Institution: Imperial College London

Unit of assessment: 13A – Electrical and Electronic Engineering

A. Overview

The Electrical and Electronic Engineering Department (EEED), one of nine departments in Imperial College's Faculty of Engineering, is one of the largest EEE departments in the UK, with 45 academic staff, 701 undergraduate and masters students, and 297 doctoral students and research staff. The Department is organised into five research groups:

- Circuits and Systems
- Communications and Signal Processing
- Control and Power
- Intelligent Systems and Networks
- Optical and Semiconductor Devices

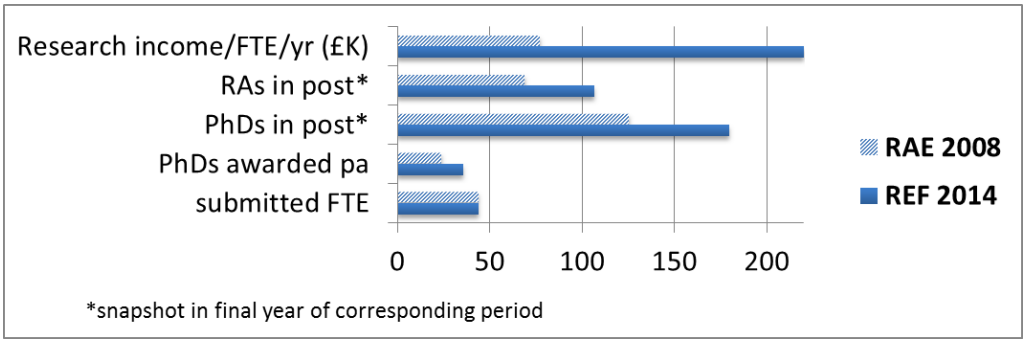
While the group structure is based on the underpinning subject areas of our field, research is also themed around application areas which cut across the groups, and which align with the research strategy of the College as a whole; in particular:

- Energy systems
- Biomedical electronics and devices
- Defence and security

The *vitality* and *sustainability* of our environment are illustrated by a number of factors:

- **Attracting and Developing Leaders:** We have recruited world-class staff in each research group, and supported them in maximising their potential. Academic leadership of our staff is demonstrated by their quality research outputs, and the prizes and fellowships they have been awarded, including (since 2008) 40 best paper prizes, 31 prestigious awards and 26 new fellowships of learned societies.
- **Enhancing the Funding Portfolio:** Our research income has nearly trebled, from £77k to £220k/FTE/year, compared to the RAE2008 period. We have also improved the diversity of our funding sources, and greatly increased the number of major grants (17 over £1M).
- **Training the Next Generation:** We attract the very best PhD candidates globally, with about 10 applicants per place. Since 2008, we have enrolled 276 new PhD students and employed 499 post-doctoral researchers. Their success is illustrated by the posts they have subsequently gained in prestigious companies and universities worldwide and the outputs they have produced. The sustainability of our PhD programme is enhanced by our recent success in two EPSRC Centres for Doctoral Training starting in 2014.
- **Providing a Quality Research Environment:** We continually develop and upgrade our research space and facilities, and provide extensive career support to researchers at all levels. The many leading researchers from other institutions who visit our department add further to the attractiveness and productivity of our environment.

Each of these factors is described in more detail in the sections that follow. The plot below illustrates that with a similar number of academic staff, we have achieved a substantial increase in overall research volume compared to RAE 2008.



B. Research strategy

B.i Departmental strategy: aims and achievements

The broad research aims of the Department, as stated in our 2008 RAE submission, have been, and continue to be:

- to deliver world-leading research and scholarship in established and emerging areas of electrical, electronic and systems engineering;
  - *our success is shown by the research achievements described in Bii, and by the grants, prizes, and fellowships awarded to us (sections D and E)*
- to be a partner of choice for industry, commerce and government by offering world-class research and state-of-the-art technical advice;
  - *our extensive work with industry is summarised in D and E, and in REF3*
- to provide top-quality education, and remain a department of choice for the world's most capable research students;
  - *evidence of the high quality of our students is provided in Cii.*

Research Directions

The Departmental Management Committee, comprising the department head, the 2 deputy heads and the 5 heads of research groups, is responsible for overall research strategy and support. Our research strategy is reviewed annually at a Departmental Away Day, which promotes interaction between groups as well as effective integration of new staff, and is attended by all the academic staff in the department. Strategic discussion is focussed on specific themes or questions; for example, in 2012 selected younger staff presented visions of their field in 20 years. We have a Strategic Advisory Group, made up of senior figures primarily from industry, and chaired by Phil Sutton FREng, which meets twice annually. Strategic issues discussed with this group include research direction, interaction with industry, and career issues for research students and staff.

