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Assessing the economic returns of engineering research and postgraduate training in the UK

Final report

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1. Executive Summary

The study

This report provides quantitative and qualitative estimates of the economic impact of the UK's investment in engineering research and post-graduate training, across the economy overall and where possible distinguishing contributions to different sectors and areas of activity.

It was prepared by Technopolis with the close support of the EPSRC and the Royal Academy of Engineering, and overseen by a project steering committee chaired by Professor John Fisher CBE FREng.

Engineering is pervasive and highly dynamic

- Engineers are a pervasive force across any modern economy, with engineering research driving innovation and improved professional practice in almost every economic sector, from advanced manufacturing to software, from financial services through to the media and government.
- There are around 450,000 engineers with graduate and postgraduate degrees (Level 4+) working in the UK, comprising 60% of all professional engineers nationally. Highly qualified engineers are distributed throughout the economy, which reflects the universal relevance of engineering skills, from numeracy to critical thinking, from design to communications.
- Engineering graduates and especially postgraduates provide the social networks, skills and absorptive capacity to not only 'do first-rate engineering,' but also to drive business development more generally; in most parts of the economy, engineers can be found at the heart of almost any new product development initiative.
- Engineering research and training have been critical to the profession's ability to evolve in response to changing industrial needs and composition, reflecting the dynamic nature of the discipline and the people. What was understood as 'engineering' 20 years ago has changed dramatically today, with a broadening of the application of engineering and engineers in the new economy and a changing emphasis on key emerging technologies even within the more 'traditional' engineering sectors.

This translates into a substantial contribution to UK economic output

- Engineering contributed an estimated £280 billion in gross value added (GVA) in 2011, which is 20% of the total UK GVA, and back to the levels last seen in 2007, before the economic crisis[1]. The estimate includes the economic output of both the more 'obvious' engineering-related sectors of the economy, such as aerospace, and a share of the output of several other 'less obvious' sectors that employ significant numbers of highly-qualified engineers, including for example, knowledge intensive business services (e.g. advertising, management consultancy), health and finance.
- Engineering qualifications attract an additional wage premium on average in comparison with the average for other scientific disciplines, estimated to be around 15% of the median salary for newly qualified graduates, which is a clear indication that engineers' skills are highly valued in the economy.

High concentrations of engineers are linked with innovation and competitiveness

- Analysis of the UK Innovation Survey (2013) shows that sectors with a higher concentration of graduate engineers, such as High-Tech Manufacturing, Computing and Telecommunications or Utilities all report higher than average levels of innovation activity

1 Previous studies have reported figures of 28% GVA (RAEng 2012) and 27.1% GDP (EngineeringUK 2014) – variations are due to methodological differences in selecting engineering-based sectors.

and innovation-related income, as well as levels of labour productivity (GVA per employee) above the national average.

- Engineering-based manufacturing, the 'broad' sector with the highest concentration of engineering skills, reports the highest percentage of firms that are 'innovation active', at circa 60%.
- Sectors with higher concentrations of engineering skills tend to export more. Each engineering-based manufacturing company exports, on average, £9.3 million, which is more than double that for all other manufacturing companies, at £3.9 million.
- Engineering-related sectors exported goods and services valued at around £239 billion in 2011, some 48% of the total value of exports for that year, which is a notable contribution and underlines the critical role played by engineering in the export economy. The share of total UK exports is more than double the engineering-related sectors' share of UK GVA.

The UK invests around £10 billion - £12 billion in engineering research each year

- We estimate that UK-based companies invest around £9.5 billion annually in engineering research and development. This is dominated by high-tech manufacturing and the communications sector, but also benefits from a wide range of smaller contributions from other sectors, as well from contributions made by SMEs and startups.
- The public sector is also a major research funder, with both the grant-awarding research councils and government departments investing heavily in very many different areas of engineering research. There are no consolidated expenditure data, however, we estimate public expenditure falls in the range, £1.5 billion to £3 billion a year (2011/12).
- The major public research funders include the EPSRC, Innovate UK and the Ministry of Defence. There are also substantial investments made by other government departments, from energy to transport to health.
- Public investment in engineering research is closely aligned with the UK's national priorities and industrial strategy, from big data to robotics to quantum technology.

UK engineering research is world-class

- The UK produces world leading engineering research. Engineering research conducted in the UK is globally recognised for its high quality. This is evident in the latest report on research activity published by Elsevier (2013), which shows that the UK remains a global research heavyweight and that engineering research, in particular, is highly influential.
- The quality of engineering research is also confirmed by analysing the REF2014 results for the five Units of Assessment (UoA) linked with engineering. The quality profile for engineering research outputs is outstanding, with 70% of all submissions classified as 'world-leading' or 'internationally excellent'. This result is significantly stronger than the profile obtained by engineering related UoAs in RAE2008 (61%).

Academic excellence translates into tangible economic benefits

- This study benefited from privileged access to 514 individual REF2014 impact case studies, which proved to be a valuable and unique source of information showcasing the impact of engineering research in all its guises. Together the case studies – from 46 different HEIs – provide exhaustive and compelling evidence regarding the economic and social impact of engineering research conducted in the UK over the past 20 years.
- The case studies are testament to the advances made possible by engineering research in areas ranging from healthcare to renewable energy by way of land-use planning and building design tools, as well as the more familiar advances in aerospace and automotive technologies (e.g. weight-saving, fuel efficiency, structural integrity).
- The figure below presents a very small compilation of selected impacts taken from the 514 case studies organised by strategic sector, also taking into account contributions from the Information Technologies research area - which has a cross-sectoral influence.

Health and life sciences	Aerospace	Automotive	Construction	Renewable energy
• Haematological sensors • Non-invasive wound monitoring systems • Prosthetics • Imaging techniques for enhanced diagnosis of vascular disease	• Composite wings in large aircraft • Improved jet-engine efficiency • Advanced calibration of machine tools • Microstructure prediction and improved material utilisation	• High compression ratio combustion engines • Lightweighting • Advanced driver assistance	• Vibration modelling • Energy efficient buildings • Geosynthetic materials • Advanced composites for bridges	• Acoustic design and assessment methodologies • Low-loss transmission systems • Network management systems for distributed generation • Design codes engineering plastics

Information Technologies and Computer Science

Tools / algorithms for better simulation of physical phenomena

Big data, visualisation and data analysis solutions (inc. machine learning and advanced analytics)

Virtual reality and virtual modelling and prototyping

Better decision support and forecasting applications (demand, risk and impact)

Sensor + software solutions

CAD / CAM improvements

Networked, distributed and web-based solutions

Engineering research attracts substantial inward investments

- The quality of engineering research conducted in the UK, as well as access to world-class engineering facilities and businesses has helped the UK to attract substantial high-value and high-tech inward investment, from Europe, the US and the Far East.
- These initiatives are helping to generate new economic activity and employment throughout the UK and are often tied to regional economic development initiatives.
- Recent examples include the £24.5 billion project from EDF Energy to build a new nuclear power station at Hinkley Point, (the first to be built in the UK for 20 years); an investment of £7.5M by BorgWarner to put in place the Turbocharger Research Institute, in Bradford, which serves as an engineering centre for JLR; and Siemens' investment (£160 million) in wind turbine production and installation facilities in Yorkshire.

Engineers are crucial to the operation of many aspects of government's work

- The Office for National Statistics (ONS) estimates there are around 1,500 engineers across the civil service. The Government Network of Scientists and Engineers (GSE) suggests the figure could be somewhat higher.
- This diverse community is actively involved in very many functions, which range from acting as 'intelligent clients' within challenging public procurement procedures through to providing the interface between academics, practitioners and policy teams in the development of robust, evidence-based policy and on key issues such as risk assessments.

Engineering research plays a key role in informing policy and providing solutions that lead to high social impact, nationally and globally

- Some examples include: management of discolouration in drinking water distribution systems, modelling to calculate the impact of a given security mechanism on individual and corporate productivity; investigative toolkit and associated techniques to support online child protection based on digital persona analysis; a tool for assessing and managing risks associated with mental-health problems; development of synthetic bone grafts with improved efficacy and reliability.
- UK researchers are currently undertaking 'tsunami engineering research' which will study the problems of assessing buildings and engineering defences against these elemental forces, and guide insurance companies in their approach to this growing problem.

2. Introduction

2.1 Scope of the study

This report provides quantitative and qualitative estimates of the economic impact of the UK's investment in engineering research and post-graduate training, across the economy overall and where possible distinguishing contributions to different sectors and areas of activity.[2] It provides an estimate of the contribution of 'engineering' to the UK economy in terms of its Gross Value Added (GVA) and number of jobs. It also explores the different routes by which engineering research achieves economic and societal impact, for example, directly through the realisation of technological advances that underpin innovation or indirectly through providing the foundation for the state-of-the art education provided to our future professional engineers.

'Assessing the economic returns of engineering research and postgraduate training in the UK' sits alongside other studies exploring the economic impact of the engineering and physical sciences (EPS), with three earlier studies having estimated the economic returns to research and training in each of three fields: chemistry, mathematics and physics.

The report has benefited from several other recent additional publications, which have provided invaluable additional evidence on the:

- Size and scope of the world of engineering (The Universe of Engineering, RAEng 2014).
- Methods and approaches used by engineers to create 'things' and make 'things' work better (Thinking like an engineer: implications for the education system, RAEng 2014).
- Demand for engineering skills (Perkins Review of Engineering Skills, BIS, 2013; Perkins Review of Engineering Skills: a year on, RAEng 2014).
- Presence of ethnic minorities and socio-economically disadvantaged groups in engineering (RAEng, 2014).
- Gender balance in the engineering profession (Women in engineering. Fixing the talent pipeline, Institute for Public Policy Research, 2104).

2.2 Defining engineering

Engineering can be defined as the "creative application of scientific principles",[3] principles that are put in practice to invent, design, build, maintain, and improve structures, machines, devices, systems, materials and processes.

This definition is incredibly broad, and is intended to make room for the fact that the scope of 'engineering' is continually evolving due to the dynamic nature of engineering-related industries and the development of the fields of applied science related to engineering, such as those related to biotechnology or computer science.

What was understood as 'engineering' 20 years ago has changed dramatically in recent years, with a broadening of its scope beyond the more traditional view of engineers as bridge builders or carmakers. This may be a matter of perception, as engineers have been at the centre of things in many different areas of the economy from the very beginning; however, it is important to underline the fact that the engineering profession is at the heart of the new economy every bit as much as it remains critical to the international competitiveness of more mature sectors.

Engineering principles and methodologies are evident and graduate engineers are employed in every economic sector, from agriculture to aerospace, from smart phones to smart grids. Engineers are manufacturing pharmaceuticals, designing intravenous infusion pumps and helping design and implement electronic health records. Similarly, mechanical engineers and

[2] The study has excluded vocational training and first-degrees from the analysis, and it focuses on higher-level degrees.

[3] http://www.sciencedaily.com/articles/e/engineering.htm

civil engineers are essential to transportation, as are environmental engineers to sustainability and energy and software engineers are fundamental to the design of global communications networks.[4]

Engineers are active in many new areas such as nanotechnology, software engineering, synthetic biology, but also finance and media. Engineering research also spans other more traditional disciplinary areas including, but not restricted to, civil, process (including bioprocess), mechanical, electrical, and electronic engineering. Furthermore, engineering research also crosses over into other areas of science, for example biology, chemistry, medicine and mathematical sciences.

Given the diversity of activities in which engineers are involved the first challenge of this analysis is drawing the boundaries for the study in terms of the definition of 'engineering', in terms of investment in research and development and in training, but also in terms of engineering-related economic sector and activity.

We have used a broad definition of engineering in this exercise, working with a range of 'engineering' definitions, drawing on manifold different data sources. In the case of engineering research, there is no single definition. The Research Excellence Framework (REF 2014) covered engineering in five Units of Assessment (UoAs), while at least half of the 111 Research Areas that make up the EPSRC portfolio have relevance to engineering. National statistics tend to only distinguish between R&D expenditure (as defined by the OECD in the Frascati Manual) and the broader concept of Science, Engineering and Technology (SET).

The government's annual SET statistics do distinguish between several different types of expenditure by socio-economic purpose, which does permit some selected analysis of the split between science and 'engineering and technology'.

Regarding postgraduate training, the Higher Education Statistics Agency (HESA) identifies nine different subject classification areas related to engineering under its Joint Academy Coding System (JACS) and provides reasonably detailed reports on enrolments and graduates for the whole of the UK HE sector. This subject classification is not applied to National economic statistics, which tend to be linked back to individual sectors or product groups and do not include a category that encapsulates all engineering-related economic activity. As such, there are no official statistics showing business expenditure on R&D (BERD) for engineering. However, prior work by the RAEng (Jobs and Growth, 2012) provides a way forward with information on the concentration of (self-declared) professional 'engineers' in absolute numbers, and as a percentage of the total workforce, across 20 sectors of the economy.

All these different definitions call for a pragmatic approach, and a definition of engineering that may need to change according to the subject of analysis. The report explains in each instance how 'engineering' is captured.

[4] http://belfercenter.ksg.harvard.edu/publication/24304/what_does_it_mean_to_be_an_engineer.html

3. Engineering contribution to the UK economy

3.1 Engineering contribution to the UK economy

3.1.1 Engineers are present across all economic sectors

There are around 435,000 engineers, with graduate and postgraduate degrees (Level 4+), working in the UK, comprising 60% of the total 730,000 professional engineers in the UK, according to the RAEng (Jobs and Growth, 2012). Graduates represent a growing share of the total engineering workforce, with an expectation if not a requirement, that any new professional engineer will be a graduate. The RAEng Jobs and Growth study further estimated there are around 2.3 million skilled people working in engineering-related occupations, equating to some 8% of the total UK workforce.[5] This second estimate includes technicians as well as graduate engineers and also goes a little beyond engineering including other SET professionals, such as physicists or chemists.

Figure 1 presents an overview of engineering employment across the UK economy, sorted in descending order using the right-hand column, the number of graduate / postgraduate engineers expressed as a proportion of the total workforce in the sector.

Figure 1 – Distribution of engineers throughout the UK economy

Sectors	SIC 2007 Definition	Number of Engineers	Engineers with Level 4+	L4+ Engineers as % of total workforce
High-tech Manufacturing	21,26	24,333	14,600	9.13%
Computing & Telecommunications	61,62	85,167	51,100	6.91%
Med-High tech Manufacturing	20, 27-30	66,917	40,150	6.18%
Med-Low tech Manufacturing	19, 22-25, 33	64,889	38,933	4.99%
Utilities	35-39	18,250	10,950	3.91%
Construction	41-43	119,639	71,783	3.37%
Business Services	68-75	83,139	49,883	1.84%
Low-tech Manufacturing	10-18, 31, 32	28,389	17,033	1.83%
Media & Publishing	58-60, 63	10,139	6,083	1.64%
Other Services	94-97	18,250	10,950	1.37%
Public Admin & Defence	84	30,417	18,250	1.21%
Agriculture & Mining	01-08	8,111	4,867	1.11%
Finance & Insurance	64-66	20,278	12,167	1.10%
Transport & Storage	49-53	20,278	12,167	0.83%
Retail & Wholesale	45-47	58,806	35,283	0.76%
Education	85	26,361	15,817	0.59%
Arts & Entertainment	90-93	6,083	3,650	0.46%
Support Services	77-82	14,194	8,517	0.38%
Health & Social Services	86-88	22,306	13,383	0.36%
Accommodation & Food	55-56	-	-	--
Total		725,944	435,567	1.45%

Source: "Jobs and Growth", RAEng (2012)

[5] RAEng (2012) "Jobs and Growth"

It shows highly qualified engineers are distributed throughout the economy,[6] reflecting the pervasiveness of engineering and underlining the general applicability of engineering principles and techniques, from analytical thinking to problem solving. **Every sector of the UK economy employs thousands of graduate engineers**, with several 'non-obvious' sectors employing tens of thousands of engineers, including most notably the retail and wholesale sector, with more than 35,000 graduate engineers and close to 1% of the total workforce (0.76%). In terms of numbers of graduate engineers, manufacturing dominates (c. 110,000), followed by construction (72,000), computing & telecommunications (51,000) and business services (50,000).[7]

High-tech manufacturing has the greatest share of higher qualifications, with graduate and postgraduate engineers comprising almost 10% of its total workforce. High-tech manufacturing includes manufacturing of pharmaceutical products, as well as of computers and electronics. Computing & Telecommunications and other areas of Manufacturing (manufacture of space-crafts, and transport equipment) also show high concentrations of graduate engineers in their workforce. There is also some concentration evident in other major areas of the economy, from Utilities (including electricity and water supply), to Construction and Business Services (including real estate activities and professional and technical activities).

More than 12,000 graduate engineers work in the finance and insurance sectors applying their engineering skills directly or indirectly. The field of 'finance engineering' has emerged in recent years drawing on tools from applied mathematics, computer science, statistics and economic theory and there are many financial innovations that have been developed by computer scientists and engineers. Furthermore, a study by Microsoft (2008) found that the UK hosts 25% of Europe's largest software companies and is an 'international powerhouse' for emerging sectors like digital media and Web 2.0 and games developers. The study also pointed out that the UK has the largest share of Venture Capital (VC) investment in software companies in Europe – at nearly one third of the total – which is another indication of the strength of the UK software industry.

Figure 2 – Number of R&D personnel employed, by sector (000s in FTEs)

	R&D Employment	Scientist and engineers
Computer programming and information service activities	24	13
Pharmaceuticals	23	10
Aerospace	13	8
Miscellaneous business activities; Technical testing and analysis	10	8
Motor vehicles and parts	14	7
Machinery and equipment	12	6
Telecommunications	8	6
Consumer electronics and communication equipment	7	5
Research and development services	8	5
Precision instruments and optical products; photographic equipment	6	4
Chemicals and chemical products	7	3
Electrical equipment	5	3
Food products and beverages; Tobacco products	4	2
Other (7 sectors)	19	10
Total	**160**	**90**

Source: Technopolis (2014). Based on BERD statistics, ONS

[6] *Idem.*

[7] A full description of those broad sectors can be found in Appendix B.

The games industry is a fast growing and innovative sector where a plethora of design and engineering skills come together to generate creative products. There are more than 1,900 games companies in the UK, which NESTA estimates could be contributing to the UK economy as much as £1.7 billion (NESTA, 2014).[8] The industry is experiencing an entrepreneurial boom, with an estimated 22% growth in the number of companies on a yearly basis. Engineers are at the centre of these developments.

Figure 2 shows the distribution of R&D personnel by broad sector. Of the 435,000 Level 4+ engineers working in different type of activities within companies, some 90,000 are doing research & development for industry mainly in the areas of computer programming, pharmaceuticals and aerospace. The figure of 90,000 refers to 'scientists and engineers,' however given the applied nature of much of the research being conducted in or for industry we have assumed the great majority of these people are carrying out engineering-related activities.

3.1.2 Pervasiveness translates into a high contribution to UK GVA

We estimate that engineering contributed around **£280 billion** to the UK economy in 2011, in gross value added (GVA), which is around 20% of total UK GVA and as such a very substantial contribution to the economy overall.[9] Previous studies have reported figures of 28% GVA[10] and 27.1% GDP.[11] The variation in these results is due mainly to the methodologies used to select the' engineering-based sectors', in particular, the level of resolution used to define the relevant sectors.

Our 2011 estimate represents an increase of 3% in comparison with the estimated £270 billion contribution for 2007, which suggests UK engineering has recovered, and even exceeded, its pre-crisis levels of economic output.

The £280 billion figure is arrived at through the estimation of two values, one for the output of the UK's primary engineering-related sectors and one for the value of engineering activity in other sectors:

- GVA of those economic sectors tightly linked to engineering such as high-tech manufacturing or computing & telecommunications. We have selected these sectors based on an a priori judgement about that sub-set of sectors within the wider economy that are most commonly associated with engineering[12]. In those cases we include 100% of the sectoral GVA in our overall estimate.
- GVA contribution of graduate engineers across all other economic sectors, where we include a proportion of sectoral GVA for each of those sectors, based on the percentage of graduate engineers in relation to the total workforce for that sector as shown in Figure 1.

Figure 3 shows the distribution of GVA across all economic sectors of the economy,[13] split between those sectors we judge to be most tightly linked to engineering and a second group of economic sectors that benefit from engineering-related skills. In the first group, the sector related to construction heads the table in terms of economic contribution followed by computer programming and telecommunications and medium to high tech manufacturing (which includes the automotive and chemicals sector).

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8 http://www.nesta.org.uk/publications/map-uk-games-industry#sthash.gJPFhMDf.dpuf

9 In simple terms, GVA is a measure of profits and salaries in a sector and excludes the value of the goods and services necessarily bought-in, to avoid double counting. GVA is HM Treasury's accepted measure of the additional value that a sector brings into the economy.

10 Jobs and growth: the importance of engineering skills to the UK economy, Royal Academy of Engineering, September 2012 http://www.raeng.org.uk/publications/reports/jobs-and-growth

11 The contribution of engineering to the UK economy, a report for Engineering UK (Cebr), October 2014. http://www.engineeringuk.com/_resources/documents/Oct%202014%20Cebr%20-%20The%20contribution%20of%20engineering%20to%20the%20UK%20economy.pdf

12 The selection of sectors 'tightly linked to engineering' was confirmed by experts in the form of the Steering Group for this study and is also supported by the data on concentration of engineers in the workforce.

13 The SIC codes contained in these sector are shown in Figure 1 and further explanation can be found in Appendix B.

Figure 3 – GVA of engineering related sectors

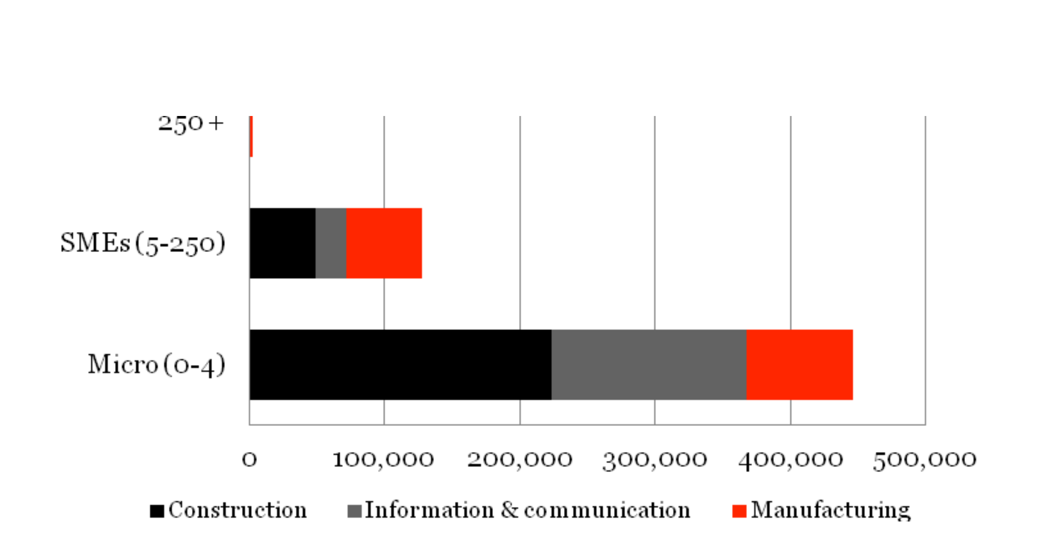
Sectors tightly linked to engineering	UK GVA (2011) (£million) [1]	Attribution: 100% [2]	Engineering related GVA (2011) (£million) [1]x[2]
Construction	£86,789	100%	£86,789
Computing & Telecommunications	£59,793		£59,793
Med-High-Tech Manufacturing	£41,334		£41,334
Med-Low-Tech Manufacturing	£33,348		£33,348
High tech Manufacturing	£22,399		£22,399
Architectural and engineering activities	£21,931		£21,931
Sub-total	£265,594		£265,594
Sectors that benefit from engineering-related skills	**UK GVA (2011) (£million) [1]**	**Attribution: Concentration of 'Engineers' with Level 4+ [2]**	**Engineering related GVA (2011) (£million) [1]x[2]**
Utilities	£33,289	3.91%	£1,302
Low-Tech Manufacturing	£43,458	1.83%	£795
Business Services	£218,365	1.68%	£3,669
Media & Publishing	£28,242	1.64%	£463
Other Services	£25,730	1.37%	£353
Public Admin and Defence	£70,400	1.21%	£852
Agriculture & Mining	£40,818	1.11%	£453
Financial & Insurance	£116,363	1.10%	£1,280
Transport & Storage	£59,179	0.83%	£491
Retail & Wholesale	£151,785	0.76%	£1,154
Education	£84,556	0.59%	£499
Arts & Entertainment	£20,410	0.46%	£94
Support Services	£62,156	0.38%	£236
Health & Social Services	£104,026	0.36%	£374
Accommodation & Food	£36,554	0.00%	--
Sub-total	£1,095,331		£12,014
Total	**£1,360,925**		**£277,608**

Source: Technopolis (2014) using data from "Jobs and Growth" (2012) and the ONS Input-output tables/ 1. Includes Finance and Insurance.

This methodology uses a combination of the approaches applied in other field-level studies (for chemistry, mathematics and physics). The study on chemicals accounts for 100% of the GVA of the 'upstream' sector (chemical-producing industry) and makes an assessment of the percentages applicable to the 'downstream' sector (chemical using industry), based on stakeholder's views (Oxford Economics, 2010). The mathematical study identifies the percentage of the workforce with 'mathematical occupations' in different economic sectors and uses those percentages to make an estimation of GVA attributable to mathematics (Deloitte, 2012). The study on physics accounts for 100% of the GVA of all the UK businesses for which physics-related technology and expertise is critical to their operations (Deloitte, 2012). A further comparison across the different methodologies can be found in Appendix B.2

SMEs and micro companies contribute greatly to these results as they dominate the industrial landscape in numerical terms. In 2012, the Inter-Departmental Business Register (IDBR)[14] shows there were more than 570,000 companies operating in sectors tightly linked to engineering (manufacturing, construction and information and communication), 99.6% of which are Micro companies or SMEs (based on employment size).

Figure 4 – Number of companies in the UK, by employment size band



Source: IDBR (2012)

3.2 Engineers as drivers of innovation and competitiveness

3.2.1 Engineers are highly valued by the labour market

Engineering qualifications attract an additional wage premium as compared with science and engineering occupations, estimated by Greenwood (2011) to be 15% for engineering occupations, which is a clear indication that engineers' skills are highly valued in the economy.

Graduates with a first degree in engineering and technology earn a median salary of £28,500 three years after graduation, compared with a median salary across all science areas of £25,500. Only 8% of engineering and technology graduates earn less than £20,000, compared with 13.7% of all science subject graduates, and 17.8% of all graduates (Perkins Review, 2013). Moreover, according to the Survey of Registered Engineers (2013), the median basic annual salary for Chartered Engineers increased by 25% between 2007 and 2013, a period that fully encompasses the global economic downturn where large parts of the working population have seen wage freezes or even reversals.

