology 7 Special Issues; Biggs, Board, Biotechnology Letters; Aquatic Biosystems; Zimmerman, Board, Chemical Engineering Science; Noirel, Associate Editor, Frontiers in Systems Biology; Wright, Editorial Board, Briefings in Functional Genomics.