The Department believes that the best research is that which follows the passions of the researchers, and consequently gives wide freedom to individual academics to choose their research directions and priorities, while providing support and resources to maximise their success. Academic staff recruitment is a key mechanism for the growth and enhancement of research in the strategic themes of the Department. Group heads and other senior staff act as mentors to junior academics, helping to guide their research in productive directions, bringing them into large scale projects, and assisting them in establishing collaborative relationships with leading researchers in other groups and institutions. For example, a new lecturer (*Georgiou*) collaborated with a senior professor (*Toumazou*) first as a Co-Investigator in the 2009 project *Bio-Inspired Artificial Pancreas*, and subsequently as PI in the 2011 project *Smart-phone platform for optimal insulin dosing in diabetic subjects*. Georgiou was subsequently awarded the 2013 *IET Mike Sargeant Award and Medal* for career progress.

Individual autonomy is promoted by our policy of allocating 30% of research overhead revenues to individual staff accounts. These funds can be used by staff as they choose, e.g. to support research students, seed new activities, travel to conferences or collaborators, and acquire equipment and other resources. This allows them to fund early work on new topics to build a stronger case for external funding.

Focus on Quality and Impact

In the evaluation of its own performance, and that of individual academics, the Department emphasises the quality of the research, and its impact within and outside the broader research community. Staff members are encouraged to publish in the highest quality journals and conferences, rather than being set quantitative targets. Success is shown by, for example, over 200 papers being published in IEEE transactions and journals during the REF period.

Multi-Disciplinary Research

The core sub-disciplines within electrical and electronic engineering underpin a vast range of technologies and applications. Collaborating closely with practitioners in the application fields, and

the other disciplines that support them, enhances the value of our research and increases the speed and extent of its external impact. To boost our inter-disciplinarity, we have made joint academic appointments with three other College departments: Mechanical, Aero and Bio-Engineering. Guidance and procedures for staff assessment have been modified, at department and College levels, to ensure that collaborative work is recognised and encouraged.

During the assessment period, our projects have included collaborators in a full range of other engineering disciplines, natural sciences and social sciences. Examples of inter-disciplinary collaborations which the department leads include *Digital City Exchange*, a £5.6M RCUK grant involving collaborators in three other engineering departments and the Business School (*Yeatman*); and *A Bio-Inspired Artificial Pancreas*, a £900k Wellcome Trust sponsored project in which we collaborate with Medicine, Physics, Computer Science and Bioengineering (*Toumazo*u). We are major participants in, and from 2014 will lead (*Green*), the Energy Futures Lab, which has participation from departments throughout the College.

Large Scale Projects

We have prioritised large projects as a valuable mechanism for extended collaboration, and to help activities reach a critical mass. The scale of our overall research activity allows us to be involved in large projects in a broad range of research areas.

The Department supports major projects in several ways. Firstly, each group has a full time administrator, who assists with the preparation of major proposals and the administration of active projects. This ensures that academic staff can focus on the science, rather than the administration. Proposal preparation is supported by senior academics; for example, we provide mock interviews for all proposals which are assessed by interviews. This has been very effective in increasing performance, as shown by the high success rate we have achieved in major bids. For example, nine proposals submitted in 2010-2013 of value (to EEED) over £1M have so far been successful, the total value of these (again, to EEED) being £13.4M. These projects have initiated major activities in diverse topics including energy storage for low carbon grids, many-core embedded systems, and implantable vagus nerve interfaces for appetite regulation. Over the REF period, the Department has been, or is currently, involved in 17 projects with budgets over £1M each (counting only Imperial's portion for joint grants).

The European Research Council (ERC) is a valuable and prestigious funding source for large projects of a fundamental nature. The Department actively encourages and supports its academics to seek ERC awards, with significant success. A total of 3 grants totalling £8.5M have been awarded: Starter grants to *Villegas* and to *Dragotti*, and a Synergy grant to *Toumazou*.

Strategy Beyond the REF Period

The general strategies outlined above will continue to shape our planning and management in the post-REF period, and will be built upon and extended. For example, we have developed close interactions with leading research groups worldwide in our key fields (see Section E), and will seek to strengthen these by increasing the number of sabbatical and other extended visits to and from these groups. We also aim to convert industrial collaborations into more strategic partnerships, for example by the establishment of funded chairs.