3.2.2 High concentrations of engineers are linked with high levels of innovation

Evidence shows that engineering-related sectors (such as high-value manufacturing) and sectors with a high concentration of workers with engineering and applied sciences skills tend to be more innovative, as well as having higher innovation-related income than comparator sectors.[15]

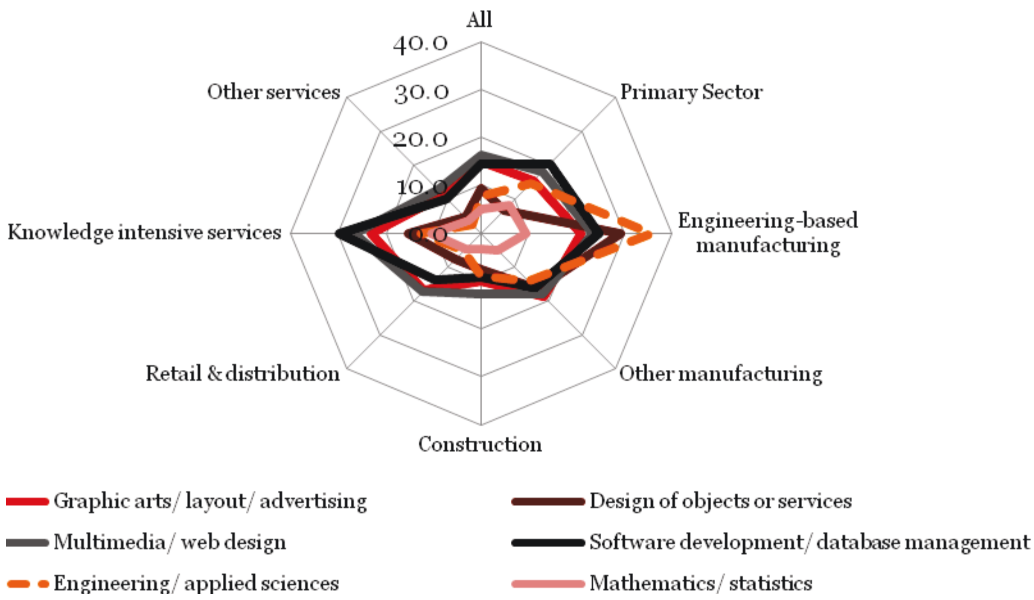
[14] The Inter-Departmental Business Register (IDBR) is a comprehensive dataset of UK businesses built up in large part by HMRC from VAT registrations and PAYE returns, which holds records of approximately 2.1 million businesses accounting for around 99% of total UK economic activity. The IDBR does not cover very small businesses without VAT or PAYE schemes (e.g. the self employed and those with very low turnovers and without employees) and some non-profit making organisations. The number of these businesses in the UK is estimated to be at 2.3 million.

[15] The Community innovation survey collects information on the percentage of workers that have engineering and applied sciences skills. It is not possible to disentangle 'engineering' skills from that definition.

This is true in terms of both input and output measures; innovative behaviours, expenditure on R&D, introducing new innovations and business practices and, in the latter, turnover resulting from new innovations and the proportion of exporting firms in-sector.

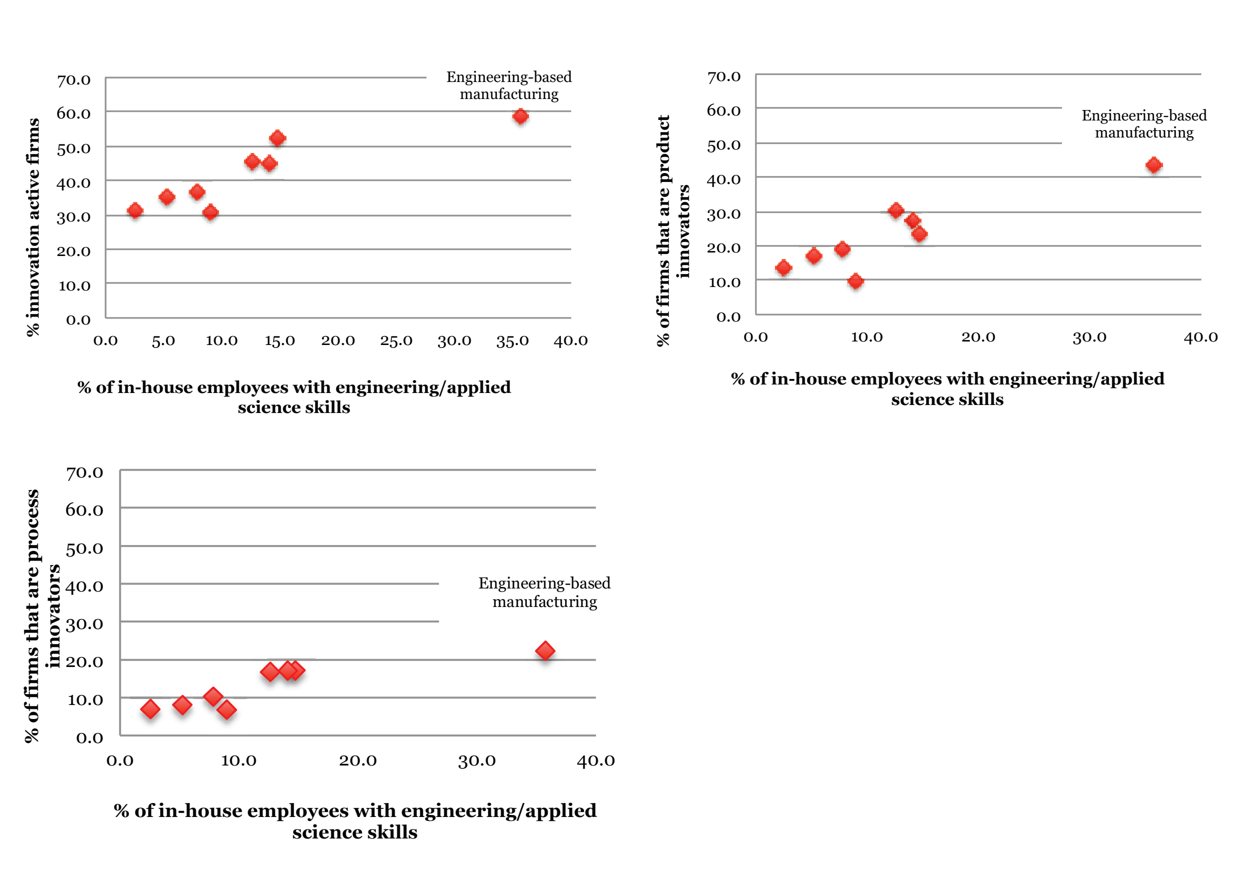
Engineering-based manufacturing, the broad sector with the highest concentration of engineering and applied science skills (see Figure 5), **reports the highest percentage of firms that are 'innovation active,' at 58.6%**, according to the UK Innovation Survey (see Figure 6). Breaking this down further, it is apparent that engineering-based manufacturing also performs best in terms of both product (43.6%) and process (22.3%) innovation activity. Each of these are significantly above the all-sector averages of 36.8% innovation active, 18.9% engaging in product innovation and 10.3% of firms engaging in process innovation. The other sectors with high concentrations of engineering-related skills are all above the all-sector average.

Figure 5 – Distribution of skills across broad economic sectors



Source: UK Innovation Survey, 2011

Figure 6 – Enterprises engaging in innovation (%) by broad sector



Source: UK Innovation Survey, 2011

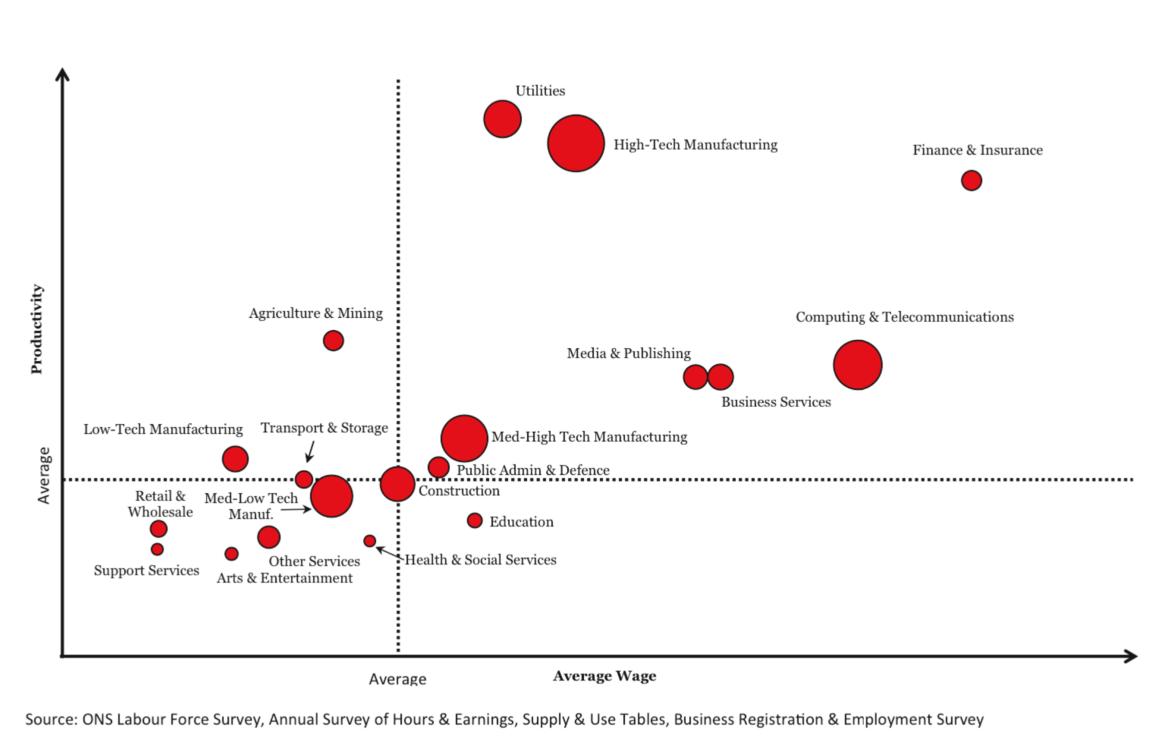
The data show that 41.2% of engineering-based manufacturing firms introduced wider innovation activities between 2008-2010, higher than the all-sector average of 30.8%. The primary sector (incl. agriculture and mining) (40.4%), knowledge-intensive services 38.6% and other manufacturing (35.4%) all performed well over the same period in this regard. Sectors with lower concentrations of engineering-related skills under-performed against the all-sector average, demonstrating that those sectors where engineering skills are prominent tend to be more innovative.

Sectors with high levels of innovation (Engineering-related manufacturing, Knowledge intensive services and the Primary sector) not only have high concentrations of engineering skills, but also a diversity of other innovation-related skills, such as design, software development and graphic arts, mathematics and statistics, shown in Figure 5.

Two main conclusions arise from this evidence: i) those sectors with high concentrations of engineering skills are a magnet for other innovation-related skillsets; and ii) the innovative activity taking place in those sectors is predicated on a range of high-value skillsets coming together, within which engineering plays a central part. Soft skills (e.g. communication skills) are no doubt also important in the workforce to promote and sustain crossovers and multi-disciplinary team working.

Figure 7 is a scattergram showing the UK's main economic sectors distributed according to their average labour productivity (y-axis) and average wage (x-axis). The concentration of graduate engineers (as shown in Figure 1) is effectively the third dimension, indicated by the size of the circle; a larger circle equates to a higher concentration. Sectors with higher concentrations of graduate engineers, such as High-Tech manufacturing, Computing and Telecommunications, Med-High Tech manufacturing, Utilities and Transport and Storage, tend to have levels of labour productivity (GVA per employee) and wages that are equal to or above the national average, with High-Tech Manufacturing and Utilities showing the highest levels of productivity with wages that are higher than average but substantially lower than Business Services, Computing or Finance.

Figure 7 – Labour productivity and concentration of graduate engineers



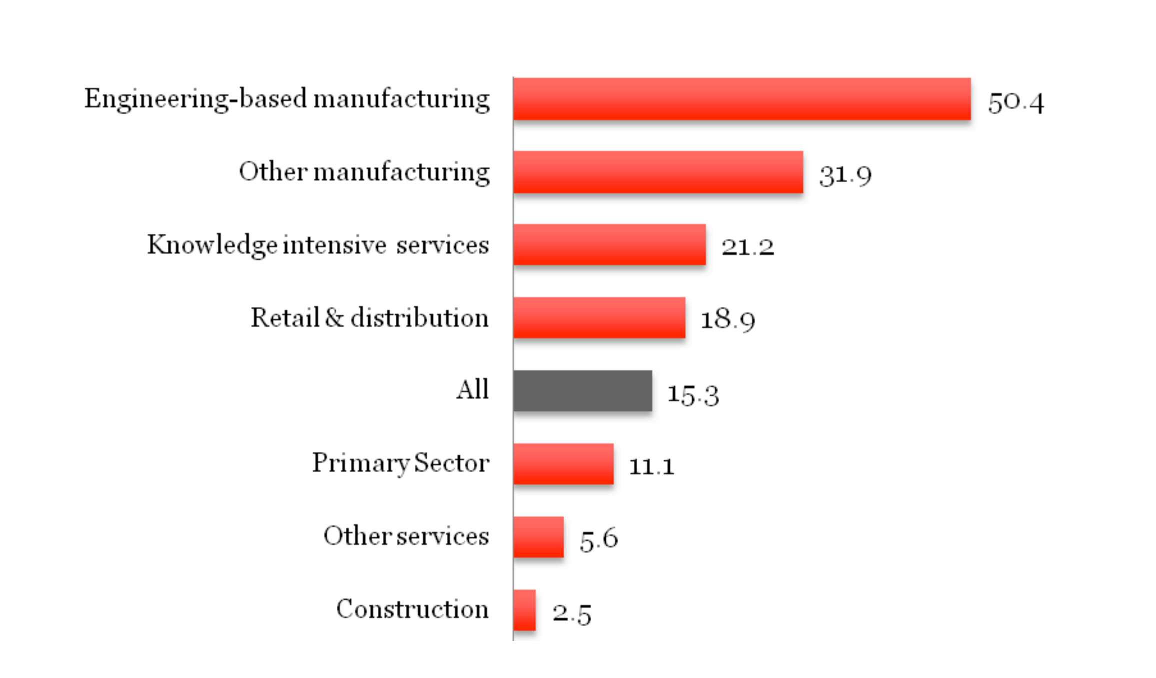
Source: Technopolis (2014). Adapted from information collected by Big Innovation Centre for the 'Jobs and Growth' Report (RAEng, 2012).

3.2.3 Higher innovation and productivity leads to higher competitiveness

Sectors with higher concentrations of engineering-related skills tend to export more. Figure 8 shows that Engineering-based manufacturing ranks first in terms of the percentage of firms in the sector that report themselves as 'exporters,' which at 50.4% of all firms, is much higher than the all-sector average of 15.3%. Engineering-based manufacturing out-performs 'other manufacturing,' which ranks second at 31.9%.

In terms of value, engineering-based manufacturing companies export, on average. £9.3 million per year per company, more than double that of other manufacturing companies, at £3.9m. The primary sector reports the highest average value of exports (per business), at slightly over £11m.

Figure 8 – Percentage of enterprises exporting (%), by broad sector



Source: UK Innovation Survey, 2011

Furthermore, the sub-set of sectors tightly linked to engineering (see Figure 3) generated exports with a combined value of around **£240 billion in 2011**, which is 48% of the total value of all UK exports for that year. Following the same methodology used for estimating GVA, we estimate that **additionally £3.2 billion** of exports can be attributed to engineers working across all other sectors of the economy.

3.3 Engineers produce high quality research

3.3.1 The UK produces world leading engineering research

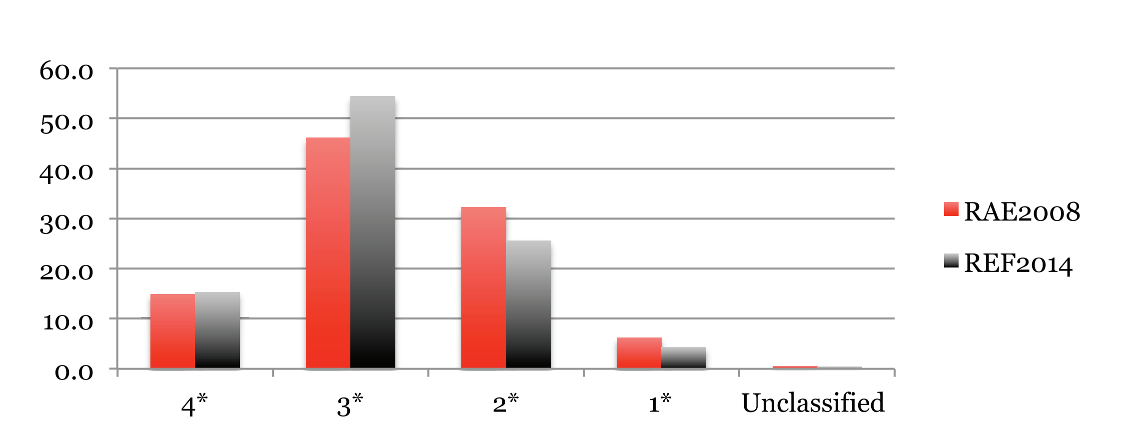
The UK's engineering research is world-class, as is shown by analysis of the results published by HEFCE from the Research Excellence Framework (REF2014) and by analysis of engineering publications. At the time of writing, the REF2014 had just been published showing strong results for the five Units of Assessment (UoA) related to engineering research:

- Civil and Construction Engineering
- Computer Science and Informatics
- Electrical and Electronic Engineering, Metallurgy and Materials
- General Engineering
- Aeronautical, Mechanical, Chemical and Manufacturing Engineering

The results show that 15% of all research outputs submitted to those five UoAs were rated as world-leading, or 4*, *Quality that is world-leading in terms of originality, significance and rigour*. In contrast, only 4% of submitted outputs were rated as 1*, *Quality that is recognised nationally in terms of originality, significance and rigour*. This distribution is skewed to the left towards the highest possible quality, as shown in Figure 9. The figure also shows an improvement in the quality profile of engineering UoAs in comparison with the results of the prior exercise (Research Academic Excellence, RAE2008).

In REF2014, 70% of all research outputs, submitted by the UoAs related to engineering research, were classified as 'world leading' (4*) or 'internationally excellent' (3*), which represents an increase of 9 percentage points in comparison with RAE2008. Moreover, the overall quality profile classified as 'world leading' or 'internationally excellent' increased from 55% (RAE2008) to 68% (REF2014).

Figure 9 – Quality profile research outputs: RAE2008 versus REF2014



Source: Technopolis based on results from RAE2008 and REF2014

More recent bibliometric analyses, confirm the overall judgement of the RAE2008 panels, namely that UK engineering research is globally recognised for its high quality. The latest international review of UK research commissioned by BIS and published by Elsevier (2013),[16] shows that the UK remains a global research heavyweight across almost all fields and that Engineering research is especially strong.

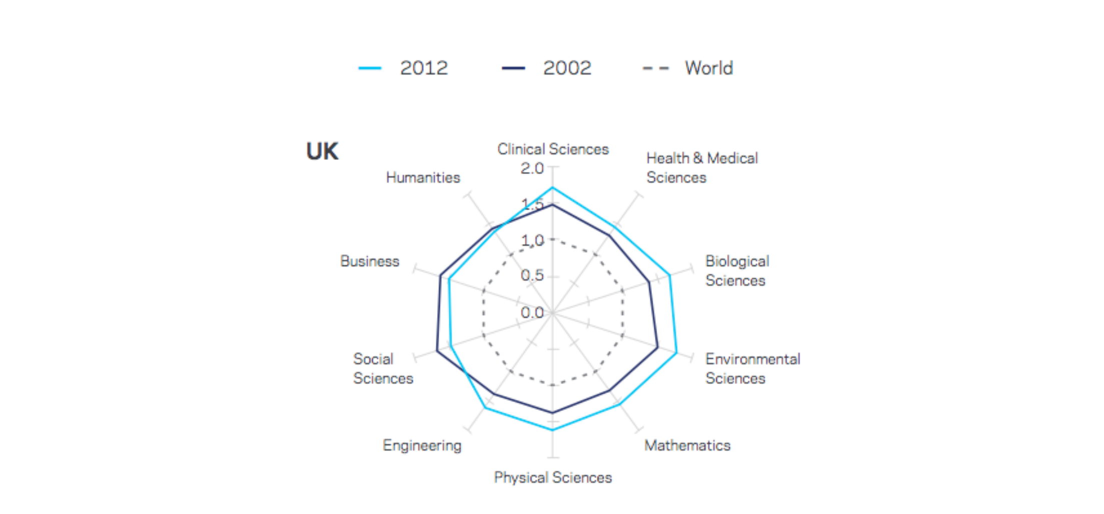
The UK's field-weighted citation impact (an indicator of the number of citations in a field, normalised for discipline specific behaviours) is typically around 150% of the world average for all disciplines. There has however been an evident change across the 10-year period 2002-2012, with the natural and physical sciences showing significant gains against the world average while the arts, humanities and social sciences have seen a reversal (see Figure 10).

UK engineering has performed strongly across the period, and the UK field-weighted citation impact is higher than for comparator countries such as USA, Germany, Japan, and Canada, which have been seen for many years as the world's leading engineering economies.

A high field-weighted citation impact is a proxy of high quality, influence, and transfer of knowledge. This high influence is achieved despite the fact that the UK produces relatively less research output in the field of "Engineering" in comparison with the worldwide level of research activity in this field.

[16] Elsevier (2013). International Comparative Performance of the UK Research Base – 2013. A report prepared by Elsevier for the UK's Department of Business, Innovation and Skills (BIS).

Figure 10 – Field-weighted citation impact



Source: Elsevier (2013). Note for all research fields a field-weighted citation impact of 1.0 represents world average in that particular research field.

A further indication of the excellence of engineering research is the UK's active participation in international R&D programmes. The EU Seventh Framework Programme for Research and Technological Development (FP7) is the world's largest research programme. The FP7 Cooperation Programme, which supports applied research and demonstration, was the largest component of the overall scheme with a total budget of EUR 40 billion to be committed over the 7-year term, between 2007 and 2014.

Up to October 2013, UK-based universities and businesses had been awarded FP7 grants with a combined value of close to EUR 7 billion, almost EUR 1 billion a year, which amounts to around 15% of the national science budget and around 3% of GERD.

A budget of circa **EUR 2.5 billion (circa £2 billion) has been allocated to the FP7 Cooperation Programme in thematic areas closely related to engineering**, such as Energy; Nanosciences, Nanotechnologies, Material; Security; Space; Transport (including Aeronautics) and ICT, which represents 11% of the overall budget across those 6 thematic areas (see Figure 11). Note that these thematic areas (and the Cooperation Programme overall) attract participants from 133 countries, hence this share is a testament of the quality of UK-based universities and businesses engaged in engineering research activities, which are capable to attract this pool of resources from a highly competitive fund.

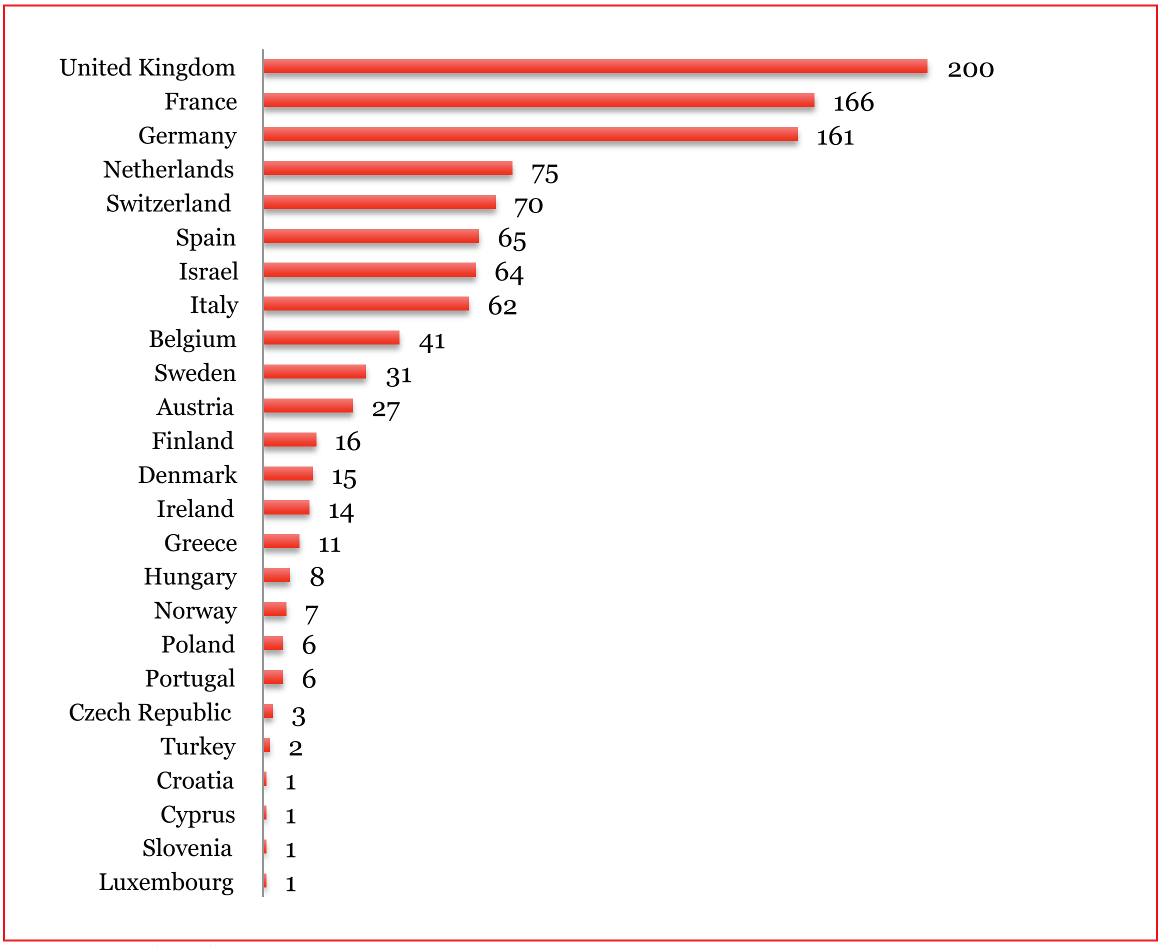
Figure 11 – UK Participation in Fp7 (selected thematic areas)

Thematic areas	**Participations**	**Total Cost (in EUR million)**	**EC Contribution (in EUR million)**
Space	250	€103.7	€ 72.1
Security	313	€155.7	€ 111.0
Energy	344	€178.3	€ 115.9
Nanotechnologies and Materials 1/	992	€468.0	€334.9
Transport (including Aeronautics)	920	€389.5	€254.5
Information and Communication Technologies	2148	€1,166.3	€845.3
Total	**4,967**	**€2,461**	**€1,733.6**
As % of total (for all participant countries)	10%	11%	11%

Source: Technopolis (2014). Based on E-corda data provided by the EPSRC. 1/ Nanosciences, Nanotechnologies, Materials and new Production Technologies

The UK also has a strong participation in the European Research Council (ERC) in the area of engineering and physical sciences (EPS). The ERC is a pan-European organisation funded in 2007 - as part of FP7 Capacity Programme - that allocates grants for research on a competitive basis through a peer review process that focuses on excellence. In the period 2007-2013 a total of 200 grants have been allocated to UK researchers in the EPS area (19% of the total number of grants for EPS), substantially more in comparison to the grant allocation across other participant countries (see Figure 12).

Figure 12 - European Research Council: Number of grants in the area of 'Engineering and Physical Sciences' (2007-2013)



Source: ESR (2015)

3.3.2 The UK has numerous engineering-related centres of excellence

The UK has many tens of international centres of excellence carrying out research in various engineering-related fields, bringing together universities with research institutes and businesses. These centres come in very many shapes and sizes, some wholly public sector while others (a growing proportion) are public private partnerships, but they all tend to share some common features: long-term structures to ensure funding continuity, collaborations to help sharpen the focus of applying research on issues of strategic importance and bring together multiple disciplines and perspectives to increase prospects for success, stronger links with real-world applications and demonstrations.

There is no single inventory or census of these national technological assets, and as such the following bullet points comprise a selection of different types of centres of excellence compiled bottom-up, simply with a view of illustrating the nature and extent of this infrastructure:

- EPSRC has been issuing calls for proposals over the past 20 years or so, launching new Interdisciplinary Research Collaborations (IRCs) funded through large, long-term grants, typically around £10 million over six years. IRCs generally involve several universities together with industrial partners and seek to create a critical mass of scientists and engineers sufficient to deliver a real impact in areas of key future industrial relevance to the UK. The three most recent IRCs will run through to 2018 and comprise health-related applications of engineering research, including a Sensor Platform for Healthcare in a Residential Environment (SPHERE) and an IRC for Early-Warning Sensing Systems for Infectious Diseases.

- Innovate UK has launched seven national centres of excellence, or Catapults, during the last several years, many of which have a clear focus on engineering. The High Value Manufacturing (HVM) Catapult is one example; a strategic initiative that aims to revitalise the UKs manufacturing industry. Its long-term goal is to stimulate growth and at least double the sector's contribution to UK GDP by developing manufacturing technologies ranging from raw materials to finished assembly products. The Catapult combines the strengths of seven existing centres, overseen by Innovate UK, across key manufacturing processes; to help businesses and research institutions accelerate new concepts to commercial reality. **The centres represent circa £200 million of government investment, delivered over a 6-year period, matched by industry.**[17]
- WELMEC Centre of Excellence in Medical Engineering – WELMEC, at the University of Leeds, was funded in 2008 by the Wellcome Trust and EPSRC. The centre is developing new ways to extend human joint and cardiovascular health, and so improve quality of life, for '50 active years after 50'. The Centre researches, develops and delivers new types of intervention for the musculoskeletal and cardiovascular systems. This is one of the four Centres of Excellence in Medical Engineering funded by the Wellcome Trust and EPSRC.
- Energy Technologies Institute – The Energy Technologies Institute is a public-private partnership between global energy, engineering companies and the UK government. This partnership shares the risk and creates affordability for the development and demonstration of new low carbon technologies. To date the ETI has delivered £49M for projects focusing on knowledge building, £65M on projects focused on technology development and £96M for projects focused on technology and systems demonstrations. The impact of ETI's investments on the UK energy system is expected be seen over the next 20-30 years and long range forecasts fed into Technology Innovation Needs Assessments estimate two types of economic value to the UK from successful innovation in technologies. This includes cutting energy costs to minimise the cost of meeting UK emission targets (estimated overall at £200bn) and providing additional value to UK GDP from business creation / development in global markets estimated at ~£76bn.[18] The ETI model has been adopted and adapted with the launch of several other public-private partnerships, to lead and coordinate applied research in the UK including for example the £2 billion Aerospace Technologies Institute (ATI) and the £70M Agri-Tech Catalyst.
- Warwick Manufacturing Group – The Warwick Manufacturing Group (WMG), an academic group based at the University of Warwick, has **an annual programme of £180M of public and private investment**. The Group works on a wide range of projects spanning across the automotive, aerospace, defence, digital, construction, energy and utilities, finance, food and drink, healthcare, IT, pharmaceutical and rail industries and collaborations with government sponsored departments, the NHS, SMEs and global corporations such as Jaguar Land Rover and AstraZeneca.[19]

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[17] HVM Catapult, About the High Value Manufacturing Catapult, https://www.catapult.org.uk/documents/2155693/0/About+the+High+Value+Manufacturing+Catapult/9833a13e-6ee3-4f09-8e10-dfa6b9d5321e?version=1.0https://www.catapult.org.uk/documents/2155693/0/About+the+High+Value+Manufacturing+Catapult/9833a13e-6ee3-4f09-8e10-dfa6b9d5321e?version=1.0

[18] Technopolis Group and MottMacdonald (2013), Energy Technologies Institute Mid-Term Review, Final Report

[19] WMG Website, http://www2.warwick.ac.ukhttp://www2.warwick.ac.uk

- Rolls-Royce Nuclear Technology University Technology Centres – Rolls-Royce funds 14 University Technology Centres (UTCs) in the UK. Each centre addresses a key technology; and collectively they tackle a wide range of engineering disciplines. They address different subject areas, from materials, to composites, power conversion, electric power and thermo fluid systems. The centres are part of an integrated approach to research and technology that enables university researchers to work closely with its highly strategic research teams, company technology specialists, and business leaders to identify and develop new technologies required for its broad portfolio of products and services. This formalised, long-term relationship with UTCs allows Rolls-Royce to have much more efficient access to high-quality research and provide university researchers with the opportunity to apply their research to real-world challenges in both the civil nuclear power and nuclear submarine programmes.[20,21,22]
- The UK also has several public research institutes and laboratories with a substantial interest in engineering research, ranging from the Defence Science and Technology Laboratory (DSTL) through to the ISIS Neutron and Muon source at Harwell in Oxford. The former has an intramural science and technology programme with an annual value of around £430M, a substantial proportion of which (30%+) is engineering-related, while the latter is a national facility of international power / standing that employs around 370 staff and supports thousands of experiments annually that feed into an estimated £100M in EPSRC research grants. There are several other government laboratories (e.g. Health and Safety Laboratory in Derbyshire) and privatised former research establishments (e.g. National Engineering Laboratory in East Kilbride, QinetiQ), which together employ several thousand engineers working on research and technology projects.

3.3.3 This academic excellence translates into tangible economic benefits

This study has benefited from privileged access to more than 500 individual REF impact case studies, which proved to be a valuable and unique source of information showcasing the impact of engineering research in all its guises. The case studies describe and quantify the socio-economic impacts that have occurred (became evident at some point in time in the period 2008-2013) and which can be directly attributed to high-quality research carried out historically, during the 20-year period since 1993.

Analysis of the 514 case studies makes clear that UK engineering research has delivered manifold notable impacts across all aspects of society, policy-related, societal and economic.

Some 60 universities were invited to share their engineering case studies with the study team, in confidence, several months ahead of the publication of the REF results scheduled for mid-December 2014. Together the 514 case studies – from 46 different HEIs – provide exhaustive and compelling evidence regarding the economic and social impact of engineering research conducted in the UK over the past 20 years. The case studies encompass 15 of the 36 REF2014 Units of Assessment (UoAs), which extends far beyond the 'obvious' engineering-related UoAs and goes to show just how diverse engineering research can be.

The REF case studies are testament to the advances made possible by engineering research in areas ranging from healthcare to renewable energy by way of land-use planning and building design tools, as well as the more familiar advances in aerospace and automotive technologies (e.g. weight-saving, fuel efficiency, structural integrity). Figure 13 presents a small compilation of notable engineering-research impacts taken from the 514 case studies, and organised around five important engineering-related sectors, which are a sub-set of the 11 UK government's

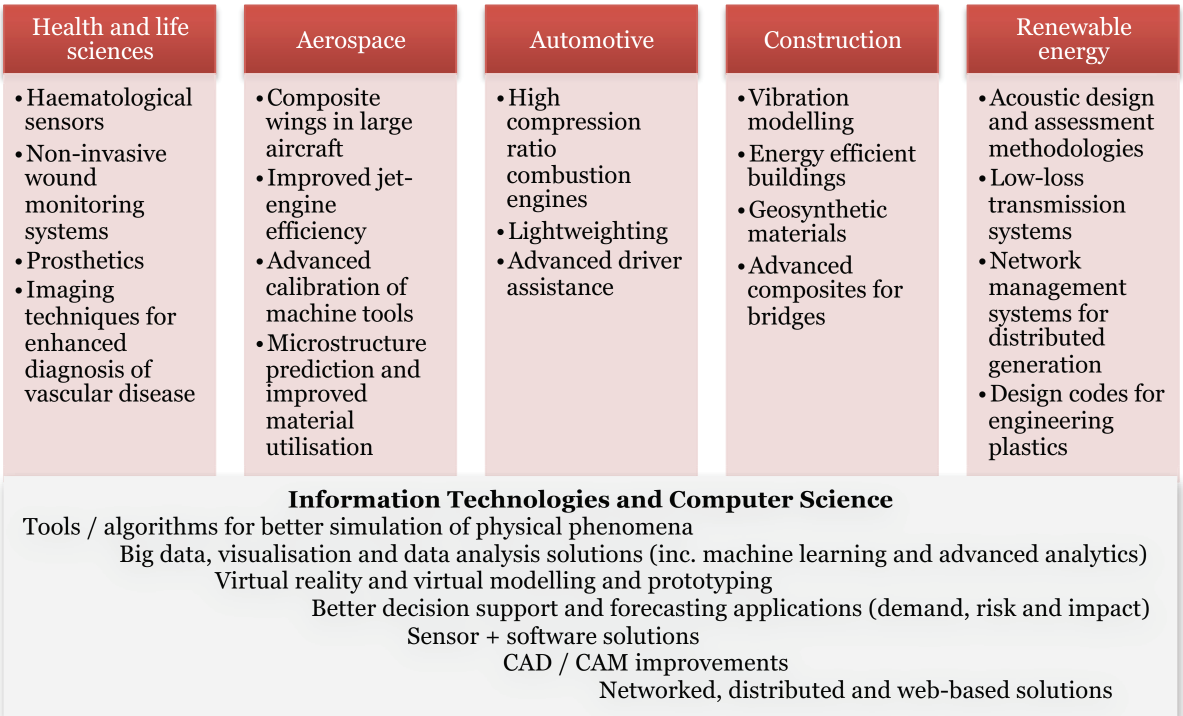
[20] National Centre for Universities and Business (2012)

[21] http://www3.imperial.ac.uk/newsandeventspggrp/imperialcollege/newssummary/news_6-5-2010-13-53-40 http://www3.imperial.ac.uk/newsandeventspggrp/imperialcollege/newssummary/news_6-5-2010-13-53-40

[22] University of Manchester, Rolls-Royce Nuclear UTC Case Study, http://documents.manchester.ac.uk/display.aspx?DocID=20126http://documents.manchester.ac.uk/display.aspx?DocID=20126

current list of strategic sectors. The figure takes into account contributions the Information Technologies research area, which has a cross-sectoral influence.

Figure 13 – Selected examples of notable innovations, by strategic sector



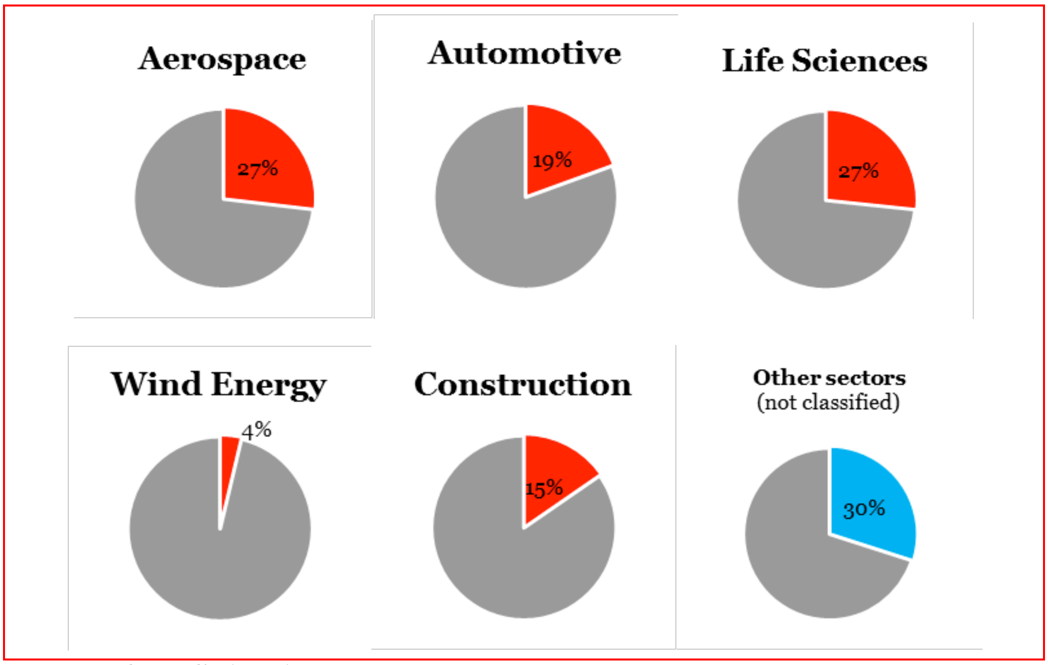
Historically, an economic impact assessment of this kind would need to develop case studies as part of its programme of research and may produce 20-30 within the typical time and budget constraints. In this study, we had access to 514 carefully drafted case studies; an order of magnitude more material and data than normal.

The individual REF case studies are a rich source of information in their own right and a systematic approach had to be put in place to analyse and assess them. Innovative text mining techniques were put in place to get an overview of the material provided and its distribution across key 'impact pathways' and strategic industrial sectors. This is to our knowledge the first attempt to try to systematise the vast amount of information contained in the REF case studies. More information on the text mining analysis can be found in Appendix C.

We identified two dimensions of interest to guide the text mining exercise analysis: (1) Pathways to impact and (2) Industrial strategic sectors.

Figure 14 shows the distribution of impacts across five different economic sectors: aerospace and satellites, automotive, construction, life sciences and wind energy, calculated using those text-mining techniques. These five sectors represent around 71% in grant value of EPSRC's active portfolio of engineering grants in the 2014 period. The EPSRC is mentioned specifically in 214 out of the 514 case studies (41.6%) in their description of the underpinning research.

Figure 14 – Distribution of specific sectors cited in REF Impact Case Studies



Source: Technopolis (2014)

Around a quarter of case studies mentioned impacts in the aerospace and life sciences sectors, while around a fifth of them did so in the automotive sector. Around 5% of the REF cases concern developments in the area of wind energy, which is a very much narrower domain than for example aerospace or construction, highlighting the work carried out in this rather new area of investigation.

Analysing the REF case studies reveals numerous instances where an individual case records a notable impact in the aerospace sector, for example, but also reports applications of technology and know-how in other fields, for example the automotive sector and indeed many other sectors. Many engineering developments are widely applicable in many different sectors. This also shows researchers' awareness of the importance of targeting multiple application sectors and their willingness to explore different routes to commercialisation for their underpinning research, which in turn could lead to a higher chance of success of the technology in the market.

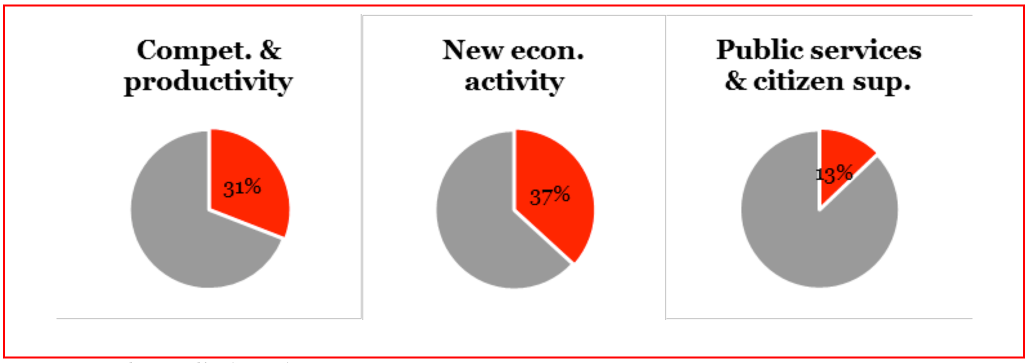
Around a third of the case studies refer to increases in productivity and competitiveness, citing examples of research that led to the development / implementation of new industrial processes or techniques and which have led to efficiency gains and cost savings for businesses and public agencies (see Figure 15).

Similarly, more than a third of the case studies relate to new or increased economic activity. This category includes research that led, for instance to the launch of new products, and new sales, but also to the creation of spin outs, which in turn create additional value to the economy in terms of new sales and new jobs. Also, more than 10% of the impact case studies mentioned specific contributions to improving the provision of public services and providing support to citizens in different ways (including impacts on policies and standards).

What we were not able to do was to arrive at any kind of aggregate estimate of the monetary value of these manifold impacts. Most case studies do include financial data; however it is presented in a multiplicity of forms, which range from estimates of the sterling value of the annual sales of a new product or an estimate of savings realised through the implementation of a new process or tool, to figures for the value of equity sales / trade sales or exports and so on. They are sometimes monetised directly or otherwise presented as a share of a larger (knowable) figure, and sometimes they relate to a single organisation or point in time while on other occasions they relate to a group of businesses and total benefits (multiple years).

While we have no easy way to relate the 514 cases back to some total body of engineering research impacts, what we can say is that the 514 enumerate several thousand examples of specific financial benefits, with a combined value that runs into the billions and would no doubt still amount to many tens of millions if the figures were annualised and adjusted for additionality and displacement.

Figure 15 – Engineering REF Case Studies across types of impacts



Source: Technopolis (2014)

This meta level analysis provides an overview of these case studies, and further qualitative analysis has been conducted to bring to life specific stories and illustrate and explain the connections between inputs and outputs.

These synthetic essays, which can be found in Appendix A, draw out particular patterns in engineering research within each of the current strategic sectors (incl. aerospace, automotive, life sciences, and wind energy) and exemplify those trends with cross-references to specific REF case studies.

Additionally, in order to add colour and interest to our analysis here, we have extracted a selection of illustrative material from the case studies, and present those excerpts in a series of text boxes. They comprise a selection of examples of how engineering research contributes to increase the productivity and competitiveness (Box 1) or has led to the generation of new economic activity through the commercialisation of research (Box 2). They provide striking examples of the economic importance of engineering research, but, also, the social benefits that arise from it. The contribution to public services is explored in Section 4.

Box 1: Competitiveness and productivity

- **Design and manufacture of composite wing structures - optimising performance and improving process (University of Bath)**

"The A350-XWB is the first Airbus airliner to have composite wings, thereby reducing structural weight compared with the current generation of metallic wings. With over 700 orders for the aircraft, the company has placed great emphasis on the need to maximise performance benefits whilst mitigating risk associated with manufacture of the all-new wing. The Bath Composites Research Unit has supplied underpinning research to: (1) Develop an algorithm that has been used to design the composite wing skins for optimised performance; (2) Analyse the laminate consolidation process for the wing spars. The impact of (1) is a direct saving of 1.0 tonne of fuel per typical flight compared with current metallic skins. This represents a total fuel saving of around 40,000 tonnes, over the design life of each aircraft. The impact of (2) is the achievement of satisfactory part quality for current production rates of spars valued at 1M each when equipped."

- **Fracture modelling saves money, increases productivity and makes mining safer (Queen Mary University of London)**

"From 1995 Professor Munjiza's research at QMUL has led to the development of a series of algorithms which can predict the movement and relationship between objects. These algorithms have been commercialised by a range of international engineering and software companies including Orica, the worlds leading blasting systems provider (via their MBM software package), and the software modelling company, Dassault Systems (via their Abaqus software). Through these commercialisation routes Munjiza's work has generated significant economic impact, which is global in nature. For example, his predictive algorithms have enabled safer, more productive blast mining for Orica's clients in one mine alone, software based on Munjiza's modelling approach has meant a 10% increase in productivity, a 7% reduction in costs and an annual saving of $2.8 million. It has also been used in Dassault Systems Abaqus modelling software, which is the worlds leading generic simulation software used to solve a wide variety of industrial problems across the defence, automobile, construction, aerospace and chemicals sectors with associated economic impact."

- **Positron emission particle tracking (PEPT) enables a paradigm shift in process design and multi-scale modelling (University of Birmingham).**

"The technique of positron emission particle tracking (PEPT), conceived and developed by David Parker from the School of Physics and colleagues in the School Chemical Engineering has enabled a paradigm shift in the understanding of a number of industry relevant chemical engineering problems. The ability to interrogate the motion of fluids and particles within opaque systems has led to its adoption across a wide range of industry sectors including oil and chemical, minerals, and home and personal care leading to improved process models. Key process improvements have been reported by six major industrial sponsors, representing significant fiscal and environmental benefits, as well as enhanced competitiveness. In addition to a continuing programme of studies at Birmingham, PEPT measurements are now performed at the iThemba National Lab in South Africa, where since 2009 a PEPT facility has been developed with assistance from Parker and funding from Anglo-American-Platinum."

- **Prolonging the Life of our Concrete Infrastructure (University of Bath)**

"Research within the Building Research Establishments sponsored Centre for Innovative Construction Materials (CICM) at the University of Bath has allowed the life of concrete structures to be extended through developing (a) proper methods for assessing existing capacity and (b) the means to increase capacity where necessary. This has prevented buildings and bridges (managed, for example, by large asset owners such as the Highways Agency and Network Rail) from being condemned as unfit for purpose, resulting in vast savings in reconstruction costs and preventing disruption to infrastructure users. The work has led to the researchers being commissioned to write guidance documents that are routinely used by infrastructure owners and consulting engineers worldwide. Over the course of the last eight years this has resulted in several millions of savings to infrastructure owners and the UK economy."

Box 2: New economic activity

- **Lab-on-a-chip technologies deliver diagnostic tools for infection and disease (University of Glasgow)**

"Fifteen years of research in advanced Lab-on-a-Chip technologies at the University of Glasgow has led to three spin-out companies: Mode-Dx, Clyde Biosciences and SAW-Dx. Since 2008 these companies have developed a range of products and services for the diagnostic screening of chronic diseases, for the detection of acute infections and for improving the drug discovery process. The three companies have secured a total of 2.3M in venture funding and secured key strategic collaborations with stakeholders including industry partners and the NHS".

- **Good Vibrations: Advancing the Cause of Energy Harvesting (University of Southampton)**

"The University of Southampton pioneering research into energy harvesting has produced proven economic impacts together with impacts on public policy and international standards. Market studies predict the market for energy harvesters will be worth over US$1.9 billion by 2017. Perpetuum, a spin-out from Southampton employing 10 people locally, has attracted 9.6 million in venture capital and developed the worlds leading vibration energy harvester. Perpetuum's harvesters are enabling the deployment of zero maintenance, battery-free wireless systems in the rail industry where the technology has revolutionised bearing monitoring. This has enabled, for the first time, real-time monitoring of rolling stock, leading to cost savings, improved reliability, efficiency and safety. Their systems have been deployed on 200 trains across the UK (South-Eastern) and Sweden (SJ AB). Southampton's research has driven wider industrial uptake of the technology and Perpetuum is also the only energy harvester approved for use with the worlds leading suppliers of wireless condition monitoring equipment (GE Bentley Nevada, National Instruments and Emerson). Promotion of the technology has led to a 1.25 million TSB competition on energy harvesting and Southampton researchers are assisting in the development of international standards and increasing public awareness of the technology."

- **Application of Advanced Control Techniques to the Process Industries (University of Manchester)**

"This Manchester based research developed algorithms and techniques that enable large-scale industrial processes, which would previously have been operated inefficiently in open-loop, to be both monitored and controlled. The spin-out company, Perceptive Engineering Limited (PEL), was formed in 2003 exclusively to exploit this research. Its current turnover is approximately 1.5m pa, it employs more than 20 full-time members of staff, and since 2008 has been growing at a rate of ~20% per year. PEL sells industrial software, which delivers advanced process control and condition monitoring. This technology is impacting on manufacturing and utility companies, providing financial savings of ~18m pa worldwide as well as delivering considerable environmental benefits".

- **XeraCarb Limited: a spin-out from Sheffield Hallam University manufacturing novel ceramic composites (University of Sheffield)**

"XeraCarb Ltd is a spin-out company formed in 2011 to exploit a class of ceramic composite materials co-invented by Jones. These materials were first devised in 2008 via a Materials and Engineering Research Institute (MERI) Knowledge Transfer activity and developed from 2009 onwards through a series of UK Ministry of Defence (UK MoD)-funded research projects. XeraCarb was spun out after the underpinning research won a national award in 2011 as the most promising UK materials system for commercialisation. The applications for XeraCarb's materials range from body- and vehicle-armour to kiln furniture and wear-resistant components. The company has attracted significant venture capital investment and is valued at over 1m. It has set up an independent production facility, appointed new employees, been awarded a TSB grant, has materials undergoing trials in respect of a number of applications, and delivered its first orders."

- **Economic benefits from spin out company, Nautricity Ltd, and adoption of new technology to extract energy from tidal flows (University of Strathclyde)**

"A step change reduction in tidal energy costs has been achieved through the development of the novel Contra Rotating Marine Turbine 'CoRMaT' tidal energy technology. The internationally patent-protected CoRMaT system reduces capital, operational and maintenance costs while increasing the extractable tidal energy resource by harnessing flows in deeper waters and from less energetic sites, which were previously considered to be uneconomic. A University spin-out company, Nautricity Ltd, was formed in 2010 to commercialise this technology. The development of this technology has changed both Scottish and UK Government policy via their introduction of programmes which demonstrate a step change reduction in the costs of marine renewables."

- **Health and economic benefits resulting from the development of non- invasive growing prostheses (University College London)**

"A team of biomedical engineers at UCL has developed a non-invasive growing implant that improves the health and quality of life of young patients who have suffered from certain bone cancers. The prosthesis avoids the costly and invasive surgical interventions of previous treatment. Instead, the prosthesis can be lengthened in a quick and pain-free procedure conducted at an outpatient clinic. As a result, it reduces the costs of bone reconstruction and growing by around 19,000 per patient, as well as reducing the risk of infection and subsequent treatment. Since 2008, more than 400 devices have been sold; in addition to the cost savings indicated above these devices have generated more than 6 million income for UCL spin-out company Stanmore Implants Ltd, which was sold for £10 million in 2008."