We have targeted several research areas for growth in the post-REF period, because of their rising importance and their fit to our researchers' skills and interests. Our activities in *energy systems* will be enhanced, with *Green* becoming Director of the cross-College *Energy Futures Lab* from 2014. We plan to establish a significant activity in *Big Data,* as members of a new College Data Science and Engineering Institute, building on our contributions to Imperial's *Digital Economy Lab*. Other topics to be grown, and in which several of our groups are already active, are *energy-efficient electronic and communication systems* and *sensor networks*.

We have recently been awarded two new Centres for Doctoral Training, one in Embedded and Distributed Systems (with the Department of Computing at Imperial) and one in Power Networks and Smart Grids (with Strathclyde). We expect to recruit 150 PhD students in total into these two Centres over the next five years, half of them in the Department. This will further enhance our cohort approach to PhD training and the alignment of our research around strategic themes.

B.ii Research Group strategy: aims and achievements

As described above, the Department encourages and supports academics in developing collaborations, addressing strategic themes, and obtaining research funding. Our success in meeting our aims can be illustrated by the research achievements of the groups.

Circuits and Systems (CAS)

The two key activities within the CAS group are biomedical electronics and reconfigurable digital systems. Both of these themes have been extensively evolved and enhanced during the REF period. In the biomedical area we have deepened our collaboration with medical and bioengineering researchers; successes include our participation in the *Medical Engineering Solutions in Osteoarthritis Centre of Excellence* (Wellcome Trust and EPSRC). Work on bio-inspired systems led to the establishment of the *Centre for Bio-Inspired Technology* (*Toumazou*); an early success is the development of an artificial pancreas [*Georgiou*04 – i.e. REF2 submission 04 from Georgiou], which is now beginning human trials. The group has also made breakthroughs in the medical application of integrated electronics, including the first integration of DNA amplification and sequencing/detection on a single CMOS chip [*Toumazou*01], which led to the establishment of the spin-out DNA Electronics. Two junior appointments, *Constandinou* (2010) and *Georgiou* (2011), have been made to support the strength and sustainability of this field.

Our leadership in reconfigurable systems is demonstrated by the award of an EPSRC Programme Grant (2013), a Challenging Engineering fellowship (*Constantinides*, 2011), and a Platform Grant (2010). The subject has been supported by the appointment of *Thomas (2010*). The group has successfully established research on computing with unreliable hardware, an increasingly important subject as integrated circuit dimensions approach the few-atoms scale [*Cheung*01]. A strategy of seeking new application areas for reconfigurable logic has led to its use in control systems [*Constantinides*04], and the group's innovation in this topic has led to an internationally leading activity in the area spanning control theory and digital design.

Communications and Signal Processing (CSP)

The CSP group carries out research across a range of topics within wireless communications and networks, speech and audio processing, digital signal processing and coding theory. During the REF period the group has grown several key areas. In compressive sensing, *Dragotti* has developed a method for robust sparse sampling [*Dragotti*01], and was awarded an ERC starter grant in 2011. This activity was boosted by the recruitment of *Dai* (2011), whose achievements include a seminal paper on compressive sensing signal reconstruction [*Dai*01] that has attracted nearly 600 citations since its publication in 2009. The CSP group has extensive achievement in array processing, including MIMO (multiple-input multiple-output) systems. This topic has been boosted by the recruitment of *Clerckx* (2011). Achievements include the first rigorous design of limited feedback for the dual-polarized channels that are expected to be the primary deployment scenario for MIMO [*Clerckx*02].

The CSP group's increased interdisciplinary activity includes collaboration with the Civil and Environmental Engineering Department, leading to the first stochastic model for characterizing movement and communications connectivity of vehicles in signalized road systems [*Leung*02]. The group has also strengthened collaboration between its signal processing and communications activities, for example in the £1.5M MoD *University Defence Research Centre in Signal Processing* awarded in 2009, which also involves collaborators in two other groups.