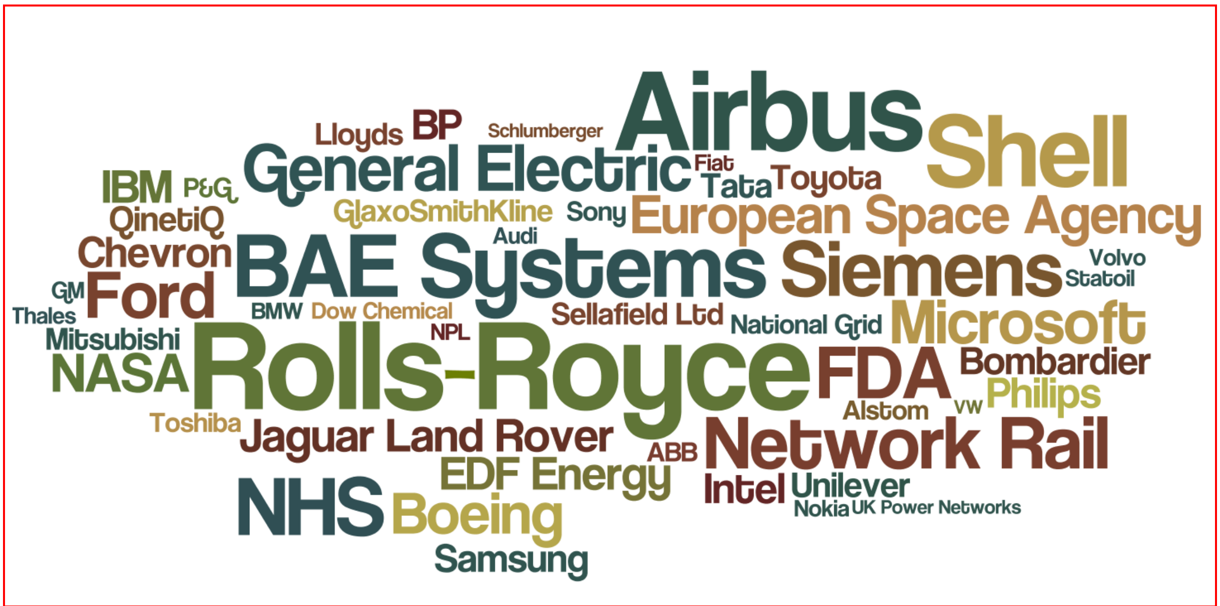
- **Imaging software for cancer diagnosis (University of Oxford)**

"Key advances in the earlier diagnosis of cancer, leading to better treatment and higher survival rates, have resulted from the commercialisation of unique imaging software that exploits research from the Department of Engineering Science. The software products that came from this research, VolparaTM, XD and XRT are now used at major cancer centres worldwide (with approximately 1100 software installations), aiding treatment of tens of thousands of patients every year. Between 2009 and July 2013, VolparaTM scanned over 1.2 million mammograms, enabling the early detection of around 1800 cancers. The products success has catalysed significant improvements in cancer care, and generated an estimated £9M in sales over the past two years for the spinout companies established to develop them (Matakina, based in New Zealand, and Mirada Medical, based in the UK)."

Additional analysis, called Named Entity Recognition (also described in Appendix C), allows identification of the level of engagement with industrial and other 'commercialisation' partners. The result of this analysis can be seen in the word cloud presented in Figure 16. The figure shows the top 50 companies by number of citations, with each of the organisations shown having been mentioned in at least five case studies. The size of the text is proportional to the number of case studies where the company was cited in the description of impact; multiple citations in one case study count as a 'single' citation. The focus on the quantum of citations clearly favours larger organisations, Rolls-Royce, the NHS, over smaller organisations. We believe there are many hundreds of smaller organisations – we cannot say definitively, as we do not have the capacity within the scope of this study to check the size and status of every named organisation that has adopted and implemented a piece of engineering research. We can see from the preceding text boxes that individual spinouts have had a hugely positive experience with strong commercial benefits, but given their niche focus they are unlikely to have been cited in different impact case studies more than once or twice.

Notwithstanding this caveat about the bias towards larger innovators, the word cloud prompts several immediate reflections, beginning with an observation that UK engineering research is engaging with large numbers of major international companies, is delivering impacts in a multiplicity of economic sectors and is providing an important underpinning for technology and innovation in the public and quasi-public sectors as well as the private sector.

Figure 16 – Top 50 organisations in REF case studies, by number of citations



Source: Technopolis (2014)

The larger the text the more numerous the links with UK engineering research. We can also see that many of the UK and European industrial champions are mentioned. In addition, these cover all of the main industrial sectors in the UK economy, ranging from life sciences and chemical industry to ICT and energy. Industries that are mentioned significantly are the aeronautic, automotive, defence and space sectors. Finally, the UK health and transport infrastructure and services are also targets for the impact of engineering research, through organisations such as the Network Rail, National Grid, UK Power Networks and the NHS.

3.3.3.1 Further examples of how engineering research translates into commercial gains

The MacRobert Award is the UK's national prize for engineering innovation that has resulted in commercial impact and benefit to society. The wining projects provide further examples on how engineering research translates into commercial gains. Many winners have drawn on publicly funded research to develop and exploit their innovations. Some notable examples include:

- **Cobalt Light Systems** (2014 winner) was formed in 2008 as a spin-out from the STFC. Cobalt's Chief Scientific Officer developed the concept behind its technology while at the Rutherford Appleton Laboratory.

  They received the award for a revolutionary technique (and dedicated technology) to determine the chemical composition of materials in sealed containers and behind a range of other barriers including plastic, glass, paper, fabric and skin. The technology is based on a novel variant of the technique of Raman spectroscopy combined with advanced algorithms to distinguish between the barrier and what lies behind it.

  This breakthrough led to the introduction of an airport security scanner last year that may soon contribute to airports relaxing the existing hand-luggage liquid ban, and use of the same technique is now being investigated for other applications including real-time diagnostic tools for healthcare and in industry to determine the composition of batch chemicals and drugs.

- **Touch Bionics** (2008 winner), a Livingston-based company, invented of the world's first commercially available bionic hand, the i-LIMB Hand. The i-LIMB Hand was a prosthetic device that looked and behaved more like a real human hand with five individually powered digits signalling a new generation in bionics and patient care.

The company was set-up as an NHS spin-out in 2003 by founder David Gow CBE FREng via Scottish Health Innovations Ltd (SHIL). An initial SMART award from Scottish Enterprise got the company started, and it has now received investment funding from existing and new investors, including Archangel Informal Investments, TriCAP, Clydesdale Bank and the Scottish Co-investment Fund. The company was initially called Touch EMAS, EMAS standing for Edinburgh Modular Arm System. In 2005 it was re-branded Touch Bionics.

- **Process Systems Enterprise Limited (PSE)** (2007 winner). The company was a spin-out from Imperial College London focussing on advanced mathematical modelling software that allowed engineers across the process industries to provide real-world solutions by building and solving complex process models in silico. PSE was founded in 1997 as a spin-out from the Centre for Process Systems Engineering at Imperial College London.

  The modelling technology that won the award (gPROMS and its successors) transformed the process industries – from large-scale chemicals industries to food and pharmaceuticals – by allowing companies to explore the decision space rapidly and take better, faster and safer design and operating decisions.

  Some of the world's largest pharmaceutical companies use the PSE software to implement innovative model-based methodologies to achieve faster and safer introduction of new drugs. **Its use in model-based wastewater plant optimisation technology is enabling energy savings of 20-40% on municipal wastewater plants.**

- **Cambridge Display Technology (CDT)** (2002 winner). The discovery of organic electroluminescence from polymers behind CDT's product came in 1989 from a research group at the Cavendish Laboratory of Cambridge University. Professor Donal Bradley FRS, Professor Sir Richard Friend FREng FRS and Dr Jeremy Burroughes FREng FRS discovered that light could be produced from conjugated polymers. In 1992, CDT was founded by Cambridge University to exploit the discovery commercially.

  Polymer organic light-emitting diodes (P-OLEDs) offer the potential of a true flat-screen TV or computer display. Displays can be created on one sheet of glass or, ultimately, plastic so they could be rolled up. They offer many advantages over the liquid crystal displays and plasma displays used in conventional flat panel displays. Today CDT is part of the Sumitomo Chemical Group.

3.3.4 Engineering research attracts inward investments

The quality of engineering research conducted in the UK, as well as access to world-class engineering facilities and businesses has helped the UK to attract substantial high-value and high-tech inward investment, from Europe, the US and the Far East. The overall balance of FDI for the UK (and Europe and the US) may be negative, with more investment outflows overall, however, the quality of UK science and engineering and the robustness of our wider framework conditions is making a positive difference. **These initiatives are helping to generate new economic activity and employment in the regions** and are often tied to regional economic development initiatives. To name a few recent examples:

- BorgWarner – BorgWarner, a $7.5 billion a year US-headquartered automotive components multinational (e.g. gearboxes, turbochargers) will build a new engineering centre and production line in Bradford (West Yorkshire) for Jaguar Land Rover (JLR), the **Turbocharger Research Institute.** This will mean an **investment of £7.5M.** BorgWarner will provide its turbocharging technologies for JLR's new family of four-cylinder gasoline and diesel engines, expected to launch in 2015. The firm is also launching a Master's degree in turbocharger engineering at the University of Huddersfield.[23]

[23] http://www.investinbradford.com/news/borgwarner-to-open-new-engineering-centre-for-jlr

- EDF Energy has obtained Development Consent to build a new nuclear power station at Hinkley Point, which will be the first to be built in the UK for 20 years. **The £24.5 billion project** will benefit from substantial investment by the China General Nuclear Power Company as well as the French nuclear power developer.
- Samsung Heavy Industries in Fife, Methil – In 2012, Samsung Heavy Industries (SHI) announced its decision to base its first European offshore wind project in Fife, in an **investment worth up to £100m and that is expected to create more than 500 jobs in Scotland**[24]. The project is known as the Samsung Energy Park Fife Offshore Demonstration Wind Turbine project (EPFODWT).
- Siemens wind turbines / blade manufacture in Hull –Siemens will invest **£160 million in wind turbine production and installation facilities in Yorkshire.** This will include the construction of the Green Port Hull assembly and service facility and a new rotor blade manufacturing facility in nearby Paull, in East Riding. Additionally Siemens's port partner Associated British Ports (ABP) is investing a further £150 million in the Green Port Hull development. The investment will provide a huge boost to the UK's offshore wind industry and the Humber region. **The combined investments of £310 million will create up to 1,000 jobs directly**, with additional jobs during construction and indirectly in the supply chain.[25,26]
- Panasonic Fuel Cell Centre in Cardiff – The Japanese electronics giant, Panasonic is to create a new fuel cell research and development centre in Cardiff as part of **a £2milion investment**.
- European Centre for Space Applications and Telecommunications (ECSAT) in Harwell - In 2009 the European Space Agency invested in a new facility, ECSAT located at Harwell Science, Innovation and Business Campus (Oxfordshire). ECSAT supports activities related to telecommunications, integrated applications, climate change, technology and science and will lead to the creation of over **100 new high-tech jobs**. A dedicated facility will be built on the campus to host the ESA teams, from 2015.

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24 http://www.scotland.gov.uk/News/Releases/2012/01/samsung31012012

25 http://www.siemens.co.uk/en/news_press/index/news_archive/2014/major-uk-offshore-wind-manufacturing-site-to-be-built-by-siemens.htm

26 http://www.greenporthull.co.uk/

4. Engineering's contributions to policy and public services

4.1 Engineers are crucial to the operation of many areas of government

The presence of, and engagement with, engineers and scientists is crucial to the operation of many areas of government work and policy-making, particularly in formulating evidence-based policy in technical areas, as evidenced by the Government Office for Science, which continues to invest in foresight and other activities such as the Global Issues Science Team (GIST).

The Heads of the Government's Science and Engineering (GSE) profession estimate there are over 12,000 specialist science or engineering posts across the civil service and around 8,000 people that identify science and engineering as their primary role within government. A GSE survey (2012) of scientists and engineers obtained responses from more than 2,100 science and engineering professionals of which around 30% had engineering backgrounds, ranging from marine to mechanical engineering. Around 34% of respondents had PhDs. The Office for National Statistics estimates there are 1,540 engineers across the civil service, which aligns broadly with the GSE estimate of around 2,700 engineers (34% of 8,000). These specialists cover more than 100 different areas of expertise. This diverse community supports open and collaborative policy-making by working closely with external experts, academics and the public, as well as across departmental boundaries to provide shared evidence.[27]

Government scientists and engineers are often skilled collaborators, facilitators and integrators, helping the civil service access expertise through links with academia and business, as well as relationships with the research community.[28] The report "The future of the Civil Service: Making the most of scientists and engineers in government" notes that there is a need to develop an understanding of policy-making and the context in which technology is applied, with engineers requiring more exposure to the policy environment, to build experience. This should be done via expansion of the professional development offered in concert with academia and civil service, particularly with relation to communications and influence.

There are several specific examples of how engineers' skills are widely spread across several areas of public policy, including Department of Environment, Food and Rural Affairs (DEFRA), Ministry of Defence (MOD), Department of Health, Department of Transport, to name just a few.

Regarding environmental policy, engineering skills are key assets for the Environmental Agency (EA), which focuses on risk management mainly in response to flooding. The development of adequate responses to flooding generates millions of pounds in savings for HM Treasury. The EA (in coordination with DEFRA) also runs an in-house "Flood and Coastal Erosion Risk Management Research and Development" programme focusing on asset management and incident management and modelling, which has active participation from EA in-house engineers. The importance of engineers to DEFRA's intelligent customer capabilities, cannot be overstated, a role that is becoming more important over time, with increased use of outsourcing and marketisation of products and services. There is also a strong role to be played within the context of pre-commercial procurement of innovative solutions for various public bodies.

Access to engineering skills and knowledge are also of strategic importance for the MOD. As an example, the Defence Science and Technology Laboratory (DSTL) maintain engineering workshops on behalf of MOD's Chief Scientific Adviser, to enable the prototyping and iteration of new ideas and technical approaches between the scientists and the engineers. This interaction allows the DSTL to come up with the most appropriate solution, by helping scientists to get a better understanding of engineering materials or manufacturing techniques. These workshops also enable rapid deployment of new approaches to fulfil urgent operational requirements – to

[27] Government Office of Science (2013) "The future of the Civil Service: Making the most of scientists and engineers in government"

[28] Idem

solve a military problem or even to provide specific items to front line personnel. Such requirements simply could not be produced elsewhere within the time frame necessary to achieve whatever operational effect is required.[29] The MOD noted that engineering research constitutes a substantial but variable fraction of its total science and technology programme. No specific figure was available, however, the US figures for the Department of Defence show that engineering research constituted around $3.6 billion (55%) of the Department's total $6.6 billion obligations (2011).

Engineering skills are also of great relevance for the Department of Health and Box 3 below provides a good example related to this area.

Box 3: Medicines and Healthcare Products Regulatory Agency (MHRA)30

Access to engineering skills is fundamental for the MHRA. One of the Agency's principal tasks is regulation of medicines. The use of highly sophisticated engineering equipment and technologies is critical for both production and analysis of medicines (e.g. spectroscopy, fermentation) and so an in-house understanding of the benefits and limitations of these technologies is required to support effective regulation.

The Agency's systems for drug safety monitoring depend on rapid analysis of large quantities of information submitted by healthcare professionals and patients, and these systems have been developed from the engineering principles of signal-to-noise ratio.

In addition the Agency relies on this kind of engineering technology for its own product analysis activity – routine batch release of certain biological medicines such as vaccines, and also analysis of suspect products following adverse incidents. These analytical technologies are developing rapidly in their capabilities. For example genomic and proteomic analyses are already being used for product analysis. Hence maintaining an understanding of these new technologies and developing the relevant in house expertise to use them is essential.

Another key function of the Agency is the regulation of medical devices. Engineering research is clearly central to innovation in this huge and rapidly expanding field, which ranges from operating tables, through anaesthetic equipment through to miniaturised metabolite sensing devices, and once again the Agency relies on in house expertise to support its regulatory role. In the Medical Devices section, a number of staff has formal engineering qualifications, and others have developed specialist knowledge through medical device investigations.

The professional engineering institutions also work closely with government to advise and improve policymaking. As an example, the RAEng has completed two reports at the request of the Prime Minister's Council for Science and Technology on the subject of energy policy. *The UK electricity capacity margin* considered the short-term risk of electricity supply not meeting demand. It concluded that, without intervention, security of supply would be put at risk and made recommendations to address the problem. Recommendations included the introduction of a capacity mechanism via the Electricity Market Reform and interim measures to cover the period while this would take effect; both of which have subsequently been introduced by government. This was followed up with *Counting the cost* that addressed the economic and social implications should electricity shortfalls occur. The study concluded that more research was needed to mitigate the potential costs generated by electricity shortfalls, which in turn has prompted action from government.

Furthermore, under the banner of *Engineering the Future*, an alliance of all the professional engineering institutions, reports have been published to provide expert advice to government on a variety of topics from modern manufacturing, nuclear new build, infrastructure resilience to global water security.

[29] These examples have been provided by the MOD in response to the consultation made by Technopolis with some selected government departments.

[30] These examples have been provided by the MHRA in response to the consultation made by Technopolis with some selected government departments.

4.2 Engineering research plays a key role in policy and public services

The 514 REF case studies include numerous excellent examples of the contributions of engineering research to the better provision of public services in areas such as security and safety, human and mental health, transport, to name just a few. Box 4 showcases five concrete examples of the contribution of engineering research to these areas of public services.

Box 4: Better provision of public services

- **Management of discolouration in drinking water distribution systems (University of Sheffield)**

"Research, undertaken at the University of Sheffield since 2001, into the discolouration of drinking water occurring within distribution systems has had economic, policy and professional practice impacts on the water supply sector since 2008. This has resulted in improved levels of service, has safeguarded water quality delivered to the public and has delivered substantial economic savings. For example, in one of the few cases where monetary value is available, Wessex Water made 63% savings on two trunk main schemes with an initial estimated cost in excess of 1M. The 4 and 7 km lengths of these trunk mains represent less than 1% of the trunk mains being impacted by our research. Our research has resulted in a step change in the concept and approach to the management of discolouration in water distribution systems".

- **Human-centred security in government and commercial applications (University College London)**

"Professor Sasse created, developed and delivered the user-centric perspective that now underpins security thinking in both corporate and public-sector domains. This perspective shaped the UK government's Identity Assurance Programme (IDAP), a federated identity solution that will provide access to all e-government services in the UK. HP has incorporated the compliance budget model into its Security Analytics product, which enables companies to calculate the impact of a given security mechanism on individual and corporate productivity. Sasse's work also underpins new and improved security products, including First Cyber Security's SOLID and Safe Shop Window tools, which protects over 70% of UK online shopping revenue; GrIDSure's one-time PIN system (now part of the SafeNet Authentication Service); and iProov's authentication service".

- **Investigative toolkit and associated techniques to support online child protection based on digital persona analysis (Lancaster University)**

"Online child protection is one of the key concerns of our time. But there are huge problems in enforcing the law in this area because enforcement agencies have manually to analyse vast quantities of online data, resulting in significant backlogs. In response, we have pioneered the field of digital persona analysis, which significantly automates the process of identifying online sexual predators who masquerade as children. This work is underpinned by internationally leading research that combines authorship attribution techniques with corpus-based natural language analysis. The results are impressive, yielding highly accurate persona analysis in the face of huge and noisy data sets, and in the face of deliberate attempts to deceive. The impacts are both wide and significant: Impact on law enforcement agencies we have provided sophisticated analysis tools which are being used by law enforcement agencies nationally and internationally; On the economy we have fostered the creation of a spin-out company, Isis Forensics; On education, in close collaboration with the secondary education sector, we have developed educational programmes on online protection for children at Key Stages 2-5; On public policy wrt Internet governance, we have made significant contributions to the debate on online protection, coupled with public awareness measures".

- **The GRiST computer decision support system: a new tool for assessing and managing risks associated with mental-health problems (Aston University)**

"The Galatean Risk and Safety Tool (GRiST) is a clinical decision support system (CDSS) conceived and developed by computer scientists at Aston University from 2000 onwards, where it is being delivered as a cloud-computing service. It is used every day by mental-health practitioners in the NHS, charities, and private hospitals to assess and manage risks associated with mental- health problems. Between 1/1/2011 and 31/7/2013, clinicians provided 285,426 completed patient risk assessments using GRiST. It has changed organisational and clinical processes by its systematic collection of risk information, explicitly linking data to clinical risk judgements, and showing how those judgments are derived. Increasing international awareness has come through presentations to mental-health practitioners in Europe, America, and Australia".

- **Fixing Fractures Fast: ApaTechTM Development of Synthetic Bone Grafts with Improved Efficacy and Reliability (Queen Mary University of London)**

"Seminal materials research at QMUL and its technological transfer via the QMUL spin-out ApaTechTM, has led to the development of a range of cost-effective synthetic bone graft (SBG) products (ApaPoreTM, ActifuseTM and InductigraftTM), which safely and effectively stimulate rapid bone healing and are more reliable than previous autograft procedures. The use of the ApaTechTM range of products has delivered impact on health and welfare by reducing post-operative infection and improving recovery rates. To date, ApaTechTM products have been used to treat over 370,000 patients in over 30 countries. In 2010, ApaTechTM had 4% of the US SBG market, a $20 million annual turnover, employed 160 people in nine countries, and was sold to Baxter International for $220 million. By 2012, ApaTechTM products had a 10% share of the global SBG market (treating 125,000 patients per annum), estimated to be worth around $510 million. Other impacts include altering surgical clinical practice, moving away from the use of autograft".

The benefits of UK engineering research provide high impact solutions nationally, but also globally. As an example, UCL engineering department has ERC grants for tsunami engineering research, which will study the problems of assessing buildings and engineering defences against these elemental forces, and guide insurance companies in their approach to this growing problem. The new ERC grant will allow the creation of a unique tsunami generator, 100m long. This new resource will be used for testing and quantifying the effects of tsunami waves on built environments, and the failure limits and performance of coastal defences.

5. Investment in engineering research and training

5.1 Engineering research is strongly aligned with UK industrial strategy

The UK government spent around £9.7 billion on R&D in 2011/12.[31] This includes expenditure by government departments, research councils, higher education funding councils and international receipts from the EU RTD Framework Programme. It also includes defence-related R&D expenditure, as well as civil R&D.

The UK Science, Engineering and Technology (SET) statistics are published annually and present a summary of key science, engineering and technology indicators, prepared in collaboration with the Office for National Statistics (ONS). The SET statistics include data on all public sources and destinations of research funding, with numerous subsidiary analyses, however, they do not include an analysis of expenditure by discipline and consequently it is not possible to disentangle the engineering element from within those statistics.[32]

What is clear from the SET statistics is the evolution in the composition of Gross Domestic Expenditure on R&D (GERD) in the UK over the past 20 years, with a long-run increase in the national science budget being balanced in the public finances by reductions in the expenditure of government departments (including defence) and the ongoing downsizing and privatisation of government research establishments. There is a similar picture for UK business expenditure on R&D, which has been flat or in decline for more than 30 years, driven by globalisation and industrial restructuring. Against this less than encouraging backdrop, the UK has made substantial additional investments in the university sector and in centres of excellence that help to bring together public and private sectors. With reducing Business Enterprise Expenditure on R&D (BERD) and increasing Higher Education Expenditure on R&D (HERD), industry has a growing incentive to work with the science base directly (setting agendas, sharing costs and providing more immediate commercialisation pathways). The picture for engineering research specifically is more positive with engineering-related sectors doing most to sustain levels of BERD and numerous major additional investments (e.g. from Innovate UK), new programmes (e.g. cross-council programmes in areas like energy) and new research infrastructure (e.g. high-performance computing centres).[33]

We estimate that the share of R&D investment in engineering research is likely to be somewhere in the range, 15-30%, with:

- A lower bound of 15%, which is the percentage of "Engineering and Technology' research by value reported to be *performed* in government and academia;[34] to

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31 This figure is taken directly from Table 2.1: Net Government expenditure on R&D by departments (cash), UK, 2002-03 to 2011-12, presented in the 2013 UK Science, Engineering and Technology (SET) statistics available online in pdf and spreadsheet formats, at www.gov.uk/government/statistics/science-engineering-and-technology-statistics-2013

32 The study team wrote to the Chief Scientists at each of the government departments where we judged there was likely to be a substantial investment in engineering research. Government chief scientists were supportive of the study, and remarked on the importance of engineering research to the departmental remit, however, they were unable to disentangle what proportion of their total R&D expenditure is engineering research. They tend not to report on expenditure by discipline, and as such, felt there was no basis by which they could even offer a first approximation. Interviewees suggested they would need to carry out a dedicated exercise to review all of their current and recent R&D contracts in order to determine whether they might be classified to engineering, in full or in part. That kind of internal exercise was not considered to be feasible, at least within the scope of the present study.

33 The engineering research community has been less vocal perhaps than for example their counterparts in the physics and astronomy communities, as regards the potential importance for advances in understanding and innovation of certain types of research infrastructure. All things being equal, a new laser facility like EXFEL ought to be of greater relevance to a wider constituency than some of the undoubtedly breath-taking achievements of for example ESA's space exploration programmes (admittedly there is a strong supply-side benefit for the businesses that build and operate these science missions).

34 This figure is calculated using Information from the ONS and Eurostat, which provide information on expenditure by 'fields of science' based on the sector of performance. The 'fields of science' is a UNESCO (2007) classification system that comprises six broad categories (from natural sciences to the humanities) and includes "engineering and

- An upper bound 32%, which is the share of engineering research and training within the overall portfolio of EPSRC research, the main government funder of engineering research.

The upper bound may seem high given that the EPSRC focuses mainly on physics and engineering, while the government funds research across a wide range of areas. However, it has to be taken into consideration that the MoD, which accounts for 13% of the overall net government expenditure on SET, probably has a higher share of investment related to engineering, and that virtually all the thematic areas supported by Innovate UK (as well as the Catapults) are highly linked to engineering R&D.

As explained in the prior paragraphs (and further extended in Footnote 29) it has not been possible to obtain estimates of 'engineering research' from those organisations. Additionally, Innovate UK and the Ministry of Defence may perhaps have relatively higher engineering portfolios (in relationship to their overall R&D expenditure); however, if this is the case it would probably not be appropriate to apply that share to the entire government R&D expenditure. In that sense, the 32% estimated by the EPSRC seems like a reasonable compromise. The activities undertaken by these three organisations, and related to engineering research, are further described in the subsections below.