Control and Power (CAP)

The Department has a long history of international leadership in control theory. Maintaining this leadership has been pursued through the hiring and support of new staff. A particular success was the recruitment of *Angeli* in 2008, whose contributions include the initiation of a new sub-field of economic model predictive controllers [*Angeli*01], and the use of control theory in systems biology [*Angeli*03]. Expansion of research on control problems in industry has been supported by the recruitment of *Parisini* (2010), who has since established a major collaboration with Danieli Automation, and developed new schemes for control systems running over packet networks

[*Parisini*03]. The work of established group members continues to have high impact, as evidenced, for example, by *Astolfi*'s 7 plenary lectures at control conferences and two IEEE transactions best paper prizes (e.g. [*Astolfi*01]) during the period.

In the power field, a key success of the group has been its influence on government and corporate policy through its research results and collaborations. CAP staff are members of many key advisory committees, including the Scientific Advisory Committee of *Research Councils UK Energy Programme* and the Steering Committee of the *SmartGrids European Technology Platform* (*Strbac*), while *Green* is RCUK Energy Networks Champion, and manages the *Energy Networks Research Hub*. The group has collaborations with all major UK power companies, and the influence of its work on energy supply includes evidence to the House of Commons Select Committee enquiry: "The future of Britain's electricity networks" [*Strbac*03]. Collaboration between the power and control staff within the group has been successfully increased, as shown by major new projects including the programme grant *Control for Energy and Sustainability* (£5.5M from 2009). The group's activity in power electronics has been boosted by the recruitment of *Hui* to a joint position with the University of Hong Kong (0.2 FTE at Imperial), whose recent achievements include the invention of electrical springs for the stabilisation of smart grids [*Hui*04].

Intelligent Systems and Networks (ISN)

The ISN Group covers the large scale information processing and communication systems that are at the core of our IT and Communication based society. Its research topics include:

- Mobile and animated cooperating robots and their ability to learn and adapt
- Network analysis methods that scale to very large systems
- Information theoretic foundations of sensor, data and social networks
- Machine learning in random environments, including vision, robotics, and the Internet
- Agent based systems, with objectives driven by economics, sustainability, and negotiation.

Each topic is collaborative within the group and with College and external partners. The group's range of collaborative projects is indicated by a research portfolio currently above £5M. Significant results include the development of the "Cognitive Packet Network", a self-aware routing algorithm for packet networks [*Gelenbe*01].

Two academic appointments have been made during the REF period, *Kim* (2010) and *Gündüz* (2012). *Kim* has added to our capability in machine vision and learning, including collaborations with Omron and Samsung, as well as a wide range of universities in the UK and abroad. *Gündüz* has added to our activity in information theory, with important contributions in, for example, energy efficiency in network communications [*Gündüz*03].

Optical and Semiconductor Devices (OSD)

The OSD group's general strategy is to develop novel devices using advances in materials and fabrication techniques. During the last two decades the group has built up a leading position in the UK in MEMS (micro-electromechanical systems), and during the REF period it has been successful in developing new application areas from this capability. One of these is *energy harvesting*, the small-scale production of power from ambient sources. During the REF period this activity has grown substantially, with over 2000 citations to date, and 13 plenary or other invited talks. Working devices and systems have been demonstrated for aerospace [*Yeatman*04], body mounted sensing [*Yeatman*01] and industrial monitoring [*Holmes*04]. This topic is an example of inter-group collaboration (with *Control and Power*) on a strategic theme (*Energy Systems*). Another successful application area has been compact mass spectrometers based on MEMS components. Collaborative work with the group's spin-out company Microsaic Systems [*Syms*03, *Syms*04] underpins the instruments which the company launched during 2011-13. The group's MEMS research has also been applied to space exploration, with contributions to the instrumentation that discovered evidence of running water in the Phoenix Mars mission in 2008 [*Pike*01, *Pike*02].

The group's activity in the field of meta-materials has been supported by the recruitment of *Sydoruk* (2013). Important contributions include fundamental results on the limitations placed by noise on the performance of negative refractive index materials [*Syms*02], as part of a

collaboration with the Physics Department in a £4.9M Leverhulme grant in meta-materials. The group has also extended its device work into applications in the nano-scale; successes include nano-structured silicon for thermoelectric devices [*Fobelets*03], and the spin-off of a battery materials company (Nexeon Ltd) based on nano-structured silicon.

C. People

C.i Staffing Strategy and Staff Development

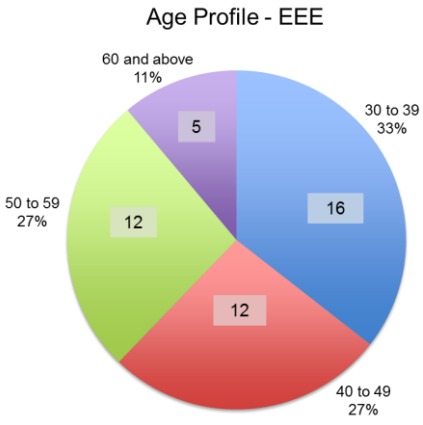
Recruitment and Retention

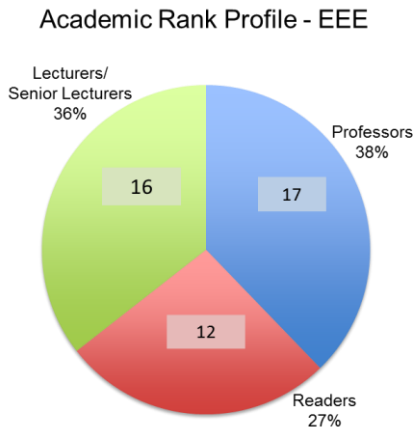
Recruitment of permanent academic staff is carried out regularly, with recruitment exercises in each of the years of the REF period. Excellence in research and teaching are always the primary criteria, but candidates' fit to the strategic needs of the Department is also considered. During the period we have recruited 13 new members of academic staff, and a number of these have supported growth of our strategic themes, for example *Constandinou* in Biomedical Electronics and *Hui* in Energy. Generally we recruit early career staff of high promise, but in some cases an established senior academic is recruited for strategic reasons, such as *Parisini* to support control applications, or when an exceptional opportunity arises, such as *Hui*.

Building a supportive and productive work environment is the key to staff retention, and this is actively pursued. Our success is shown by the low number of academic staff (4) leaving for other jobs during the period, despite numerous approaches received from other institutions by many staff.

Succession and Staff Profile

An element of our recruitment strategy is to develop and maintain a healthy balance of staff across the seniority spectrum, in order to ensure sustainability and succession. This we have achieved, both for age and academic seniority, as illustrated in the charts below. Age and seniority are also well balanced within each group, and our hiring policy aims to sustain this balance. We also plan well in advance for succession in key posts such as group heads and HoD, and develop our staff for senior managerial responsibility by providing junior and mid-career staff with opportunities in a variety of departmental posts, such as MSc coordination. Selected staff also attend College leadership training courses.





Career Development Support

All academic staff and research fellows annually produce a Personal Review and Development Plan (PRDP) and discuss it with their line manager. This provides recognition of achievement, offers development guidance, particularly in relation to achieving promotion, and encourages performance benchmarking.

All eligible academic staff and research staff are positively assessed each year for possible promotion; individuals discuss their case with their head of group or HoD, and cases put forward are reviewed by a departmental committee. Line managers may act as advocates for candidates, but contribute to decisions equally with other panel members by anonymous vote. Supported candidates are assisted in preparing documentation for the College process and for their

interviews; those not supported are provided with feedback and guidance. A valuable factor in retention is that promotions are merit-based, and are not limited by the number of staff at a particular level. During the REF period 4 staff were promoted to senior lectureships, 7 to readerships and 6 to professorships.

To help new academic staff get established, the Department preferentially allocates them PhD studentships, and they are given reduced teaching loads for the first 2 years. The College offers a wide range of courses on topics such as writing research proposals, managing research budgets and managing research staff and students. For staff on probation (normally for 3 years), attendance is compulsory, while others are strongly encouraged to attend where appropriate. The Department grants start-up funds (currently c. £100k) to new staff. Our success in building our strategic research themes through support and mentoring of junior staff is evidenced by the success of these staff in winning major grants in thematic areas. Examples include the ERC starting grants of *Villegas* and *Dragotti*.

Sabbatical research periods, in both academic and industrial environments, are actively encouraged, and are financed by the Department or by learned societies or industry. Staff are encouraged to arrange such visits to the best groups in their specific fields. During the REF period, 11 staff have been on sabbatical leave; host organisations have included MIT, UC Berkeley, Microsoft, and the Universities of Delft, Tokyo and Cambridge.

As part of a vibrant research environment, the Department has a strong series of research seminars, organised by groups but promoted to staff and students across the Department. Over 500 such seminars have been held during the REF period, divided about equally between internal and external speakers. In addition, the Department organises three prestige lectures each year, the Dennis Gabor, Alec Reeves, and Peter Lindsay lectures. Each attracts a large audience (100 – 250), including many of our external collaborators and supporters.