Using this range (15%-32%) we estimate that the UK **government spends between £1.5 billion and £3.1 billion a year in engineering research,** based on R&D expenditure figures for 2011/12. We provide a closer look to the portfolio the EPSRC and Innovate UK portfolio in the following subsections.

5.1.1 Engineering and Physical Sciences Research Council

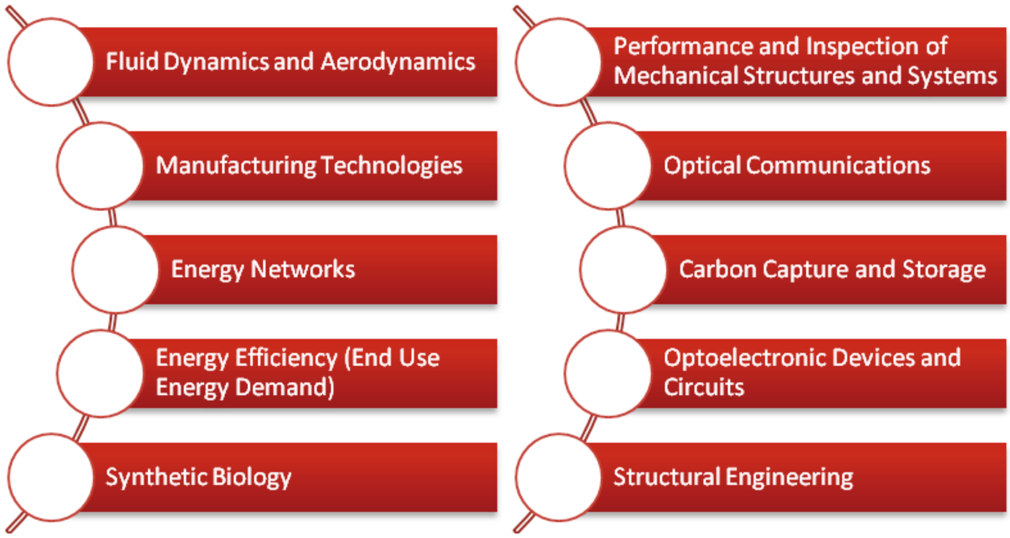
The EPSRC is the UK's main agency for funding research in engineering and the physical sciences. EPSRC spent around £222 million in 2013 in engineering research (based on the department of the grant holders[35]). Engineering research represents 32% of its total active portfolio of research grants and fellowships.

As at September 2014, the EPSRC has an active portfolio of £960 million in research grants and fellowships supporting engineering and related research, skills and innovation. This portfolio covers a wide range of research areas from fluid dynamics to ICT networks & distributed systems and clinical technologies (see Figure 17).

technology." This category includes 11 sub-fields, which map reasonably well onto the definition of engineering research used by the EPSRC.

35 This requires fractional counting since one grant can be allocated several grantholders from different departments. 'Spend' means expenditure within that financial year.

Figure 17 – Top 10 areas supported by EPSRC where engineering research is a key component part



Source: EPSRC (2014)

These grants include EPSRC funding for a number of large research projects and centres in the UK through the:

- EPSRC Centres for Innovative Manufacturing – EPSRC support 16 centres that receive five years funding to retain staff, develop collaborations, carry out feasibility studies, and support up to two research projects. The EPSRC support is used as a platform to secure further investment from industry and other funders. The centres covered areas such as photonics, regenerative medicine, medical devices, additive manufacturing, among others.
- Interdisciplinary Research Collaborations (IRCs) – centres of scientific and technological excellence. Collaborations are funded through large, long-term grants, typically around £10 million over six years. IRCs generally involve several universities together with industrial partners. Recent IRCs include the SPHERE IRC which will develop sensor technologies for healthcare in a residential environment; the multiplexed 'Touch and Tell' optical molecular sensing and imaging project, which will design, make and test a cutting-edge bedside technology platform which will help doctors in the intensive care unit (ICU) make rapid and accurate diagnoses; UK Centre for Tissue Engineering.

There is a good alignment between the EPSRC portfolio (see Figure 18) and the UK government's current growth strategy:

- £482 million (50% of total) of EPSRC research grants that support engineering and related research, skills and innovation align with 7 of 11 Strategic Sectors.
- £642 million (67% of total) of EPSRC research grants that support engineering and related research, skills and innovation align with the 8 great technologies.

> *"There has been good progress on Collaborative R&D in recent years and there is a great opportunity now to combine this success with the UK's world-class university base to create a truly world-class innovation ecosystem. We need to significantly increase investment in applied R&D, to consolidate excellence in order to establish critical mass, and to create alignment through the intellectual value chain. These three changes will enable us to build significant programmes that link scientific discovery to collaborative R&D through to manufacture, giving maximum return on investment for the UK"*
>
> *Tony Harper, Head of Research, Jaguar Land Rover Limited*

Figure 18 – EPSRC grants and fellowships in engineering departments (active portfolio 2014) – strategic technology areas and sectors

8GT

Life Sciences, Genomics & Synthetic Biology	£274.3M
Robotics & Autonomous Systems	£230.6M
Advanced Materials	£163.7M
Regenerative Medicine	£144.7M
Energy Storage	£111.0M
Big Data	£99.7M
Satellites	£38.3M
Agri-Science	£27.3M
Quantum Technology	£7.2M

Strategic sectors

Information Economy	£112.3M
Life Sciences	£102.8M
Construction	£87.0M
Aerospace	£82.7M
Automotive	£58.5M
Nuclear	£17.2M
Offshore Wind	£8.9M
Other	£9.5M

Source: EPSRC (2014)

Circa 40% of the 514 REF impact case studies that we analysed cite EPSRC research as the foundation stone of the subsequent advances and social and economic impacts. In that sense, the impact case studies underline both the power of engineering research and the role of the EPSRC within the national innovation landscape. The case studies name-check numerous other funders, from Innovate UK to the MoD, as well as very many private companies, but the EPSRC stands apart in terms of the number of citations. The case studies also provide a great window into the EPSRC's support for applications and products that were and are of strategic national importance. The many examples of economic impact generated by research funded in the last 20 years are presented in a small selection of extracts in Sections 2 and 3. Further case studies are developed in an essay form in Appendix A of this report.

Several other research councils invest in engineering research and training in the UK. The Biotechnology and Biological Sciences Research (BBSRC) is a significant research council funder of chemical engineering, spending between £30-35 million for each of the years 2008/09 to 2012/13. These investments include:

- The Bioprocessing Research Industry Club (BRIC), a partnership with EPSRC and a consortium of leading companies to support innovative bioprocess-related research, including that needed for the manufacture of complex biopharmaceuticals.
- The Integrated Biorefining Research and Technology Club (IBTI), a £6 million five-year partnership with EPSRC and companies aimed at developing biological processes and feedstocks to reduce our current dependence on fossil fuels as a source of chemicals, materials and fuel.
- The BBSRC Sustainable Bioenergy Centre, a £24 million investment that increases UK bioenergy research capacity.
- The Industrial Biotechnology Catalyst, in partnership with Innovate UK and EPSRC, which provides a form of research and development funding which focuses on a specific priority area and aims to help take projects from research to as close to commercial viability as

possible. The Catalyst model supports projects in priority areas where the UK research base has a leading position and where there is clear commercial potential.

The Natural Environment Research Council (NERC) also invests in engineering-related research. An important area that NERC has supported is the development of technologically advanced environmental sensors and autonomous systems, both in its own research centres and universities. Sustained long-term funding has enabled the National Oceanography Centre (NOC) to develop new marine technologies, primarily in the areas of sensors, robotic vehicles, acoustics and communications. Technologies, such as deep sea autonomous vehicles, have been developed for exploring and researching the oceans, enabling marine science and to drive innovation and economic growth for marine industry and regulators.

In 2014 NERC announced that, in collaboration with EPSRC, they would be investing in a Marine Autonomous and Robotic Systems (MARS) Innovation Centre, based at the National Oceanography Centre (NOC). The centre will enable the growth of a cluster of marine autonomous systems companies, based on the strength of the research capability at NOC.

Furthermore, engineering research makes a significant contribution to the Science and Technology Facilities Council's (STFC) portfolio of activity, both by ensuring large facilities (such as the Diamond Light Source) continue to run for the benefit of the wider research community, as well as running major research programmes, such as at CERN.

Finally, there are also examples of successful partnerships in the health domain where the research councils, including the Medical Research Council (MRC), and other funders, in particular the major medical charities, support engineering research in the UK. Examples include:

- UK Regenerative Medicine Platform – established by BBSRC, EPSRC and the Medical Research Council in 2012 to address the technical and scientific challenges associated with translating promising scientific discoveries in this area towards clinical impact.
- The Wellcome Trust/EPSRC medical engineering centres of excellence – focused around the themes of medical imaging, osteoarthritis, human joint and cardiovascular health, and personalised medicine, these centres provide an environment for engineers, physical scientists and medical researchers to work collaboratively to undertake and translate exploratory research into products that can improve healthcare.
- Cancer Research UK/EPSRC cancer imaging centres - to develop new imaging techniques and uses for existing advanced imaging technologies. These techniques will enable doctors to see therapies at work and identify at an earlier stage, which treatments work best.

5.1.2 BIS and Innovate UK

BIS invests a substantial share of its total budget (£645M, in 2011/12) on engineering-related R&D, mainly delivered by Innovate UK, formerly the Technology Strategy Board.

Innovate UK programmes spent a total budget of £302M in 2011/12 (and forecast £815M in 2014/15) with activities ranging from grant funding for the High Value Manufacturing Catapult through to support for collaborative research grants for key enabling technologies (e.g. lightweight advanced materials) and the provision of small research grants for individual SMEs (e.g. Smart).[36]

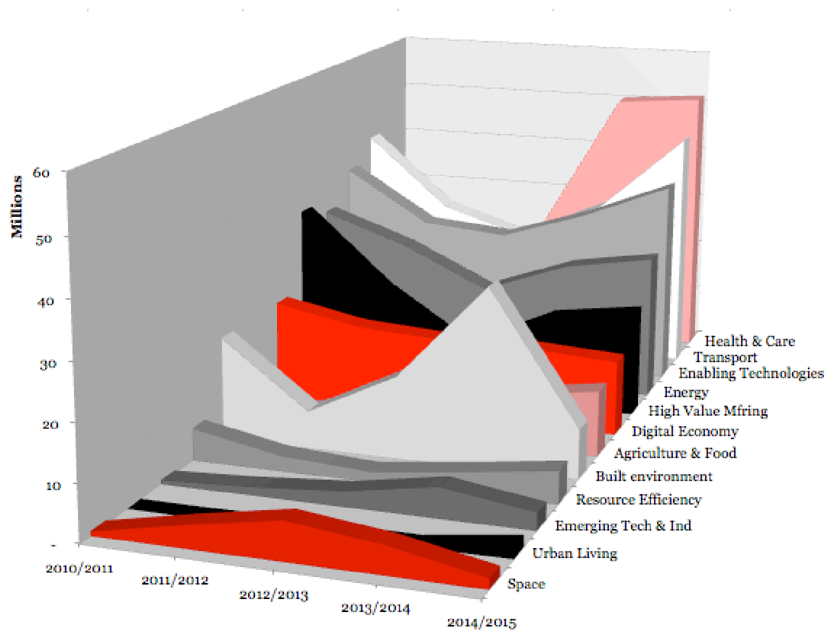
Innovate UK falls in the 'upper bound' of our estimates for public expenditure on R&D related to engineering (32%) and will invest around £260M in engineering research in 2014/15 based on a rapidly expanding overall budget (c. £100M in 2011/12).

The great majority of the budget invested by the thematic programmes (project funding through competitions) is closely related to engineering (£214 out of £229 million in 2014/15) (see Figure 19). This does not include the budget allocated to the Catapults and Knowledge Transfer

[36] This budget includes mainly grants allocations, but exclude administrative and delivery costs, as well as co-funding. 'Spend' means expenditure within that financial year.

Network. The distribution of budget for thematic areas is shown in Figure 19 while the actions taken to support the engineering related thematic areas are described in Figure 20. The presence of 'engineering research and skills' across those thematic areas reveal just how imperative it is to invest in engineering if the UK government is to be able to advance its industrial strategy and face the economic and social challenges that lie ahead.

Figure 19 – Innovate UK Investments



Source: Innovate UK (2014)

Figure 20 – Innovate UK investments relating to engineering (forecast expenditure 2014/15)

Action area	**Description of main activities**	**Budget (in millions)**
Health & Care	Resources are allocated to help growing sustainable businesses that can deliver step-changes in efficient and effective health and care. The resources allocated will fund nine new competitions and will serve to continue supporting the Biomedical Catalyst and launch the 'grand challenge' for the second phase of the long-term care revolution.	£51.5M
Transport	The UK is investing in the development of a transport system that allows efficient, cost-effective and sustainable movement of people and goods. The current investment commitments will be allocated to launch a Transport Systems Innovation Platform, run collaborative R&D competitions covering on and off-highway vehicles, marine, aerospace and rail transport; support a further European competition for marine vessel technology.	£45.3M
Enabling Technologies	Innovate UK will run three 'technology-inspired innovation' competitions for feasibility studies in enabling technologies and invest in activities focused on identified technology challenges, with impact across a wide range of sectors, including materials for aggressive environments, the integration of 'omics' technologies, robotics and autonomous systems, electronics systems, user experience, and software quality and testing.	£38.2M
Energy	Investments related to this thematic area will be allocated to fund 11 new competitions, launch an Energy Catalyst with the research councils and DECC and develop a programme to demonstrate energy supply chain innovation.	£26.9M
High value manufacturing	Innovate UK high value manufacturing programme aims to grow the contribution of manufacturing to UK GDP. Commitments will be invested in 10 new competitions.	£19.6M

Action area	Description of main activities	Budget (in millions)
Digital economy	Investment will include 11 new competitions and continue the IC-Tomorrow programme for digital micro businesses, including networking support and funded competitions.	£13.8M
Built environment	Investment directed towards transforming the sector and delivering high-quality, carbon efficient buildings. The investment will be allocated to four new competitions, including competitions in digital design and engineering, specifically in building information modelling.	£9M
Resource efficiency	Several planned activities include running three new competitions in resource efficiency, organise an entrepreneur mission to San Francisco in 'clean and cool' technologies and ensure that the benefits of resource efficiency are captured in a wide range of Innovate UK's competitions.	£5.9M
Urban living	Activities and actions will include launching five new competitions that support integration of city systems. Innovate UK estimates that by 2030 there will be a £200bn global market annually for integrated city systems, covering functions such as health, energy, water, waste, communications, buildings and transport. The development of such systems calls for a wide range of expertise including engineering, but also in project management, architecture, energy and transport systems, communications and the digital economy, finance, legal and insurance.	£2.1M
Space applications	Resources will be allocated to support innovation in new applications using satellite data and space-based satellite systems.	£1.9M

Source: Innovate UK Delivery Plan 2014/15. Data on forecast expenditure provided by Innovate UK.

In addition, Innovate UK currently supports seven Catapults that support engineers and engineering business in the creation of innovative solutions to tackle market opportunities and respond to societal challenges. This network of Catapults represents a £1bn public and private sector investment over five years.

- High Value Manufacturing Catapult - The HVM Catapult's long-term goal is to stimulate growth in the manufacturing sector and more than double the sector's contribution to UK GDP. The Catapult gives scientists, engineers and entrepreneurs access to a pool of expertise and experience within academia, research, industry and government. It combines the strengths of seven existing centres across key manufacturing processes, bringing these centres together to develop manufacturing technologies, which can span from raw materials to finished assembly processes. It also enables innovation to cut across sectors by bringing together businesses from diverse industries and giving access to a pool of world-class expertise, equipment and processes invested and supported by UK government.
- Offshore Renewable Energy Catapult - The aim of the Offshore Renewable Energy Catapult is to coordinate, lead and facilitate the rapid development and commercialisation of innovative technologies and technological solutions that also give maximum economic impact in the field of offshore renewable energy. The technologies used in wind, wave and tidal power are relatively immature compared to conventional fossil fuel power and much needs to be done to make them more efficient, cost effective and commercially deployable at mass scale. The Catapult aims to achieve this with a series of innovation programmes aimed at improving the risk profile around new offshore renewable energy technologies such that they become financially viable. The Catapult will identify, prioritise and address critical areas of the industry where innovation can play a key role in understanding and reducing risk, as well as accelerating the deployment of technologies, which have the potential to reduce the cost of energy.
- Satellite Applications Catapult - The Satellite Applications Catapult is an independent innovation and technology company, created to foster growth across the economy through the exploitation of space. It focuses on working with SMEs, academia and end users to develop market leading satellite-based applications and providing an accessible collaborative environment to accelerate the UK's space growth potential. Currently, the Catapult is mainly supporting improved maritime communications (looking at applications

such as fishing monitoring, integrated logistics and supply chains, and vessel efficiency); transport (particularly inter-vehicle communications and reliable positioning,); and exploration of technologies to build an infrastructure to access satellite data in a faster and cheaper way.

- Digital Catapult - The Digital Catapult is a national centre to rapidly accelerate the UK's best digital ideas to market to create new products, services, jobs and value for the UK economy. Its focus is on data and metadata – on the data value chain, helping businesses create, collect, transport and analyse data. The Catapult is supporting the development of next generation connectivity, including the first large-scale**,** pilot/demonstrator for 5G telecommunications in the world. The 5G Innovation Centre (5GIC) consortium is mostly led by engineers and has been brought together by the University of Surrey and involves a wide range of industrial partners including most of the UK mobile phone network operators plus Huawei, Samsung, Fujitsu Laboratories Europe, Rohde & Schwarz and AIRCOM International.
- Transport Systems Catapult - The Transport Systems Catapult centre seeks to exploit the massive potential market for new products and services that will support the integration of transport and its systems. The efficient and cost-effective movement of people and goods is crucial: constraints on land and investment mean that the only way to overcome this challenge will be to work in a coordinated and collaborative way, to develop improved transport systems and thereby unlock latent capacity. The Catapult will drive development of a national transport systems-modelling facility and host a virtual test environment where world-class physical testing can be linked to the digital models. It will position the UK as the leading provider of innovative and integrated transport solutions to the rest of the world, exploiting a market estimated to be worth £900bn by 2025.
- Future Cities Catapult - The Future Cities Catapult will help UK businesses create integrated products and services that meet the future needs of the world's cities. Cities are powerful engines of productivity but they face enormous challenges from a changing climate, population growth, shifting demographics and the ever-growing demand for resources. There is a rapidly growing market for innovative solutions that integrate and optimise their major systems whilst managing the downsides. The UK has world leading companies in project management, engineering, architecture, energy and transport systems, communications and the digital economy, finance, legal and insurance. The ability to bring together the cluster of companies needed makes the UK a major global centre to design, finance, risk manage and execute large infrastructure projects, helping UK businesses to develop high-value, integrated urban solutions which can be sold to the rest of the world.
- Cell Therapy Catapult - The Cell Therapy Catapult was established in recognition of the need for concerted long-term translational activities in order to realise the full value of cell therapies. Cell therapy research and manufacturing heavily relies on biomedical and genetic engineering, a field that applies engineering principles and design concepts to the development of diagnostics and treatments. The Catapult will take products into the clinic – de-risking them for further investment - provide technical expertise and infrastructure to ensure products can be delivered cost effectively. This activity is expected to generate investible therapies, clinical data, manufacturing processes and regulatory pathways and skilled, trained and experienced professionals to help deliver health and wealth.

Box 5 shows an example of how research supported by Innovate UK has led to the development of a new, leading-edge manufacturing technology.

Box 5: Innovate UK leading the manufacturing revolution

Reclaim, a research project co-funded by Innovate UK, has developed 'game-changing' hybrid manufacturing technology. This new technology combines additive manufacturing (i.e. 3D printing) with high-speed computer controlled machining and in-process inspection. The project had a total investment of £1M (including £537K of grant funding from Innovate UK) and includes eight partners:

- Delcam (computer-aided modelling)
- Renishaw (rapid scanning Sprint™ inspection head)
- Precision Engineering Technologies (machine integration)
- Electrox (laser processing)
- The Welding Institute
- De Montfort University (laser cladding process)
- Cummins Turbo Technologies
- The Manufacturing Technology Centre

The machine permits swiftly switching from one part of the process to the next. It works as a series of heads and docking systems, which allows virtually any machine that uses computer automated programmes (or robotic platform) to use non-traditional processing heads in the spindle and conveniently change between them. The process of switching from one head to the other is completely automated and it takes only seconds. This means that changing from adding metal to cutting it simply requires a tool change, instead of a different machine.

The research project led to the creation of a spin-out company, Hybrid Manufacturing Technologies Ltd (HMT), formed in 2012 to commercialise the new technology. HMT is now developing the next generation of hybrid manufacturing systems: the AMBIT™ multi-tasking system. It is working with Delcam (UK pioneer of computer-aided manufacturing [CAM] programmes, developed by academics at Cambridge University) and the Manufacturing Technology Centre (part of the High Value Manufacturing Catapult) to explore commercial applications for the system.

The system was originally developed to integrate laser cladding (process of pouring metal or powder into a component) with precision machining and inspection, for remanufacturing and repair. However, it's commercial applications span far beyond that and HMT anticipate the technology is also suitable for production of new components, including fabrication from the ground up, or addition of features and functionality to existing parts.

<u>References:</u>
Innovate UK (webarchive.nationalarchives.gov.uk/20141008133515/https://www.innovateuk.org/-/leading-a-remanufacturing-revolution)
Hybrid Manufacturing Technologies Ltd (http://www.hybridmanutech.com/)

5.1.3 Ministry of Defence (MoD)

On the defence side, the MoD makes very substantial use of engineering R&D within the context of its near-term research programmes, but it is also actively supporting engineering through its development programmes too. In 2011/12, MoD spent £753M in research and £533M in development, making it the government department that spent the most on R&D activities (41% of the total budget allocated to the civil departments).

Box 6: The Quantum Technology Partnership

In partnership with the Royal Society and EPSRC, the MOD has worked with industry, academia and other Government Departments to analyse the UK quantum landscape and explore how the UK might exploit emerging quantum technologies for the benefit of defence, security and the wider UK economy. The resulting roadmap describes technology development in quantum clocks, communications, sensors, simulation and computing; the associated enabling technologies and molecular and solid state advances that have the potential to be beneficial.

The quantum technology partnership is now helping the MOD progress through the roadmap and is supporting the UK in establishing the skills we will need, covering a broad spectrum including:

- Leadership, vision and governance
- An understanding of technology readiness, likely system constraints and user needs

- Skills in transitioning science to technology and system engineering
- Progressive programme and project management
- Dynamic risk management
- Management of intellectual property
- System engineering, interoperability and standardisation
- A suitable collaborative landscape incorporating Government, industry and academia
- Identification and preparation of suitable markets

Potential applications of quantum technology include:

- Sensing position, acceleration and gravity with unprecedented precision;
- Navigating without Global Navigation Satellite Systems;
- Imaging underground structures and mineral, oil and other reserves.

The strong UK research base is expected to lead to commercialisation into multiple £billion markets particularly in quantum communications. Although work is still at an early stage and success remains uncertain, there is great potential for high economic impact and new game changing capabilities for UK defence and security. Cross-government collaboration will ensure UK progress greatly exceeds the sum of individual contributions.

Source: MOD

5.2 Industry is also a heavy funder of engineering research

In 2012, the value of R&D expenditure performed by UK businesses was nearly £17 billion, 66% of which was funded through businesses' own funds. The UK government and overseas funding accounted for the additional 8% and 23% respectively.[37] [38] This means that UK businesses invest £11.2 billion in research and development activities.

If we take into account only those broad sectors tightly linked to engineering, such as mechanical engineering, electrical machinery, transport equipment, aerospace and other manufacturing activities (excluding chemicals), we can conclude that investment in **engineering R&D invested by and performed in UK businesses is circa £9.5 billion** (sectors highlighted in grey in Figure 3), **SMEs account for circa £380 million (4%) of that investment**.

This is of course just a lower bound as engineering research and development also takes place in any of the sectors named in the table below. Figure 21 reveals the wide distribution of research engineers across a wide range of sectors in the economy. The definition is however too broad as it includes 'scientists and engineers' in a single category. If investment in all sectors that have "Scientists and Engineers" among its R&D personnel are accounted for, then investment is up to £10.9 billion, which is a (high) upper bound.

[37] Overseas funding includes EC Programmes, which account for £42 million (0.2%) of R&D expenditure performed by UK businesses.

[38] The importance of UK Government funding for R&D in UK businesses differs greatly across sectors, with shipbuilding, machinery and equipment and electrical equipment deriving 89%, 47% and 35% respectively of their total performing R&D expenditure from government funds.

Figure 21 – Employment and expenditure in R&D, performed in UK businesses (2012)

Sectors/Product groups	**Employment in R&D (Full time equivalent in thousands)**		**Current and capital expenditure on R&D (£million)**
	Total	**Scientists and Engineers**	
Sectors tightly-linked to engineering			
Pharmaceuticals	23	10	2,679
Computer programming and information service activities	24	13	1,393
Motor vehicles and parts	14	7	1,388
Aerospace	13	8	1,068
Machinery and equipment	12	6	660
Telecommunications	8	6	551
Consumer electronics and communication equipment	7	5	500
Precision instruments and optical products 1/	6	4	395
Chemicals and chemical products	7	3	262
Electrical equipment	5	3	233
Computers and peripheral equipment	2	1	123
Other manufactured goods	2	1	110
Fabricated metal products except machinery and equipment	2	1	44
Construction	1	1	37
Sub-total	126	69	9,443
Sectors that benefit from engineering-related skills			
Miscellaneous business activities	10	8	498
Research and development services	8	5	386
Food products and beverages; Tobacco products	4	2	175
Extractive Industries	2	1	128
Wholesale and retail trade	3	2	113
Rubber and plastic products	2	1	76
Sub-Total	**29**	**19**	**1,376**
Other (with no R&D personnel recorded)	--	--	261
Total	**155**	**88**	**11,080**

Source: ONS/BIS Research and Development in UK Businesses, 2012

5.3 International comparisons

We presented an overview of the international performance of UK engineering research, using bibliometrics data and citation analyses, in the previous section of the report. The UK makes rather less use of patents compared with other major engineering economies around the world, hence a comparison with EU and US patent statistics is not especially illuminating.

There are very few international comparisons that look at the distribution of research expenditure by field, due to widely varying classification systems. Eurostat publish several sets of STI statistics of some relevance to engineering research, in principle at least, including time-series statistics for the EU28 member states and selected international countries (China, Japan, Russia, US, etc.) on:

- Total number of researchers by sector (government, academic and private) and field of science.
- Total intramural R&D expenditure (GERD) by sectors of performance and fields of science.