The importance of our researchers' personal and career development, and lifelong learning, is recognised and supported at all levels within the College. The College has implemented fully the *Concordat to Support the Career Development of Researchers*, and was awarded the European *HR Excellence in Research* badge in December 2012. The College's flexible working policy is applicable to all staff.

Post-Doctoral Research Assistants

Career development for PDRAs is done in collaboration with the College's Post-Doc Development Centre, which provides training sessions, career planning and advisory services. All PDRAs have an annual PRDP session with their supervisor, following the same principles as described above for academic staff. The key criterion for promotion from PDRA to Research Fellow is demonstrable research independence, and we provide extensive mentoring to develop these skills. Our success in career development of PDRAs is shown by the permanent positions they have obtained subsequently, including academic posts in the Universities of Oxford, Southampton, Surrey, Manchester and Utrecht, and in companies including Google, Siemens, Altera and Cambridge Consultants.

Competitively-won Fellowships

Besides fellowships of learned societies and international organisations (section E), the Department has been successful in winning a number of competitive fellowships. These include a Challenging Engineering fellowship from EPSRC (*Constantinides*), a Leverhulme Trust Fellowship (*Draief*), the two ERC starter grants (*Dragotti* and *Villegas*), and 2 RAEng visiting Fellowships (*Chua* and *Poor*). In addition, early stage researchers have won 3 of the Imperial College Junior Research Fellowships, which are selected in a College-wide competition, and one Royal Academy of Engineering Fellowship (*Kollensperger*).

International Staff Appointments, International Recruitment and Visiting Scholars

The Department is highly international, with academic staff from 15 countries. The 13 staff recruited during the REF period come from 9 different countries, and all but 3 had their previous posts outside the UK. This is evidence of our ability to attract the best talent globally – most of these new staff had selected the Department over opportunities in prestigious universities in the

US, Europe and elsewhere. Our PDRAs and other research staff, and our research students, are equally diverse. We also welcomed 23 academic visitors spending sabbatical leave in the Department, from 11 countries, during the period.

Equality and Diversity

Of the Department's academic and research staff, 29% are black and minority ethnic (BME), and 12% are female, a level we are committed to increasing. The College has systematic, transparent and fair hiring procedures, and has family-friendly policies whereby meetings and teaching duties are scheduled with parental duties in mind. Maternity returners are offered Elsie Widdowson Fellowships, which provide a year free from teaching and administration, to ensure that maternity leave does not damage a research career. There is provision for generous and flexible paternity leave, and access to Imperial's OFSTED outstanding subsidised nursery and play schemes. The College's commitment to equality-related activities is shown by its support of a dedicated Equalities Unit, and a range of support networks. The College's internal leadership programme for BME staff, iLead, has been so successful that Stellar HE, a development programme for BME leaders across ten higher education institutions, was modelled on it. Calibre, a leadership programme for disabled staff, has also been established at the College. Imperial has a Silver Athena SWAN award at institutional level. It continues to be a Stonewall Diversity Champion.

C.ii Research Students

Research students play a critical role in our research, and recruitment of high quality postgraduates is key to our research vitality. The quality of our environment is indicated by our attractiveness to applicants; postgraduate applications consistently outnumber places by nearly 10:1. Our research students are from a diverse range of backgrounds, with 32% and 50% of registrations from the EU and overseas respectively during the period. The proportion of female postgraduates was 25%. Recruitment of top quality students is supported by a strong scholarship and bursary programme. For the 2012/13 intake, 12 students were supported by EPSRC awards, 5 by industrial CASE, 16 by departmental awards and 6 self-funded. All PhD students receive conference travel grants funded by the department of at least £700, in addition to their other support.

The Director of Postgraduate Studies is responsible for monitoring PhD progress, with close cooperation from supervisors, all of whom receive supervisor training. All students attend a one-to-one meeting at least annually with the PG Tutor, and are assigned a member of staff outside their group as a Mentor. The Graduate School provides a professional development programme that supports PG students, with specific emphasis on their future careers. The College is the only university to have won the Times Higher Education Award for Outstanding Support for Early Career Researchers twice: in 2006 for its innovative and integrated approach to supporting young academics within the Graduate School, and in 2008 for initiating a course called "Finish Up, Move On", aimed at helping PhD students complete their PhDs and move on to the next stage in their careers.

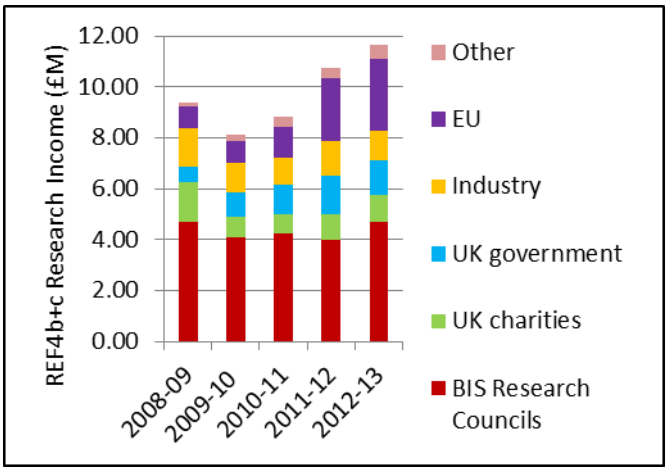
During the REF period we awarded 215 PhDs, compared to 156 in RAE2008. The quality of these graduates and their work is indicated by their subsequent career success. Twenty of them have gained academic positions, in the UK and 6 other countries, 97 have research jobs in academia, industry or government institutes, and a further 53 have other jobs in engineering industry. The sustainability of our PhD programme is supported by our half share in two Centres for Doctoral Training (CDTs) to be funded from 2014, in High Performance Embedded and Distributed Systems, and in Future Power Networks and Smart Grids.

D. Income, infrastructure and facilities

The Department has been very successful in attracting research income. Income has nearly trebled from £77k /FTE/yr in RAE 2008 to £220k /FTE/yr in REF2014. As the chart shows, not only has the total volume increased, the balance of sources has also improved, with the proportion from BIS research councils dropping from 50% to 40% during the period. Both trends indicate the sustainability of our research support.

Sustainability is further indicated by the future income already secured, totalling £10M, £8.1M, and £4.9M for 2013/14, 2014/15 and 2015/16 respectively.

We have also been successful in large scale and high prestige grants. These include the 3 ERC grants previously mentioned, 6 EPSRC Programme grants, 2 Platform Grants and one Basic Technology grant awarded or running during the period, as well as 29 FP7 projects, of which 6 brought over £500k to the Department. The sustainability of winning large grants is indicated by the fact that of 17 grants over £1M that were active during the period, there were 13 different PIs. Industrial grants and contracts have also been successful, with support from 22 different companies.



Department staff are extensively involved in consultancy for industry. Much of this is carried out via the College's in-house consultancy company Imperial Consultants Limited, for whom our staff carried out 122 projects with a total value £4.6M during the period. This work enhances our relations with industry, helps keep our staff up-to-date, supplements their income, and brings some extra funds to the Department (typically 10% of project value).

We continuously invest in our infrastructure and facilities. Important developments during the period included the Maurice Hancock Energy Integration Laboratory (£1.2M), completed in 2008, and the Energy Futures Lab space (£1.8M of which £600k in period), a multi-departmental facility hosted in the EEE building. The facilities for biomedical electronics have also been enhanced, with College investment of £200k in refurbishment and £150k in equipment associated with the creation of the Centre for Bio-Inspired Technology. We regularly upgrade all research space including offices and laboratories, to provide a positive and efficient working environment which is attractive to potential staff and students. During the period £660k has been invested in research space in addition to the specific refurbishments mentioned above. We also benefit from access to extensive research facilities in other departments, including the Department of Materials, which has invested over £6M in research equipment during the period. Our investment in research facilities will expand in the coming period with, for example, the department's participation in the recently announced £14.3M multi-university capital equipment grant for a National Centre for Grid Scale Energy Storage. This will be led by the College, with *Strbac* as Director. The department will also participate in the joint Imperial-Huawei innovation lab in Big Data, which will have an anticipated initial funding of £5-50M.

E. Collaboration and contribution to the discipline or research base

E.1 Collaborations

The Department is involved with a wide range of collaborations within the College, and with academic and industrial researchers all over the world. Our key collaborations within College are: the *Energy Futures Lab* (*Green* as incoming Director, *Strbac* academic lead on smart-grid), the *Digital Economy Lab* (*Yeatman* as Co-Director and PI of *Digital City Exchange*), the *Institute for Security Science and Technology* (*Yeatman* as Advisory Board member), the *Institute for Biomedical Engineering* (*Toumazou* as Founder and Chief Scientist), the *Centre for Plasmonics and Metamaterials* (*Syms* and *Sydoruk* as key members) and the *Centre for Terahertz Science and Engineering* (*Lucyszyn* as co-founder).