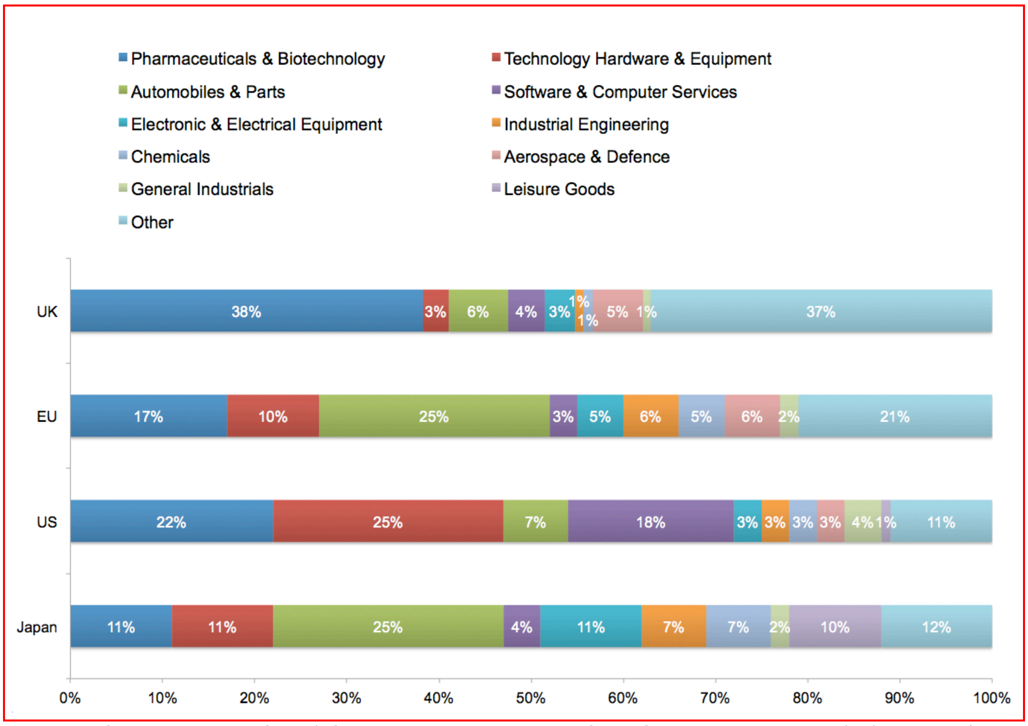
Unfortunately, the data is rather incomplete across specific fields of science. For engineering and technology, for instance, the 30+ countries reporting aggregate data reduce to around 10 for this specific field, and all of the key comparator countries are missing, including the UK itself: for example, there are no data reported for France, Germany, Italy, Japan or the US.

The US National Science Board publishes an annual review of Science and Engineering Indicators, which highlights developments in international and U.S. science and engineering (S&E) and includes an analysis of *industrial* R&D by selected sector and country. It does not deal with engineering directly, but does show data for around 15 countries, including the UK, for pharma, motor vehicles, communications, computing and services. This reveals a similar picture to the EU R&D scoreboard, revealing the dominance of pharma in the UK industrial research landscape. The 2014 National Science Board Science and Engineering Indicators Report includes an analysis of US federal obligations (civil and defence) for research, by agency and major science and engineering fields. This analysis shows that engineering research accounts for around $10.1 billion (17%) of the $58 billion total federal obligations for basic and applied research. Life sciences dominate, with $30 billion (52%), driven by the Department of Health's $27.5 billion, however, engineering research is a strong second, with multi-billion dollar programmes in several departments, including Environment, Defence and Health.

- Department of Defence: engineering accounted for around $3.6 billion of $6.6 billion
- Department of the Environment: engineering accounted for c. $2.3 billion of $6.8 billion
- Department of Health: engineering accounted for around $2 billion of $27.5 billion
- National Science Foundation (not mission oriented in the traditional sense): engineering accounted for around $0.7 billion of $4.9 billion
- NASA: engineering accounted for around $0.6 billion of $6.6 billion
- Other agencies: engineering accounted for around $1.6 billion of $6 billion

Returning to the private sector, the EU Industrial R&D Investment Scoreboard does allow comparison of the sectoral distribution of business expenditure on R&D (BERD), based on data taken from the annual reports of the top 2000 companies, by R&D spend, globally. Figure 22 uses data from the 2013 Scoreboard (2011/12 expenditure figures) to compare the UK R&D expenditure profile with those of the EU (including the UK), Japan and the US. The broad sectors covered encompass several of the economic sectors that rely most heavily on engineering. The analysis shows quite marked differences in specialisation across countries, from the perspective of these large multinationals' investments, with the UK being very heavily specialised in pharmaceuticals for example, while expenditure in Germany is equally dominated by automotive. The UK does have a relative strength in several engineering-related sectors, including aerospace, software and computing, albeit it is relatively less well represented in technology hardware or electronics.

Figure 22 – Sectoral R&D expenditure as a share of all BERD, for selected countries



Source: The 2013 EU Industrial R&D Investment Scoreboard, European Commission, JRC/DG RTD

5.4 Private and public investments in engineering training

Engineering skills are in high demand in the labour market. Recent evidence in the 'Review of Engineering skills' by Professor John Perkins (BIS, 2013) show that employers struggle to meet the demand for engineers in general, and more senior staff in particular; there is a need to keep on investing in high-skill engineering training. Professor Perkins (BIS, 2013) calls for continual investment in 'continuous professional development' and a re-think as to how the profession can inspire and support more young people to enter engineering.

Higher-level engineering knowledge and skills, as developed through PhD training programmes for example, is widely seen as being critical to the ability of companies to address the more complex, higher-value segments within their wider market place and to otherwise drive business improvement and innovation. In one respect, having enough of the right kinds of postgraduates can be critical for an industry's international competitiveness and even the performance of a country's knowledge economy more generally. We should also remember that this absorptive capacity is valued at least as much for its social capital as it is for its technical proficiency.

5.4.1 Public investment in engineering training

Funding for engineering doctorates comes from a variety of sources, with the EPSRC being the dominant funder, particularly for UK resident students. The EPSRC spent **£33 million** in 2013 in training grants related to engineering (based on departments of grant holders). In 2014, EPSRC had an active portfolio of grants for engineering postgraduate training **of £322 million**, allocated across the following main instruments:

- Centres for Doctoral Training (CDTs) (also called Doctoral Training Centres (DTCs))– Centres have been in existence since 1992 when EngD centres were established, with Life Science Initiative doctoral training centres set up in 2002. A major call for new centres was announced in 2008 to strengthen postgraduate training and ensure a flow of highly-qualified people into research and industry. Currently there are 78 engineering-related institutional and consortia level centres that support around 780 doctoral students each year). EPSRC is investing £500 million in its new generation of CDTs, with centres winning 5-year grants to train doctoral students in close collaboration with industry and targeting strategic and emerging sectors where there is evidence of higher-level skills shortages that may attenuate growth or otherwise weaken competitiveness if left unchecked. The areas range from the familiar UK 'top sectors' in aerospace or pharmaceuticals as well as newer fields like offshore renewables or bioprocessing. The CDT instrument provides the higher education sector with the flexibility to anticipate and respond to the more dynamic / niche areas of industrial demand for doctoral level skilled people. More information on the role of CDTs is provided in a case study presented in Appendix A.

- Doctoral Training Partnerships (DTPs) – the DTPs are funding packages awarded through periodical awards to institutions to cover the costs of a quota of individual PhD studentships, including tuition fees, stipends and research support. By funding institutions rather than directly supporting individual postgraduates, EPSRC allows universities greater flexibility in the way individual PhDs are organised and funded.
- Industrial Cooperative Awards in Science and Technology (Industrial CASE) – provide funding for PhD studentships where businesses take the lead in arranging projects with an academic partner of their choice. Students currently receive funding for a full EPSRC studentship for 3.5 years and companies provide **additional** top up to the project of a minimum of a third of the EPSRC funding.

5.4.2 UK Industry invests heavily in engineering training

The majority of post-graduate education courses for engineers are developed in collaboration with industry and most will include some elements of practice-based education. Most Masters courses will include an industry project as the centrepiece of the overall learning experience, for example. PhDs have tended to be somewhat more academic historically, however, the EPSRC has worked with industry across much of the 20 years since it was founded in 1994 to expand and strengthen industrial engagement in its higher-level training awards. Industrial CASE is the obvious example, however, the new Centres for Doctoral Training (CDTs) are another excellent example of an innovative format, where the learning experience is both highly professionalised (in pedagogic terms) and strongly oriented to industry needs in emerging fields, where HEIs and mainstream doctoral grants may not easily reach.

There is no estimate of the total expenditure on engineering training for the private sector, however, an increasing proportion of EPSRC training grants – individual awards and centres – attract some level of private co-financing, which will run into the tens of millions a year. Industry spends substantially more on CPD and other training and it is possible to arrive at a first approximation for this figure based on the cost estimated by the Continuing Vocational Training Survey (CVTS), which is an EU-wide survey run every five years that collects information on learning activities sponsored by employers to support employees' skills development.

According to the most recent survey (CVTS4, 2013), 83% of employers provide some form of CVT and around 54% support CVT delivered by external providers. The average total cost of CVT courses per employee in the UK was £288 in 2010.[39] This includes the direct costs of the course (fee) and well as the opportunity costs or labour costs of participants. Additionally, the survey estimates that 31% of the UK workforce had access to formal CVT courses in 2010.[40] Based on these national estimates (and the estimated number of engineers in the UK workforce – 730,000) we calculate that companies in the **UK spent £65 million a year on external training for engineers**. The figure would be somewhat higher if we were to include the opportunity cost of the various internal programmes and more informal training activities (e.g. seminars and conferences).

[39] Average among companies that offer CVT.

[40] Employees participating in CVT courses as a share of all employees in all enterprises (i.e. training and non training enterprises). Eurostat (indicator: trng_cvts42). Based on the CVTS, 2010.

5.4.2.1 Engineering doctoral graduates have high levels of employment

The majority of PhD graduates (60-65%) leave HE to enter industry or other employment (Perkins, 2013). Vitae publishes analyses of the Destinations of Leavers from Higher Education Longitudinal Surveys (DLHE) on a biennial basis and these data show clearly that 'Engineering and Physical Sciences' PhDs have significantly different career paths as compared with other broad disciplines, with for example, around 87% of all postdocs in full-time paid employment within 6 months (77% for all disciplines) and around 60% in positions in the private sector (business, manufacturing, research non-HE, other sectors) where the average for all disciplines is closer to 40% (HE is the single biggest destination; training future researchers / academics).

Once they are working in the industry, engineers have access to further training. Approximately two thirds of companies identified as employers of engineering and IT staff in the UK offer formal on the job training, based on figures for 2013.[41] The percentage of companies that offer formal on the job training was highly variable over the last four years going from 48% to 65% of companies. Furthermore, more than 40% of companies offer support to undertake Master or PhDs, a proportion that seems to have increased in the last 3 years.

However, Perkins (2013) finds that employers are supporting fewer graduate students. Over the past 5 years the proportion of self-funded students has risen from 42% to 68%, while the proportion funded by industry or their employer has fallen from 17% to 12%, perhaps reflecting financial pressures more generally and possibly the changing balance of employment opportunities within smaller and larger businesses.

Information obtained from the Engineering and Technology Skills & Demand in Industry Annual Survey shows an increasing gap between the expectations of employers regarding new recruits and their actual skills. The survey found that 42% of responding employers judge their recent engineering and technology recruits did not meet their reasonable expectations as regards levels of skill; for graduates, the concerns relate primarily to their practical experience and technical proficiency. This points to the need to keep investing in practice-led education and training, using programmes like Industrial CASE or the Doctoral Training Centres to provide students with more of the practical experiences and soft skills viewed as being critical by industry and complementary to their strong academic and theoretical training. This same industry survey also shows a trend among employers placing relatively greater emphasis on the recruitment of senior and experienced engineers.

5.4.2.2 Higher skills needs for the Knowledge Economy

On the subject of skills needs, the government supports an annual review of employment trends across the economy, led by the Institute of Economic Research at Warwick University, which, amongst many things, looks at the changing composition of employment by occupation over time (broadly, looking back 20 years and projecting forwards 10 years). Figure 23 shows a clear trend, with a long-run reduction in the number and share of administrators, skilled trades and operatives and a long-run expansion in the number and share of managers and other professionals. Globalisation has seen the outsourcing (loss) of millions of lower-skilled jobs, at least in the internationally traded sectors (carers, leisure and other services have seen strong growth). To some extent, we have been left with an occupation structure we term 'the knowledge economy' as the professional and managerial jobs have been less easy to export. This is a familiar situation in other countries too, whether that is France, Germany or the US. The UK has not stood still of course, with successive governments focusing on improving educational attainment levels and improved support for science funding in research and education. Industry has responded too, and there is an evident long-run growth trend among science and engineering occupations, which are expanding in absolute terms (total number) and requiring new recruits from universities or overseas to cope with growth and natural replacements. The 10-year forecasts through to 2022 extrapolate past growth rates, in the main; however, the current study makes clear the situation is dynamic and that engineering research itself may have a profound impact on the future productivity (and hence employment levels) of engineering,

[41] Engineering and Technology Skills & Demand in Industry Annual Survey 2013

with multiple advances in engineering methodologies, modelling systems and design tools. Not only are China and India ramping up their domestic engineering capacity, but engineers are also inventing new solutions that may require fewer of these polymaths in the longer term. From this perspective, the challenge is for UK-based export-oriented businesses to win the race to develop and implement these new automation tools and thereby cause other countries to shed engineering jobs rather than the UK.

Figure 23 – Changing Composition of Employment by Occupation, 1992-2022

SOC2010 Major Groups, United Kingdom Employment Levels (000s)	1992	2002	2012	2017	2022	2012-2022 Net Change	Replacement Demands	Total Requirement
1. Managers, directors and senior officials	2,179	2,710	3,303	3,571	3,889	586	1,378	1,964
2. Professional occupations	3,958	4,997	6,270	6,917	7,444	1,175	2,536	3,711
3. Associate professional and technical	2,981	3,704	4,182	4,452	4,764	583	1,541	2,124
4. Administrative and secretarial	4,419	4,208	3,756	3,490	3,270	-486	1,607	1,121
5. Skilled trades occupations	4,065	3,747	3,522	3,327	3,216	-306	1,195	889
6. Caring, leisure and other service	1,534	2,271	2,859	3,189	3,508	649	1,324	1,973
7. Sales and customer service	2,222	2,579	2,698	2,622	2,633	-64	953	889
8. Process, plant and machine operatives	2,406	2,167	1,989	1,859	1,775	-214	730	515
9. Elementary occupations	3,393	3,586	3,348	3,202	3,280	-67	1,237	1,169
Total	27,157	29,969	31,926	32,630	33,781	1,855	12,501	14,356
Percentage Shares	**1992**	**2002**	**2012**	**2017**	**2022**	**Percentage Changes**		
1. Managers, directors and senior officials	8	9	10	11	12	17.7	41.7	59.4
2. Professional occupations	15	17	20	21	22	18.7	40.5	59.2
3. Associate professional and technical	11	12	13	14	14	13.9	36.9	50.8
4. Administrative and secretarial	16	14	12	11	10	-12.9	42.8	29.8
5. Skilled trades occupations	15	13	11	10	10	-8.7	33.9	25.2
6. Caring, leisure and other service	6	8	9	10	10	22.7	46.3	69
7. Sales and customer service	8	9	8	8	8	-2.4	35.3	33
8. Process, plant and machine operatives	9	7	6	6	5	-10.8	36.7	25.9
9. Elementary occupations	12	12	10	10	10	-2	36.9	34.9
Total	100	100	100	100	100	5.8	39.2	45

Source: IER estimates, MDM revision 12015

6. Final remarks

This study has provided wide-ranging evidence of the critical role played by engineering research and training in supporting a dynamic and growing economy.

Our quantitative analysis has revealed the pervasive nature of engineering across the economy and its prominent role in driving growth in emerging sectors and underpinning global competitiveness through innovation and renewal in established sectors.

It has explored the different routes by which engineering research achieves economic and societal impact, for example directly through the realisation of technological advances that underpin innovation or indirectly through providing the foundation for the state-of-the art education provided to our future professional engineers.

Our qualitative research has benefitted from unique and privileged access to more than 500 REF impact case studies, which provide an unprecedented catalogue of tangible impacts attributable to research investments. Those benefits encompass new businesses, new products and services as well as increasing levels of productivity and competitiveness. The material also provides incontrovertible evidence of engineering research impact on public policy and public services.

Taken together, the extent of the manifold benefits and the critical contributions made to both social wellbeing and economic dynamism, we have a strong sense that increased investment, by public and private sectors, would further protect and strengthen the performance of UK plc in global markets in the longer term.

Appendix A : Case studies

This appendix contains 6 case studies:

- Engineering research in the UK's automotive sector
- Engineering research in the UK's construction sector
- Engineering research in the UK's aerospace sector
- Engineering research in the renewable energy
- Engineering research in the NHS
- Centres of Doctoral training

1. Engineering research in the UK's automotive sector

1.1 Introduction

For the past decade, and especially since the last economic downturn, the automotive sector worldwide has been facing an ever-increasing set of complex challenges. On one side, consumers demand vehicles with less fuel consumption without sacrificing performance. They also demand improved car safety features, more interactive and connected vehicle systems and increased customisation options, at a minimum cost. On the other side, in addition to these seemingly incompatible requirements, policy and policy-makers also expect new car companies to produce vehicles that are safer and less contaminating, with less waste derived from manufacturing or recycling and less reliance on scarce raw materials.

Engineering research across UK Universities has been giving answers to these challenges for the past two decades. A general look across submitted REF case studies with impacts in the automotive sector allows us to draw an overall picture of such contribution (Table 1).

Table 1 Automotive 'impact landscape'

Underpinning research	Outcomes / Impacts of the research	Industry drivers / Challenges	'Mega-trends'
New modelling and simulation tools (CFD and other phenomena) Improvement in CAD/CAM tools VR tools for automotive design	Improved next-generation car prototyping Development of industry-standard modelling tools	Downsizing & Turbocharging of engines Reduction of inefficiencies in combustion Better design and ergonomics	**Consumer demands:** Less consumption with maintained or improved engine performance → Improved efficiency Improved car safety More connected / interactive vehicles Mass customisation without increased cost **Policy demands:** Less accidents and injuries from accidents Less polluting cars and car manufacturing, with less waste and reliance on scarce materials
Diagnostic engineering (fault detection) Development of new materials for engines Acoustic monitoring of fuel injection Wear and friction modelling Biofuel research (combustion / efficiency / emissions)	Improvement in turbocharger capability and higher compression ratio petrol engines		
Lightweight components, adhesives and other	Weight reduction and improved recyclability of		

Underpinning research	Outcomes / Impacts of the research	Industry drivers / Challenges	'Mega-trends'
advanced materials Multi-material structures and their recyclability	engines and materials		**Industry needs:** Increase R&D capabilities Strengthen relations across the supply chain Improved productivity in car design and manufacturing Leverage other funding sources (regional/EU) New economic activity and growth Access to new markets Address specific skills gaps
Remote sensing Car 2 Infrastructure communications	Novel engine and emission control strategies, combustion control	Move towards intelligent transport systems	
Automotive radar systems and sensors Vehicle stability systems and sensors	Advanced driver assistance systems (ADAS)		
ICT & Human factors research	In-vehicle information systems		

Source: Technopolis (2014)

We can observe that the different areas covered respond broadly to the current challenges and trends of the industry, which underpins the relevance of the work that has been carried out across UK institutions. In each of these areas, we can find different examples of impacts, focusing on the generation of new economic activity, improvements in competitiveness and productivity of existing industry, or impacts in the public arena. Most of these examples of impact apply broadly to the automotive industry, and these are highlighted in the following sections. However, other examples concern specific developments carried out in the context of collaborations with specific automotive companies. In the case of large vehicle manufacturers, these cases provide an overview of how different research carried out across the UK contributes to the competitiveness of several of the country's industrial champions. We have decided to illustrate such a perspective from the point of view of one of the UK's largest automotive manufacturers, Jaguar-Land Rover (JLR) in Box 1.

1.2 International & domestic competitiveness and productivity

Downsizing and turbocharging existing internal combustion engines is one of the ways to improve their performance and efficiency. However, this strategy makes engines operate closer to their mechanical limits. As a result, there is a need for improvements in the design stage and for these to be translated into manufactured products that are reliable and fulfil the client's expectations. Improvements in engine technologies, and particularly in turbocharger capability and higher compression-ratio engines, have been carried out at the University of Huddersfield and the University of Leeds.

The work carried out at the University of Huddersfield included diagnostics engineering (fault detection), developments of new materials for engines, techniques for the acoustic monitoring of fuel injection and wear and friction modelling. A strategic partnership between the university and BorgWarner Turbo Systems in 2011 was one of the key deciding factors for JLR's decision to award BorgWarner a contract for its supply of turbochargers and for BorgWarner to establish one of their bases in the UK. The university supplies BorgWarner with collaborative R&D capability and bespoke postgraduate training. Regional Growth Funds (RGF) were leveraged to support this deal, that will contribute to JLR's new family of four-cylinder engines, expected to launch in 2015 and manufactured at JLR's new Engine Manufacturing Centre near Wolverhampton. These partnerships will further benefit from the work of the Advanced Propulsion Centre and the activities of the Leeds City Region LEP, to foster growth, high-value jobs and new economic activity in the region.

The University of Nottingham has developed novel engine and combustion control strategies that minimise emissions and reduce pollution. These engine management techniques are currently in use in vehicles sold by UK car manufacturers. Given the scales of production, the overall impact of small gains in engine efficiency across the board is very significant, and the developments contribute to the international competitiveness of the products manufactured by UK-based automotive companies.

Box 1 The value of automotive engineering research in the UK in JLR

Jaguar Land-Rover (JLR) is one of the most important car manufacturers in the UK, with £15.7b revenue from 2013 and a total workforce of around 25,000 people. Since 2008, JLR has invested £355m in engine manufacturing activities in the UK, creating 10,700 new jobs. Currently, five of the six JLR's main facilities are located in the UK, with the remaining one being in India. While these include R&D, manufacturing and vehicle assembly facilities, JLR also draws considerable expertise and input from the UK's R&D University system.

For example, experimental research and computer modelling in the School of Mechanical Engineering of the University of Leeds has led to long-term collaborations with JLR and GE Precision Engineering. These collaborations tackled technical issues such as control of fuel/air mixing, ignition, burn rates and knock suppression, resulting in engines that are more reliable and up to 30% more efficient than previous generations. The resulting improvements in computer modelling code were incorporated by JLR into their internal engine system modelling packages, translating these efficiency gains into all their future vehicles. Since 2010, these collaborations were consolidated in the UltraBoost project, which also involved Shell and the Universities of Bath and Imperial College.

Active car safety is nowadays mostly related to advanced driver assistance systems (ADAS). Stability control algorithms developed by Loughborough University between 2002 and 2006 were incorporated by JLR to control their active differential systems in cars sold onwards from 2009. Drivers of more than 20,000 Jaguar supercharged cars worldwide since 2009 have been enjoying these developments, which were also included in F-type models and extended, in a modified form, to vehicles such as the Range Rover Sport.

New automotive radar systems are the result of more than two decades of radar research at the University of Birmingham. These developments underpin useful safety features such as adaptive cruise control (ACC), blind spot monitoring, and lane change merge aids. The first two of these are available across the range of JLR vehicles, while the third is included in select models from 2014. Over time, all these technologies trickle down from the luxury vehicle segment to the rest of the range, where most consumers adopt them. The research carried out was a critical component in establishing the scientific and technological feasibility of these technologies in the first place.

In-vehicle information systems (IVIS) developed combining ICT and human factors research are one of the results of the Transportation Research Group (TRG) at the University of Southampton. In 2008, TRG's research in IVIS was adopted by JLR in a study that analysed more intuitive voice-actuation systems with the aim of maximising the potential of new vehicle technologies while minimising their distractions for the driver. Thanks to this research, JLR was able to implement design philosophies that improve the usability of their systems, with an estimated business value for the company of £1 million.

Source: Technopolis (2014)

1.3 New or improved economic activity

Reducing fuel consumption in new vehicles depends on improving the efficiency of existing internal combustion engines and reducing the weight of new vehicle designs. Improved prototyping is needed in order to produce these next-generation vehicles while containing production costs. Advances in prototyping in the automotive sector are nowadays mostly driven by computational and software developments, which allow companies to simulate more complex vehicle systems without resorting to costly and inflexible physical prototypes and experimental studies.

The development of industry-standard modelling tools is one of the most important aspects of advances in prototyping. At the beginning of the 90s, the Mechanical Engineering department at Imperial College developed the foundation of what is now one the world-class modelling and simulation tools for Computational Fluid Dynamics (CFD) and other physical phenomena. These foundations are commercialised under the STAR-CD and STAR-CCM+ software by Computational Dynamics Ltd., whose turnover grew by 250% since 2008 to around $190m per annum, employing 80 of their 750 staff in London.

Improvements in CAD/CAM tools are also needed in order to cope with increasing complexity of vehicle assemblies, stock parts and Bill of Materials (BOM). The Heriot-Watt/Edinburgh Partnership in Engineering (ERPE) developed smarter software contributing to more agile part searching and representation of complex product data in the late 90s. These developments were commercialised in 2005 as ShapeSpace, which was later partially acquired by US Actify Inc.

Weight reduction and improving the recyclability of engines and materials used in the automotive industry is also one of the trends towards less consuming and polluting new vehicles. Producing lightweight components, adhesives and other advanced materials for the automotive industry requires the development of novel designs, design guidelines, manufacturing procedures and standards. The Department of Mechanical Engineering and Mathematical Sciences at Oxford Brookes University has been working for more than 20 years in providing these solutions. For example, materials data used by UK automotive companies in the simulation of vehicle structures has its origins in the developments of the University.

Nanoforce Technology Ltd, a spin-out wholly owned by Queen Mary University of London (QMUL), is developing multi-material structures and composites. The creation of Nanoforce Technology Ltd was the result of QMUL's long history in research in new materials and processes. Automotive parts based on one of the developed composite materials (Biotex) are currently under evaluation by several car manufacturers in the UK and worldwide for their next generation vehicles.

1.4 Better provision of public services and support to citizens

Another one of the trends affecting the automotive sector is the move towards more intelligent vehicle and transport systems. Here the UK's R&D system is also generating great contributions towards tackling the technical challenges that arise. This area of development generates multiple impacts on public services, by influencing safety standards and providing new tools to increase the efficiency of public transport networks, while reducing their impact on the environment.

Remote sensing and car-to-infrastructure communication applications are being researched by Oxford Brookes University, with research tasked at identifying and proposing new strategies to dynamically limit the amount of pollutants from vehicles in urban areas to meet pollution targets. The results from this research were shared through the AVERT Foresight project to both engineers in automotive companies and Transport for London (TfL), where they are already having an impact on policy and customer awareness.

Underpinning research carried out at Queens University Belfast has directly fed into the development of hybrid powertrains by Wrightbus Ltd. The company won the New Bus for London contract worth £230m and supplying 600 buses to Transport for London. The full fleet reduces annual CO2 emissions in London by 230,000 tonnes, improving air quality and reducing greenhouse gases. The company continues to develop hybrid powertrain technology and expand into new markets globally.

The University of Leeds has investigated the benefits and capabilities of in-vehicle intelligent speed adaptation (ISA) system, aimed at reducing injuries and saving lives. A key impact of this research has been the recognition by Euro NCAPs in 2013 of ISA systems within the safety ratings of new cars.

The University of Nottingham's research on the high strain rate behaviour of composite materials has led to the development of passively safe street furniture, commercialised by Frangible Safety Posts Ltd. In addition to the additional savings and business generated at least one life has already been saved in a car accident as a direct consequence of the product's performance.

Imperial College has contributed to improvements in the Performance and Management of Mass Transit Systems in Major Cities, with applications in 5 global consortia comprising over 70 metro, suburban rail and urban bus operators. Potential financial benefits, as quantified by mass transit operators, are on the order of 0.5 billion between 2003 and 2013.

Imperial also worked on models to assist in the appraisal and decision making processes related to transport investments. This research instigated reforms in the UK's approach to Cost Benefit Analysis (CBA) and empirical evidence has been incorporated by the UK Department for Transport (DfT) since 2009. Since 2007 these models have been incorporated as standard textbook methodologies and have been applied to around $150b of international transport investment globally. In the UK, recent applications include the official economic evaluations of CrossRail (2010) and High Speed 2 (2010, 2012).

The University of Leeds developed scheduling research that led to optimised cost efficient public transport. These optimising algorithms and software that led to the spinning out of Tracsis in 2004. Its products are currently used by more than 40 bus and train companies who previously relied on manual processes. A minimum estimate of a £230m saving in crew costs have been achieved in the UK over the 2008-2013 period. These tools are used nowadays by bidders in all UK rail franchise tenders, contributing to a more efficient and reliable rail transport. This success led to the Tracsis floatation in 2007, achieving a market capitalisation of £46.7m in early 2013.

2. Engineering research in the UK's construction sector

2.1 Introduction

Construction is a vital sector of the UK economy. According to recent statistics of the BIS Construction Strategy, it contributes to nearly £90bn of GVA to the UK economy (or 6.7% of the total) and provides 2.9m jobs in over 280,000 businesses, accounting for around 10% of total UK's employment. The UK also has the sixth largest green construction sector in the world, with an estimated 60,000 jobs that are to be supported by the insulation sector alone by 2015. Annually, the growth of the green and sustainable building construction industry is expected to be around 22% between 2012 and 2017, presenting a substantial opportunity for growth and jobs in the overall economy.

At the same time, however, the construction sector runs the risk of falling behind other important economic activities. Construction was hit hard by the 2008 economic downturn and the impact was mostly felt in low-technology small businesses operating across the construction value chain. The construction sector is seen as a traditionally low innovator and currently it is seen as lacking the career prospects, and therefore attraction potential, that highly skilled professionals in several engineering disciplines look for. Additionally, the loss of competitiveness in the sector due to high construction costs and the lack of access to finance can hamper the contribution of the sector towards economic growth and jobs in the UK economy.

In order to revitalise the image of the industry and increase its competitiveness and exports, both industry and research providers are striving to produce innovations that lower construction costs and reduce environmental impact, while simultaneously increasing sector productivity and improve building performance. Although innovation uptake across the board in the sector is still low, engineering research in the UK provides many examples of impact of successful innovations in construction and civil engineering. These innovations have an aggregate economic impact that is hard to ignore. Moreover, they inspire and bring forward more research and development activity, and promote the benefits of innovation to the wider industry. An overall look at the main examples of impact shows us that engineering research across UK Universities is spread across areas that align nicely to the challenges needed to provide a more competitive sector (Figure 24). Some of these examples of impact are described in more detail in the following sections.

2.2 International & domestic competitiveness and productivity

Research at the University of Bradford has contributed to the development of innovative acoustic materials produced from industrial waste, which would otherwise have been destined for landfill. These were licensed to the company Armacell in 2003. Now the company reuses up to 95% of its production waste to produce new acoustic products with up to 50% better acoustic performance than its competitors. This has resulted on annual turnovers of more than £4m for Armacell and prevents more than 500 tonnes per annum of plastic waste from going into landfills, enabling economic growth while reducing pollution and increasing quality of life in new buildings.

In the area of steel framed buildings, the results of work carried out at the Geotechnical Engineering Research Centre at City University London have contributed to savings of around 25% in the amount of steel needed for such buildings, making them on average 9% cheaper than their concrete equivalents. Research results have been incorporated both into design guidelines and software tools, used in producing many landmark buildings constructed during the past years. Steel frame build times are reduced by 13% and resulting buildings can be 20-50% more energy efficient. The work undertaken has helped bring new products to market but most importantly, it has made a significant contribution to the increasing success of the steel industry in the UK commercial building market.

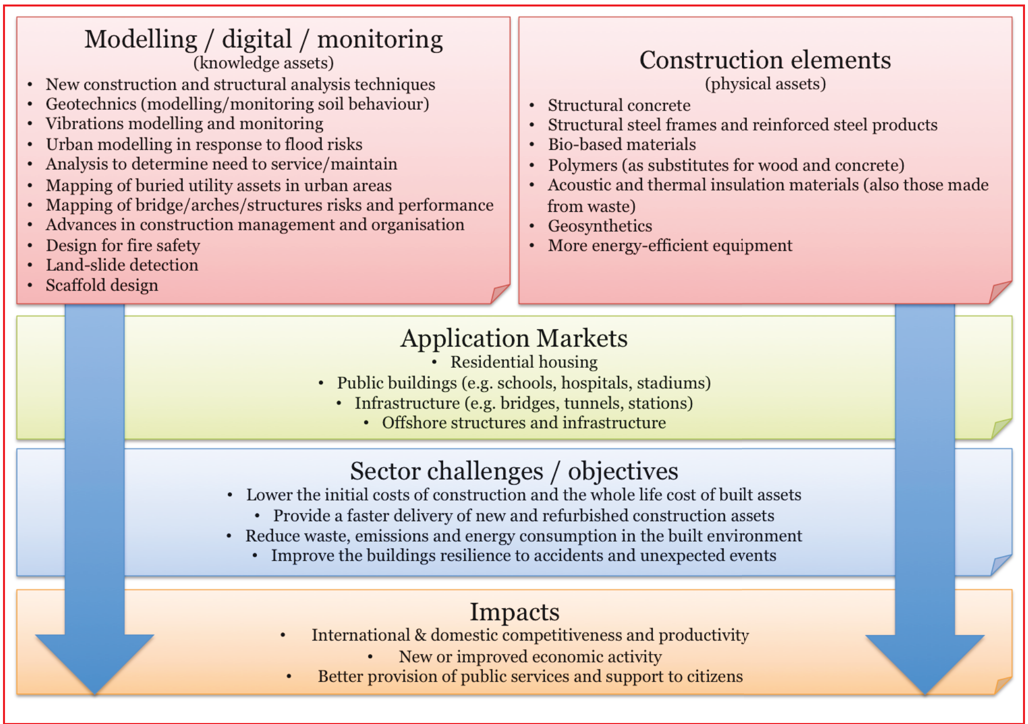
In the same area, Imperial College London has also contributed substantially to the use of structural stainless steel. Their research results have been included in national and international design codes. These have also led to general cost savings, further promotion of the use of stainless steel in construction and a reduction in the use of construction resources, influencing producers, code writers and practitioners across the construction value chain. International stainless steel producers such as Ancon Building Products report step-changes in their design capabilities thanks to these developments.

Also in the area of steel, research carried out at Swansea University has contributed to the development of new coatings for Tata Steel Europe, used in high durability construction products. Thousands of tons of steel products are being produced incorporating these developments, and new strategic partnerships have been developed with Tata, NSG and BASF to develop functional coatings. These have generated substantial additional investments in new production lines, as well as in a national centre for scaling solar energy advanced manufacturing, together with Imperial College.

In the area of slender structures such as scaffolds, the research by Oxford Brookes University has also contributed to make these more economical and quick to deploy. The work has influenced technical guidance and European standards that apply both to scaffolds and storage racks.

The deterioration of concrete structures is a concern in most developed countries. In the area of structural concrete the Edinburgh Research Partnership in Engineering ERPE (Heriot-Watt/Edinburgh) has carried out substantial work on the effective design and operation of concrete infrastructure and on new standards to extend the life of concrete infrastructure with fibre reinforced polymer. These developments have impacted international practice and their economic impact has been estimated at around £100m per annum on infrastructure maintenance savings worldwide.

Figure 24 - Engineering research contributions to the construction sector



Source: Technopolis (2014).

2.3 New or improved economic activity

Novel numerical limit analysis methods developed in the Department of Civil and Structural Engineering of the University of Sheffield. These were incorporated in the software of the spinout company LimitState, allowing practitioners to model real-world problems related to infrastructure maintenance far more quickly. Currently over 100 industrial organisations in more than 30 countries licence the software and the revenues of the company have increased more than threefold in the last 5 years. In addition to new economic activity, the use of the software allows practitioners to realise significant productivity and economic benefits. For example, £500k saved on a weekly basis by a single organisation due to new rapid response offshore design capability and £500k saved by a client on a single project, due to the software showing that a planned bridge strengthening programme was unnecessary.

Cardiff University has developed acoustic emission monitoring and data analyses technologies with the aim of transforming the inspection of bridges. These technologies have been commercialised by Mistras Group Ltd and have increased the turnover of the company by £7.5m, with £5m attributable to the research. Additionally, this more reliable and progressive means of bridge monitoring has had an impact on the prevention of safety risks and reduced costs and emissions derived from avoiding unnecessary works.

Also in the area of monitoring, University College London contributed to the adoption of innovative remote condition monitoring solutions in the rail and construction industries. Through the UCL spinout Senceive Ltd, customers like Amey, Costain, Network Rail and Tubelines have benefited from these developments. A deployment of these remote monitoring technologies in the London Crossrail project has already delivered cost savings in excess of £1m, compared to use of traditional wired solutions.

In the area of construction planning, the University of Dundee has developed new tools for productivity improvement, whole life costing and sustainability assessment. These have been commercialised through the spinoff Whole Life Consultants Ltd, with sales of £1m and a recent increase in turnover of £6.8m, with increasing profitability of the business. Labour forecasting tools and productivity improvement methods are also having an impact in their clients, many of them in the public sector.

2.4 Better provision of public services and support to citizens

Design Guides and Standards for strengthening concrete structures using advanced composites have been developed and improved thanks to the work carried out at the University of Bath. This work allows for prolonging the life of concrete infrastructures and has had a substantial impact in the Highways Agency (the UKs largest bridge owning authority) and Network Rail. Combined, these two organisations are responsible for maintaining around 12,000 concrete bridges. By extending the life of concrete structures, needless demolition work has been prevented, saving over the last eight years millions of pounds in replacement costs (e.g. a two lane concrete motorway bridge costs £1.5-2m) and in disruption to infrastructure users due to road closures (estimated at around £10-15k per lane, per day).

Also in the area of bridge strength enhancements, the research carried out by Queens University Belfast has allowed London Underground (LU) and other bridge owners to save more than £80m since 2008. In the early 1990s, LU found out that around 1200 platforms on the underground system were designed according to deficient structural methods. The research findings of the university allowed LU to develop new design and assessment guidelines for arching action of LU platforms, which were finally approved in 2005 for use in the LU system. These actions to strengthen these bridges have avoided disruptions that would have resulted in enormous congestion, economical losses of billions and negative social impacts.

In the area of construction planning, the research carried out by University of Birmingham has improved the capabilities of the industry in the mapping of underground utility assets such as electricity, water, gas and telecommunications. By avoiding inaccurate location of buried assets, substantial cost savings can be realised by service and public infrastructure providers. In addition, the public is impacted to a lesser extent by wasteful excavations and disruption to services. The work carried out in this field has included development of proof-of-concept devices, specifications later included into British Standards, and the collaborations necessary to train new civil engineers in the use of these techniques. The impact on practitioners and professionals of the sector is a necessary building block to realise substantial economic impacts from the management of buried assets going forward.

The work of Newcastle University in developing new electrokinetic geosynthetics (EKG) has had an impact in changing standards and applications for these types of materials. Commercialised through the spinout company Electrokinetic Limited, these technologies have been incorporated by infrastructure providers working on upgrading some of the UK's critical infrastructures. For example, during 2011-12, projects for a value of £1m (in research investment) carried out by Network Rail and the Highways Agency realised cost savings and emission reductions of 30% and 40%, respectively, compared to established methods. This work has also led to the recognition of this technology for reinforced soil in 2010 by British Standards.

Work on new construction solutions to improve energy efficiency in buildings has been carried out in Brunel University, particularly focusing on the development of cool roof technologies. Research at the University has confirmed the urban heat island effect existing in London and has actively advocated for the deployment of these insulation materials. In 2010, the Greater London Authority in their Climate Change Adaptation Strategy committed to assessing and promoting cool roof technologies in London.

3. Engineering research in the UK's aerospace sector

3.1 BIS technology strategy for aerospace

In their report on "Implementing the strategic vision for UK aerospace", BIS describes aerospace as "the cornerstone of UK high-value manufacturing." As the largest aerospace sector in Europe and the second biggest globally, employing over 230,000 people and representing 12% of the total R&D spend in British manufacturing, it is an impressive industry. However, the industry is fast moving, and currently shifting towards a greener, lower-carbon future. This will require a range of novel technologies: for wing and engine manufacture and design; aero structures; and advanced systems and equipment.

These are already areas in which the UK is world leading, though this status cannot be taken for granted. Success will depend on the industry's ability to innovate and lead in four key areas of technology: aerodynamics, propulsion, aero structures and advanced systems, which reflect those. These areas are the focus of the UK Aerospace Technology Institute (ATI), designed to ensure that the UK focuses R&D efforts and makes the best use of funding. A general look across submitted REF case studies with impacts in the aerospace sector allows us to draw an overall picture of relevant contributions that answer these challenges (Table 2).

Table 2 Aerospace 'impact landscape'

Key area	Underpinning research	Outcomes / Impact of the research	Strategy drivers / challenges
Aerodynamics	Automatic mesh generator and compressible flow solver	Improved aerodynamic performance through mesh technology	Push the technological boundaries of aerodynamics by channelling funds to those best placed for R&D Showcase the UK's capabilities in complex aerodynamics to the global market
	Aerodynamic efficiency of blades involving application of endwalls	Reduced fuel burn	
	Aerodynamic interaction at compressor / combustor interface		Reduce fuel emissions by 20% over the next 20 years Enable future aircraft to carry 20% more passengers with the same fuel
Propulsion	Experimental / computer models of fuel burn rate		
	Investigation into fluidic vortex valves	Improved jet engine efficiency / robustness	
	Cold-dwell sensitivity in near-alpha titanium alloys		
	Composite optimisation algorithms	Weight reduction and improved composite wing performance	Move from structural concepts developed in metal and adapted for composites to tailored structures with fibres placed exactly where necessary
	Aero-acoustics	Aircraft noise reduction	Make an aircraft taking off quieter than the traffic around an airport
Aero structures	Fluid-structure interaction / structure dynamics / vibration	Improved engine reliability through reduced vibrations	
	Machine tool accuracy	Improvement in machine tool accuracy reducing timescales	Improved build tolerances and new joining technologies
	Laser cleaning for electron beam welding	Cost savings in pre-weld cleaning processes	
	Microstructure prediction	Reduced manufacturing scrap rates for titanium blades	New materials and manufacturing processes
	Plasma surface engineering	Weight reduction	
	Adhesive properties / issues with lightweight materials	Weight reduction	
Advanced systems	Critical systems and data driven technology	Improved air traffic safety	
	Modelling of frequency, location and consequences of runway accidents		

The report from BIS sets out target objectives in each of the key areas. Table 2 links the impacts identified in a number of the REF case studies to these target objectives, which demonstrates that current research covers the key areas and often meets the target objectives. In addition, the impacts in this area can be classified more generally:

- International competitiveness and productivity
- New economic activity
- Better provision of public services and support to citizens

Analysis along these lines allows an assessment of the impact of this research on society as a whole, rather than just on a specific sector. Examples of how the impacts in aerospace, identified in REF, fit into this framework are discussed below. There are also a number of close partnerships between universities and firms (both large and small) that are contributing to the competitiveness of UK industry in this sector. A Rolls-Royce / Imperial College Technology Centre on vibration (VTC), and a collaboration between Messier-Bugatti-Dowty (MBD) and the University of Sheffield Advanced Manufacturing Research Centre (AMRC), are shining examples.

3.2 International competitiveness and productivity

Making the transition from using traditional materials to composites in the manufacture of aeroplanes is currently the best method for reducing weight, which in turn reduces fuel requirements. This reduces both costs and emissions making the industry both greener and more efficient. The Bath Composite Research Unit has carried out research in this area that means the new Airbus A350-XWB is the first aircraft with composite wings, saving 1 tonne of fuel per typical flight compared to traditional metal. Also successful in saving weight, though this time using titanium rather than composites, was research carried out in the Department of Materials Science and Engineering at the University of Sheffield. An innovative surface treatment for titanium alloys was developed which has the potential to allow about 2700 steel bearings to be replaced with lightweight titanium ones on A350/A380s. The associated cost savings are estimated at £7.6m per plane together with a reduction of ~36,000 tonnes of CO_2, due to reduced fuel requirements over the lifespan of each aircraft.

The role of the UK industry champion Rolls-Royce as a major player in jet engine manufacture means a number of important advances have been made in this field. Work carried out at the VTC (Imperial) into vibration reduction has led to cost savings of over £130m in seven years through improved engine reliability. Also at Imperial, research into the prediction of the microstructure of nickel super alloys and better understanding of defect formation contributed at least £100m p.a. in savings at Rolls-Royce. This industry giant also benefitted from research at the University of Sheffield on fluidic vortex valves that led to improved jet-engine efficiency, securing orders in excess of $3.6bn for engines that employ this technology. The same engines included new profiled endwalls, the result of research carried out at Durham and predicted to reduce CO_2 emissions by 4400kg over a typical flight.

Advances were also made in manufacturing leading to cost and time saving contributing to the competitiveness and productivity of UK industry. The University of Huddersfield produced in-depth understanding of the contributing factors to inaccuracies in machine tooling. Resulting techniques allowing rapid calibration have reduced timescales from days to hours. Research at the University of Manchester into laser cleaning of Ti alloys in preparation for electron beam welding has led to savings of over £1m p.a. at BAE Systems.

3.3 New economic activity

The strength of the aerospace industry in the UK, along with already existing excellent university / industry partnerships and the importance of reputation in such a high-exposure industry mean there are relatively few successful spinouts in this field. There are exceptions, however. Research that provides modelling tools and software to companies resulting in cheaper and less risky exploration of new designs has produced a spinout company. This spinout from the University of Southampton has had strong technological and economic impacts in its own right. Another example is a spinout from Swansea University that was started following research into mechanical behaviour of engine components. Swansea Materials Research & Testing Ltd (SMaRT) had an initial turnover of £1m. Investigations into aircraft acoustics at the University of Southampton have benefitted over 177 million passengers worldwide. It also resulted in the development of 3D living-room sound systems, which have achieved global sales of $7.2m. Research at the University of Durham into software for performing stress analysis on aerospace components has also led to a successful spinout, Concept Analyst, Ltd. Their software is currently licensed by BAE Systems and Spirit Aerospace, with trials taking place at Airbus UK and Bombardier, Canada.

UK university research has led to new economic activity in the aerospace industry that does not necessarily take the form of spinouts. For example, the research into valves at the University of Sheffield (see section 3.2) contributed directly to 360 orders of Rolls-Royce jet engines employing this technology. Another example is research into composites and metal forming at the University of Ulster that underpinned Bombardier's entry into the commercial narrow body aircraft market, worth $43bn annually. The C-series wing project, which uses composite technology, employs 800 people directly, plus 2,000 more in the supply chain. Bombardier has secured 177 firm orders for the C series aircraft. This research has also resulted in a number of spinouts and the £6m N. Ireland Advanced Composites and Engineering Centre, which currently has 10 member companies. Research at the University of Surrey's Space Centre has formed the basis of a satellite built by a former Surrey spinout, Surrey Satellite Technology Limited. The satellite, named GIOVE-A, was the first satellite launched to provide navigation and timing signals for Europe's Galileo constellation (European GPS). GIOVE-A was built in just 30 months and at a fraction of the costs of other competitors.

3.4 Better provision of public services and support to citizens

As aviation services are not part of the public provision, direct improvements in the aerospace industry do not directly affect public services. However, with millions of people living near airports, and even more using aeroplanes for business and pleasure, it is an industry that impacts significantly on society. It is also a major producer of carbon dioxide and is therefore contributing to global environmental damage. Research in aviation that positively impacts on society can be divided into two main categories: reductions in noise and air pollution; and improvements in safety.

Research at Southampton is directly addressing the problems facing those living nearby airports, and consequently one of the government's specific objectives regarding aviation. Noise Technology Centres in collaboration with both Airbus and Rolls-Royce have provided "tools to understand, predict and reduce noise pollution from commercial aircraft, ensuring that they are on track to meet the EUs stringent noise reduction targets. Implementation of this new technology is already benefitting millions of people living near busy airports in the UK. Air pollution is being tackled by the numerous attempts to build lighter aircraft and reduce fuel consumption, including the examples in section 3.2. Research at the University of Leeds into burn rates and high pressure explosions have led to improvements in safety, as well as reducing emissions thanks to efficiency gains of 30%. The University of Manchester's research into UK aviation emissions was instrumental in getting aviation recognised as a serious source of greenhouse gas emissions.

Improvements to safety have been made in a variety of areas. Research at the University of Exeter was described by NATS as "an outstanding improvement to our safety." The research automatically optimises systems to simultaneously maximise alerts to truly dangerous situations, while minimising false alarms. Also concerning airports, research in Loughborough that classified accidents and modelled the effectiveness of runway end safety areas has been validated at 8 airports worldwide and implemented at 3. In a separate field, engineering materials research at Imperial has led directly to UK, US and International Standards and Codes relating to the service life of high temperature components and the fracture resistance of plastics, composites and adhesives. These Standards and Codes are now the basis of fracture-mechanics methodologies used by Airbus and Rolls-Royce among others.

Some universities have described the impact their research has had in generating public interest in engineering or disseminating knowledge in schools. For example, research at Swansea into a computational aerodynamics design system, not only led to interest from BAE Systems, but also resulted in a large-scale education programme involving 5,000 schools. Another outreach programme is a toolkit for communicating materials research developed at the University of Manchester, which through use of 3D X-ray imaging and an exhibit at the Manchester Museum of Science & Industry has "engaged and enthused hundreds of thousands of members of the public." This successful attempt to stimulate interest in science and engineering was recognised by the RAEng through the award of its Nexia Solutions Education Innovation Prize.

4. Renewable energy

4.1 Introduction

We identified 19 REF Case Studies, from within the overall portfolio of 514 Case Studies, that make explicit reference to applications in the energy sector. In around half of those cases, the application areas include offshore wind.

The great majority of these 19 Case Studies have demonstrated a variety of different sorts of impacts and most have delivered measurable benefits in a range of industrial sectors, from aircraft to bridges, from power companies to consulting engineering and design organisations. Energy, and renewable energy, is typically just one area of application. Indeed, the cases derive from five UoAs 12, 13, 14, 15 and 16.

Notwithstanding this point about the degree to which each case is concerned only with renewables, the following bullet points give some sense of the spectrum of energy-related innovations made possible by this body of engineering research:

- Engineering design tools for various aspects relating to power transmission systems
- Engineering design tools for various aspects relating to renewable power generation, at device or system level
- Acoustics design and assessment methodologies / tools for application to environmental noise pollution (wind turbines)
- Design codes and standards for the use of engineering plastics in wind turbines
- Low-loss, lightweight transmission systems applicable to wind-turbines
- Network management (smart grids) systems for distributed generation
- Sensors for condition monitoring of wind turbines

4.2 Offshore Wind

In 2013, the UK had more offshore wind turbines operating than the rest of the world[1] with a 56% share of total installed capacity which equates to ~3.6GW installed capacity. Energy generated from offshore wind has risen rapidly to ~10.9TW in 2013, an increase of 45.8% compared with 2012, with load factors of over 37.5% achieved (for reference the load factor of gas is 27.9%)[2]. The UK is also home to the world's largest offshore wind farm; the London Array, capable of generating 630MW electricity; enough to power nearly half a million homes in the UK and create CO_2 savings of 925,000 tonnes a year[3]. Growth in offshore wind has been driven in large part by the UK Government providing unprecedented levels of price support to low-carbon power generation in the form of the Renewables Obligation and Contracts for Difference (CfDs).

To support the delivery of economic benefits from offshore wind by promoting innovation, investment and economic growth in the supply chain the UK government has issued the Offshore Wind Industry Strategy – Business and Government Action in 2013. The Government and Industry (*developers and suppliers*) are now working together in a newly formed 'Offshore Wind Industry Council' to drive and implement this strategy and to ensure the UK supply chain is in a strong position to deliver cost competitive, high quality energy with the highest possible

[1] BIS Offshore Wind Industrial Strategy (2013)

[2] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/170736/energy_trends_march_2013.PDF

[3] http://www.londonarray.com/the-project-3/

standards in health and safety, in order to compete globally and create a sustainable UK-based supply chain. By 2020, the UK will require billions of pounds of investment in new low carbon electricity generation plant to replace plants that are coming towards the end of their lifetime and investment in low carbon electricity generation such as offshore wind is essential to not only meet demand, which is growing, but also to help the UK to achieve its legally binding greenhouse gas emission targets.

The compilation of REF case studies relates most clearly to two aspects of the UK's Offshore Wind Industrial Strategy, which is supporting innovation and boosting market confidence. The other three priority areas are less relevant, albeit many of the case studies are making indirect contributions to skills and supply chains. For reference, the five headline priorities are as follows:

1. Providing market confidence and demand visibility
2. Building a competitive supply chain
3. Supporting innovation
4. Finance
5. Building a highly skilled workforce

The cases include multiple examples of product and process innovations, new businesses as well as several policy impacts.

The following sections present each of the case studies in a series of mini-tables the content of which is extracted directly from the impact summary section of each of the REF Impact Case Studies. Each mini-table has a final row with our 'tagging' of the case, as regards its application area and the types of benefits realised.