Outside the College, more than 100 collaborative projects have been active during the REF period. This has resulted in a very extensive range of collaborative research outputs. Since 2008 the department has published papers with co-authors from over 400 organisations in 48 countries: 38 UK and 229 non-UK universities, and 28 UK and 130 non-UK companies and research institutes. Examples are, for Universities: Aachen, Berkeley, Cambridge, Caltech, CMU, ETH, INRIA, HKU, Leeds, Manchester, Peking, Princeton, Southampton, Stanford and Tokyo; for industry: ABB, Alstom, Alcatel Lucent, BAE Systems, ESA, Google, Microsoft, National Grid,

NASA, Panasonic, Philips, QinetiQ, Samsung and Siemens. Of the 176 REF2 outputs submitted, 89 (or 50.6%) are with co-authors external to Imperial College.

E.2 Wider Influence, Leadership and Contributions to the Discipline

Members of the Department have sat on a range of panels and committees, which contribute to policy both within and beyond the discipline. Department staff hold or have held Directorships of two Defence Technology Centres (*Vinter* and *Gelenbe*), and memberships of the Long-Range Planning Committee of the IEEE Power and Energy Society (*Green*), the Defence Scientific Advisory Committee (DSAC) (*Vinter*), two EPSRC Strategic Advisory Teams (SATs) (*Constandinides* and *Vinter*), the Technology Transfer Committee of the Wellcome Trust (*Toumazou*), the Government Chief Scientific Advisor's Committee on Speech Technology (*Naylor*), and 65 EPSRC, EU and other Award Panels. We have provided evidence to the House of Commons Select Committee on Energy and Climate Change and the House of Lords Select Committee on European Union (*Strbac*).

A wide range of appointments, activities and honours demonstrate the wider contributions of our staff to leadership in the research community, and the esteem in which they are held. Our vitality is demonstrated by our number of elected fellowships, 26 of which were received since 2008. One current (*Toumazou*) and 3 Emeritus and Visiting Professors (*Mayne*, *Young*, *Solymar*) are Fellows of the Royal Society; 4 current Professors (*Vinter*, *Syms*, *Yeatman*, *Toumazou*) and 4 Emeritus Professors (*Spence, Aleksander, Constantinides, Mayne*) are Fellows of the Royal Academy of Engineering. Furthermore, there are 11 Fellows of the IEEE, 17 Fellows of the IET, 3 Fellows of BCS. Recognition by the international academic communities is indicated through these achievements since 2008: 3 staff elected to Academia Europaea (*Leung, Vinter, Toumazou*), one as Chevalier des Palmes Academiques of France (*Gelenbe*), *Hui* elected as Crouch Senior Research Fellow and to the Australian Academy of Sciences and Engineering, and *Gelenbe* elected to the Hungarian and the Polish Academies of Sciences. In 2013, *Toumazou* was appointed the first holder of the Regius Professorship in Engineering recently bestowed on Imperial College.

Since 2008, our staff have been awarded 31 prestigious medals and prizes. These include the IET Oliver Lodge Medal for Achievement in ICT (*Gelenbe*), the RAEng Silver Medal (*Yeatman*), the IET Crompton Medal (*Hui*), the Dennis Gabor Award 2013 of the Hungarian Academy of Sciences (Gelenbe), four separate IET Innovation Awards (*Villegas* and *Toumazou*), the IET Mike Sargeant Achievement Award (*Georgiou*) and two NASA Group Achievement Awards (*Pike*). Members of staff and their students won 40 best paper awards in the current REF period.

Our staff have been active in journal editorship. During the period they have served as Editors-in-Chief or Editors of 14 journals, including IEEE Transactions on Control Systems Technology, Sustainable Energy, Communication and Automatic Control, and The Computer Journal, and served as Guest Editors on 20 special issues in prestigious journals. In addition we hold or have held 72 positions as Associate Editors or Members of Editorial Boards.

Various leadership roles were taken by our staff at international conferences and workshops during the REF period. Staff have served as General Chair and Technical Programme Chair on 31 and 17 occasions respectively, as members on more than 200 technical programme committees, and chaired 25 technical tracks or special sessions. We have given more than 56 Keynotes, 42 Plenaries and around 200 invited talks or tutorials at conferences since 2008.