4.3 Case study extracts

ID4
UoA13 - Electrical and Electronic Engineering, Metallurgy and Materials
Aston University
From the lab to wind turbines and beyond ... the global commercial impact of Astons fibre Bragg grating research
Aston's fibre Bragg grating research on optical sensing has had a global commercial impact, in particular the development of low-cost fibre FBG sensor interrogation methods. The work has been carried out with a diverse range of companies (including BAE Systems, Airbus, Insensys, Schlumberger) working across different sectors including oil and gas, aerospace and marine. Specific impacts include the acquisition of 70% of the stock of Insensys Wind for US$15.7 million by Moog in 2009 and continuing employment by Smart Fibres, Moog Insensys and Astasense.
Photonics: Low-cost optical sensor that monitors condition of structures, and is able to work with vibrating structures (like wind turbines) that other sensors struggle with Process innovation Spinoff company / IP leading to jobs and income

45
14 - Civil and Construction Engineering
University of Bradford
Sustainable strategies for noise mitigation through improved assessment of noise impact and enhanced design of noise barriers
Research at the University of Bradford has resulted in more accurate and efficient predictions of traffic sound propagation and faster determination of sound reflection effects, enabling more effective design and positioning of noise barriers. Software derived from our research is used in 40 countries to map traffic noise and plan evidence-based targeting of Noise Reduction Devices (NRDs), thus increasing efficiency and sustainability. Beneficiaries include the public, through improved quality of life from reduced noise pollution from transport and wind turbine sound, and governments and public administrations through policy tools to influence noise management. The reach of our research is demonstrated by its incorporation into national and EU-wide policy and guidance on sustainability in design and use of NRDs.

Noise abatement – software tool used to design / position noise barriers, which has been used for wind turbines Process innovation Spinoff company and jobs / growth associated with sales of licences for tool

95
12 - Aeronautical, Mechanical, Chemical and Manufacturing Engineering
Imperial College London
1. Standards for the Application of Materials in Industry
Impact on industry, academia and government institutions from engineering materials research in the Mechanical Engineering department has been delivered through it directly leading to UK, USA and International Standards and Codes relating to three themes: Predicting and assessing the service life of high-temperature components. Determining the fracture resistance of plastics, composites and adhesives. Predicting the catastrophic failure of plastic pipelines. The results of the research of staff in this unit have led directly to UK, US and International Standards and Codes: ASTM Standards E1457-07 (2012) and E2760-10 (2012); R5 EDF Energy Code of Practice (2012); BS 7910 (2013); ISO 25217 (2009); ISO CD 15114 (2011) and ISO 13477 (2008). These documents all cite peer-reviewed publications by staff from this unit. These Standards and Codes are now the basis of fracture-mechanics methodologies used by leading engineering companies like Airbus, EDF, E.ON, GKN, Rolls-Royce and Vestas, whose commercial success depends upon technological leadership. In this way our research has led to savings by UK industry of many millions of pounds, as detailed in Section 4.
Design standards / codes for use of plastics etc. Used in offshore wind, but not a major focus

99
12 - Aeronautical, Mechanical, Chemical and Manufacturing Engineering
Imperial College London
5. Successful Commercialisation of Advances in Computational Fluid Dynamics
Computational Dynamics Ltd, partnering with adapco and trading as CD-adapco www.cd- adapco.com is the world's largest independent CFD-focused provider of engineering simulation software, with major products STAR-CD and STAR-CCM+. It was formed by Professor David Gosman and Dr Raad Issa and its turnover has grown more than 30 fold since 1993 and by over 250% since 2008 to currently around $190M pa. It employs around 750 staff, of whom roughly 80 are located in the London office. The company won a Queens Award for Exports in 1997. Key technologies that underpin this growth were developed since 1993 in the Mechanical Engineering department at Imperial College. CD-adapco has over 7000 users of its software, working at 3000 different companies. It makes a major contribution in maintaining the competiveness of UK industry via improved understanding and design and lower costs through the reduced need to undertake expensive experimental studies.
Engineering design – new CFD software tool Startup company with very impressive growth But not specifically developed for energy applications, although tool has been used

117
13 - Electrical and Electronic Engineering, Metallurgy and Materials
Imperial College London
Case 5 - Design and optimisation methods for power networks impacting industrial strategies and government policies
The Power Systems research team at Imperial made pivotal contributions in the design of power transmission networks, the equipment within these networks, and non-conventional electricity systems. Since 2008, the impact of their research has been to: I2) support the Fundamental Review of Supply Quality and Security Standards; I1) influence government policies by contributing to House of Common Select Committee (2010); I3) assist National Grid in defining new investment affecting 3bn worth of network assets now approved by the regulator (2013); I4) provide tools to develop the first offshore networks design standards in 2008, saving an estimated 500m by 2013 to date and a projected overall saving of 1-2bn by 2020; I5) advance Alstom's design concept for next generation HVDC converter stations for offshore wind connection from TRL 1 in 2009 to TRL 4 in 2013 supported by 3 new patents; I6) enable UK Power Network to plan network investment of 1.18bn and make savings of 130m (2013) through applying new technologies and demand response; I7) facilitate a scheme for off-grid energy kiosks for electrification in rural Africa yielding social gains and a business opportunity.
Renewable energy – design tools for high power DC transmission networks

123
14 - Civil and Construction Engineering
Imperial College London
1: New design methods from piling research that improve the foundation safety and economy of offshore structures
The Imperial College Pile ICP effective-stress pile design approaches for offshore foundations offer much better design reliability than conventional methods. Their use delivers substantial economies in many hydrocarbon and renewable energy projects, better safety and confidence in developing adventurous structures in others. The ICP has enabled production in otherwise unviable marginal hydrocarbon fields, new options in high-value deep-water projects and helped eliminate installation failures that can cost hundreds of million. We present evidence that the research delivered direct benefits exceeding 400m since 2008 in projects known to us, with larger worldwide benefits through project risk reduction and independent exploitation.
Energy / offshore structures

170
13 - Electrical and Electronic Engineering, Metallurgy and Materials
University of Sheffield
International commercial impact from the creation of the spin-out company Magnomatics Ltd.
Research in the Department of Electronic & Electrical Engineering at the University of Sheffield has generated economic impact through the creation of a spinout company, Magnomatics Ltd, commercialising high performance electric drives, in particular those employing magnetic gearing technologies. Magnomatics employs 35 full-time staff, had a turnover of 1.4M for the year 2012, and its technologies are now being developed for applications in utility scale wind turbines, hybrid vehicles and marine propulsion.
Energy - high performance electric drive suitable for large wind turbines Startup … In July 2006, Magnomatics Ltd was spun-out from the University of Sheffield in order to commercialise the high performance electric drives employing magnetic gearing arising from the research at Sheffield. Magnomatics is now recognised as a world leader in magnetic gearing- based products and services, and has a worldwide customer base, mostly large multinationals and governments. Magnomatics Ltd : Currently employs 35 full-time staff. Had a turnover of 1.4M for the year 2012. Had a total investment of 3.4M, with a latest investment of 2.5M was completed on 16th November 2012. The purpose of the investment is to enable Magnomatics Ltd to complete the development of its technology for the electric/hybrid vehicle markets. As stated in the FP7 Work Programme 2012, for wind turbine applications, the pseudo direct-drive is now recognised as an innovation which can have a major impact on large wind turbine head mass. In theme 5, Energy [S8], the pseudo direct-drive is specifically mentioned as one of the major innovations which should be investigated for future 10MW-20MW wind turbines. Magnomatics Ltd, together with Siemens Wind, Ramboll Group, Gamesa and other academic partners which include the University of Sheffield are currently partners on an EU funded project, investigating the feasibility and design of light weight 10MW-20MW future wind turbines. In 2013, Magnomatics Ltd has received a 1M grant from the Regional Growth Fund, in order to further the development of its magnetic transmission systems, such as the magnetic CVT and the high-torque PDD, and create 41 new jobs by 2015 [S9].

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13 - Electrical and Electronic Engineering, Metallurgy and Materials
University of Southampton
13-07 Reliable Cable Systems for Energy Security
The supply of electrical energy to centres of demand is an increasingly important issue as our power generation sources decarbonise. Without innovation in our use of high voltage cables, security of supply to our major cities cannot be guaranteed. Our research has: Identified how outdated international standards governing the rating of power cables can undermine network performance. Developed improved rating methods which will save National Grid 1.2 million annually. Informed new international technical guides. Designed, in conjunction with major industrial partners, cables that optimise transmission for lower operational costs, minimise the risk of network failure and cut carbon emissions.

Energy – reliable cable systems Not clear that it has much to do with renewables

196
15 - General Engineering
University of Southampton
15-02 Dezineforce - pioneering cloud computing
Cloud computing is now used ubiquitously in consumer and commerce domains yielding unprecedented access to computing and data handling at affordable prices. Work in this field was pioneered at the University of Southampton (UoS) from 1998 onwards and commercialised from 2008 through Dezineforce to enable companies to exploit cloud computing in engineering: The technology was applied in industries including aerospace and defence, energy, civil engineering and automotive. For small companies, we successfully demonstrated access to computing power and enhanced design tools delivered via the Cloud. e.g. Intelligent Flow Solutions used our tools to develop an innovative Wind Turbine Farm design with an increased lifetime return of over 55 million compared to alternative arrangements. Large companies benefited from more efficient ways of collaborative working and advanced design search/ optimisation technologies, which had not been possible before. For example Arup achieved a 1 million+ figure saving on a stadium design in the Middle East. The IP was sold to Microsoft in 2011 with staff moving to roles in Microsoft's Azure Cloud/ senior teams. Throughout this period the team has also engaged in outreach to inspire and educate the next generation of scientists and engineers about High Performance and Cloud computing including a YouTube video with 485,000 hits and over 300 articles in media.
Engineering design tool delivered through the cloud. Has been used in renewable area, but nothing obviously specific to energy as opposed to other areas of engineering design Startup company launched but appears to have ceased trading IP sold to Microsoft

209
15 - General Engineering
University of Southampton
15-31 Micro-Wind Turbines: Field Trial And Policy Impacts
The University of Southampton's research into micro-wind turbines, small-scale devices for generating electricity at the point of use, has been instrumental in the shift away from turbines mounted on buildings in urban areas to more productive pole-mounted devices in the countryside. It has informed public understanding of the potential and limitations of micro-wind power, and helped inject a new realism into the process of micro-wind power generation, forcing manufacturers to retreat from claims that could not be met. The research has been used to help set government subsidy levels for micro-wind power, and as a basis for modelling projections of future energy.
Renewable energy - Micro windpower (evidence about appropriate types of sites for micro-wind, and the problems with siting on buildings) Part of the evidence used by DECC to switch for installation grants to a feed-in-tariff, and also used to set the tariff levels for micro-wind

258
15 - General Engineering
Cardiff University
Acoustic Emission Monitoring -Transforming the Inspection of Bridges
Cardiff University's research in acoustic emission monitoring and refined data analysis has been applied to large, complex structures and has subsequently transformed the inspection processes of concrete and steel bridges. This has been commercialised by Mistras Group Ltd. to provide a safer, more reliable and progressive means of bridge monitoring, enabling the company to acquire a global reputation and increase its turnover to 7.5M per year -5M relating to Cardiff research. Cardiff's innovations have had major international impacts (in UK, Europe, India and USA) through: x Significant economic gain; x Enhanced industrial practice; x World-wide dissemination to engineering professionals; x Prevention of serious safety risks to society; x Markedly reduced CO2 emissions and reduced negative effects on regional economies.
Acoustics – not renewables or energy

263

7 - Earth Systems and Environmental Sciences
Manchester Metropolitan University
Offshore Renewable Energy Deployment
Examples are provided of significant impact by the Centre for Mathematical Modelling and Flow Analysis (CMMFA) upon the Marine Renewables and Offshore Wind communities. In particular, CMMFA informed the design of a novel wave energy converter being commercialised for connection to the national grid. CMMFA has also contributed to a study of the design parameters for an offshore wind power station as part of a larger interdisciplinary collaborative research effort. This work responds to and informs the RCUK Energy Programme via underpinning research, capacity building and provision of trained personnel thus enacting UK Government Energy Policy.
Marine renewables – design tool for wave energy

277
13 - Electrical and Electronic Engineering, Metallurgy and Materials
Newcastle University
Development of an open network communication protocol standard
Research during the 1990s at Newcastle University resulted in the development of CANopen (Control Area Network open), a manufacturer independent communication protocol for connecting multiple devices used in industrial systems. It has resulted in opening up the market by providing the platform for a low-cost simplified method of connecting off-the-shelf devices to communicate effectively over a network, benefiting the global economy and inspiring innovation. The significance of the impact is evident by the wide incorporation of the technology in a diverse range of products ranging from health care, automotive, renewable energy, rail and aerospace industries. The reach of the impact is evident by its use in product development by national and international companies and is the de-facto European standard EN 50325-4 (CiA 301).
Network communication protocol Has supposedly been used in the renewable energy sector, as well as multiple other sectors

306
15 - General Engineering
Edinburgh Research Partnership in Engineering ERPE (Heriot-Watt/Edinburgh)
Low Loss Hydraulic Power Transmission for Wind Turbines
This addresses improvements in the design of hydraulic transmission systems, for vehicular and renewable energy generation systems, by replacing the mechanical gearboxes to reduce their significant energy losses. This ERPE design of novel digitally controlled hydraulic transmission systems has culminated in the licensing, manufacture and production of high efficiency hydraulic gearboxes, now registered as the Digital Displacement (DD) patented technology. This novel technology enabled the formation of the spin-out company Artemis Intelligent Power Ltd., with 30 staff in 2008, which was acquired by Mitsubishi Heavy Industries Ltd., in 2010, enabling the growth to 50 employees today.
Low Loss Hydraulic Power Transmission for Wind Turbines Patented technology Spinout

361
16 - Architecture, Built Environment and Planning
University of Salford
Applied Acoustics in the built environment and its broader uptake
Applied acoustics in the built environment and its broader uptake is focused on the development and commercial adoption of techniques and technologies resulting from research in applied acoustics, demonstrating the following impact: Developing standard methodologies in the areas of Rain Noise, Building Envelope design, Low Frequency Noise, Structure-borne Sound, Surface Acoustic Diffusion and Multi-porous materials; The adoption of standard practice in local and national government bodies in the UK and internationally, in test houses, the construction industry, consultancies and extending into automotive and aerospace industries; Commercial application of technologies deriving from the research in reducing environmental noise, improving environmental and performance acoustics, bringing economic and environmental benefit.
Acoustic research leading to new design guidelines to reduce environmental noise, relevant to very many applications including wind turbines

362
15 - General Engineering
University of Aberdeen
MW size DC/DC converters and DC circuit breakers
The power systems laboratory at the University of Aberdeen has developed new converter topologies that have applications in connecting MW size DC power sources with DC transmission/distribution grids. These converters resolve very challenging questions of fault isolation on high-power DC networks. Scottish Enterprise funded a proof of concept project which developed a prototype, and confirmed the feasibility for various applications with interconnecting renewable power sources. Impact from the research is ongoing. Initial impact has been on public policy and services, where policy debate has been informed by our research evidence; and where decisions, regulations or guidelines have been informed by our research. Impact has also been generated for practitioners and professional services, where both a professional body and a company have used research findings in the conduct of their work, their practices have changed, and new or improved processes have been adopted as a direct result of research findings. The technology has attracted the attention of George Adamowitsch, European Coordinator for the working group for offshore and onshore grid development. He has described the Aberdeen research in his annual report to EU parliament in 2010, and the lead academic, Professor Dragan Jovcic, now sits on the Working Group for onshore/offshore grid development, developing plans for the European DC supergrid. In addition, this research has contributed to Working Group B4.52 of the International Council on Large Electric Systems (CIGRE), and their major technical brochure "HVDC Grid Feasibility study". Finally, the research has been analysed by the French power company RTE (Reseau de Transport d'Electricite). As a result of the research findings the company has adapted their approach to the planning of major offshore wind farm developments, resulting in a re-definition of the company research and development strategy.
Design of new topologies for high power DC electricity grids, which is applicable to offshore power generation including wind

435
12 - Aeronautical, Mechanical, Chemical and Manufacturing Engineering
Strathclyde University
Guidelines and standards which improve design and safety of marine structures subject to steep wave impact
Guidelines and standards underpinned by Strathclyde research have improved the design, assessment and the safety of marine structures subjected to wave impact in large steep waves. The guidelines and standards are widely used in the design of floating structures, particularly Floating Production, Storage and Offloading vessels (FPSOs) and offshore wind turbines. Since January 2008 the work has impacted the design, strength assessment and failure analysis of fixed offshore oil and gas platforms, renewable energy devices and ships. The guidelines and standards are used by designers to mitigate against damage caused by breaking wave impact, thereby improving the safety of mariners and offshore workers, reducing lost production due to downtime, and cutting the risk of environmental impact due to oil pollution. The research has also been used by Strathclyde researchers in industry-focussed studies, in legal work related to the loss of the oil tanker Prestige (2009-2013), in the assessment of the Schiehallion FPSO for BP (2010), and design of a Scottish harbour wave screen (2009) that allows ferries to access and stay in the harbour in more severe weather.
Design guidelines for marine / offshore structures, including floating wind turbines Process innovation

442
XXX - STRATHCLYDE (manually typed)
13 - Electrical and Electronic Engineering, Metallurgy and Materials
Strathclyde University
Economic and environmental benefits from adoption of active power network management scheme
Research at the University of Strathclyde directly produced the following impacts from 2008 onwards: 10 wind farms (17 MW aggregate capacity) connected to the Orkney power network from 2009 to 2013 with accompanying economic and environmental benefits; Orkney power network reinforcement deferral saving of £30M from 2009 with repeat deployments of Active Network Management (ANM) technology in other UK power networks; spin-out company formed in September 2008 with total revenues to date of £6.1M, equity investment totalling £3.5M and 35 FTE jobs created; provision of new power system options for long term network plans impacting the 2013 investment decisions in distribution network companies; contribution to the emerging Smart Grid business sector in the UK and overseas from 2008.

Development of a network management tool (Smart Grid technology) that is necessary in situations – like with renewables – where power generation is highly distributed and variable Smart Grid technology for renewable energy A university spinout - Smarter Grid Solutions, headquartered in Glasgow

506
722 Ref3b_CaseStudy-106.txt
14 - Civil and Construction Engineering
University of Manchester
Accelerated development of a tidal stream energy industry
Our research has been key to the development of investor confidence in an emerging UK tidal stream industry. We have contributed to the development and validation of commercial and open- source software for tidal stream system design and our expertise has been instrumental to the successful delivery of major objectives of two national industry-academia marine energy projects commissioned by the Energy Technologies Institute (ETI). Taken together, these outcomes have reduced engineering risks that had been of concern to potential investors. Investor confidence in tidal energy has been increased, as highlighted by Alstom's 65m acquisition of a turbine developer following a key outcome of the ETI ReDAPT project.
Renewable energy Software design tool Investor confidence / market development

5. Engineering research in the NHS

In this case study, we present an overview of a selection of the many examples of contributions of the UK's Engineering research to the life sciences sector and the National Health Service (NHS) in particular.

As the name suggests, the National Health Service (NHS) provides healthcare for the whole country. It is one of the largest organisations in the world employing around 1.7 million people across 8,000 GP practices and 2,300 hospitals.[4] It has a profound impact on the nation's quality of life. It is financed primarily through general taxation and national insurance, and with annual expenditure of around £100 billion, and growing, the health service is a major point of pressure on public finances. The cost to the exchequer is forecast to grow steadily over the next 20 years, driven by a number of external factors (sometimes linked) such as the ageing population and the rise of chronic conditions such as diabetes, obesity and dementia. The government has launched numerous institutional reforms in response to these evident challenges, however, it is generally accepted that success will also need major advances in medical technology and healthcare. Research-enabled innovation has a vital role to play.

The UK Life Sciences Strategy (2011) highlighted the importance of strengthening the collaboration between universities and industry to undertake world-class translational research as well as the need to encourage the adoption and diffusion of innovations in the NHS[5]. This shift aims to leverage the use of technology with the objective of increasing productivity and ensuring better value-for-money for the taxpayer, while at the same time improving health outcomes and the quality of care.

Analysis of the 514 REF Impact Case studies provides insight into the nature and extent of the actual contributions of engineering research, conducted in the UK university system over the past 20 years, to innovation in the health and life sciences. Our analysis of this large sub-set of

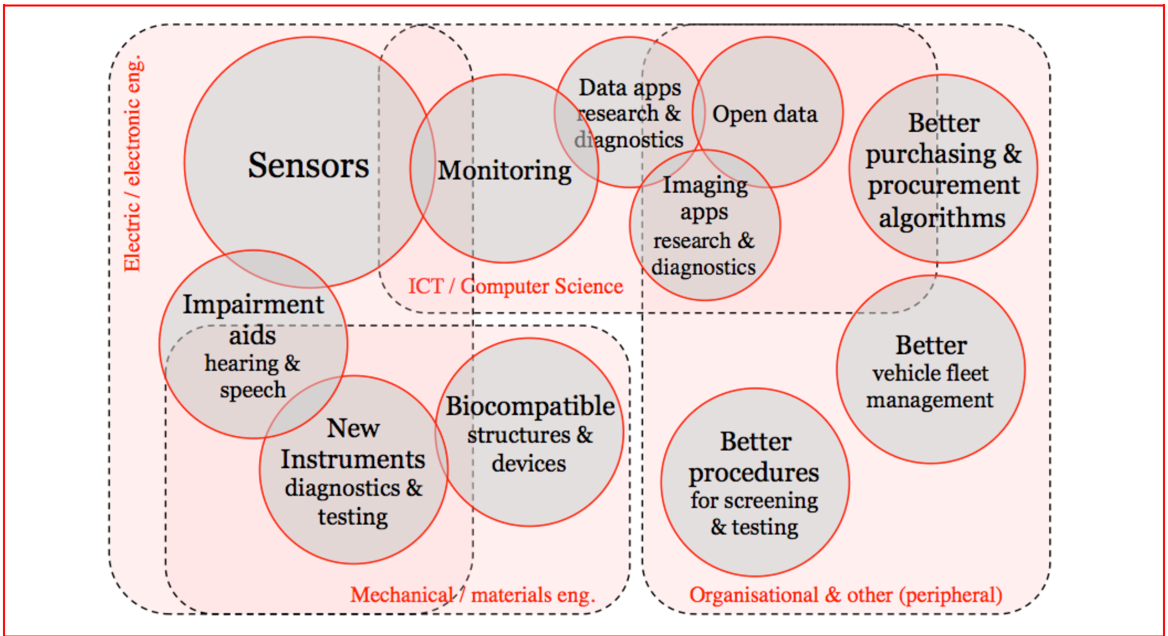
[4] NHS Confederation, key statistics on the NHS. Available at: http://www.nhsconfed.org/resources/key-statistics-on-the-nhs

[5] Department for Business, Innovation & Skills and Office for Life Sciences. UK life sciences strategy. December 2011. Available at: https://www.gov.uk/government/publications/uk-life-sciences-strategy

all REF 2014 engineering case studies found that around 27% cited applications within the medical and healthcare field.

Using keyword search strategies, we have been able to characterise and cluster those individual impact examples in order to map the demonstrated impact on the NHS in a series of interrelated technological fields or domains, which are underpinned by one or several engineering disciplines (Figure 25), with the size of the circle approximately showing the number of REF case studies.

Figure 25- Main thematic fields in selected REF 'healthcare' impact case studies



Source: Technopolis (2014)

Our analysis echoes the rather more expansive and erudite findings of an independent review group, chaired by Professor Patrick Maxwell, Head of the School of Clinical Medicine at the University of Cambridge, which produced a fascinating and persuasive account of the importance of engineering and physical sciences research to advances in the health and life sciences.[6] The two analyses both reveal the important contributions of engineering research to the health and life sciences; Professor Maxwell's work also looks to the future and suggest the intersection of EPS and HLS will become very much more important in the coming years.

Sensors

Research in sensors provides many opportunities to enhance current diagnostic techniques and medical devices and instrumentation. For example, research undertaken at City University London led to the development of new blood oxygen sensors that are able to monitor blood perfusion (the flow of blood through body tissues) in situations where current techniques fail to work. These developments speed up clinical assessment in hospitals and provide more reliable information at organ-level and in very sick patients, helping clinicians better diagnose problems and monitor the response to treatments. These sensors were piloted at the NHS (St Bartholomew's Hospital, Great Ormond Street Hospital for Children and St Andrew's Centre for Plastic Surgery and Burns) and are still in use there in further clinical trials, having already attracted interest from the main medical devices manufacturers.

The University of Glasgow has also contributed to this area with Lab-on-a-chip technologies that deliver enhanced tools for the diagnostic screening of chronic diseases, the detection of acute

[6] The importance of engineering and physical sciences research to advances in the health and life sciences, report of the Independent Review Group chaired by Professor Patrick H Maxwell FMedSci and commissioned by the EPSRC. http://www.epsrc.ac.uk/newsevents/pubs/the-importance-of-engineering-and-physical-sciences-research-to-health-and-life-sciences/

infections and for improving the process of drug discovery. These innovations are being further developed since 2008 by three spin-out companies, Mode-Dx, Clyde Biosciences and SAW-Dx, having secured strategic collaborations with the NHS amongst others.

Body Sensor Networks (BSN) research, carried out in Imperial College London, aims to develop novel sensing algorithms and technology suitable for on-body pervasive sensing suitable for healthcare, using ear-worn activity recognition (e-AR) devices. These devices allow clinicians to monitor and profile a wide variety of patient outcomes post-operatively, in order to create a platform for remote patient surveillance and early detection of complications. This technology is being used in clinical trials within the Imperial College Healthcare NHS Trust, including three trials that have been recognised and adopted by the NIHR portfolio for further support, and has been used by more than 100 patients since 2008.

The University of Strathclyde has contributed to the development of moisture sensors used in non-invasive wound monitoring systems. The system, commercialised by the university's spin-out Ohmedics Ltd under the name WoundSense™, gained the CE mark in 2010 and made its first sales to the NHS in 2012. The system was piloted for use with remote monitoring technology and is currently being trialled by the British military for monitoring complex trauma wounds.

Swansea University has also developed new haematological techniques to improve detection of abnormal blood clotting. Commercialisation of the research began in 2005 and generated new diagnostic technology developed and trialled with patients at NHS Hospitals, with a dedicated NHS hospital-based unit established for this purpose and three new companies created based on IP related to this invention. The tests of this technology at the NHS reveal that this was the only diagnostic presently capable of detecting abnormal clots in patients who appeared fully anticoagulated when tested by the current standard assays. This test has been used to target care pathways involving over 900 NHS patients at 2 hospital sites to date (covering stroke, sepsis, diabetes and cancer patients).

Finally, the University of Bristol is using its research in the area of antennas to develop novel breast cancer imaging techniques that are at the same time cheaper to carry out and more comfortable for women. A clinical trial on 100 patients was done at an NHS Breast Care Centre and Micrima, the university spin-out company set up to exploit these developments, has already received £3.3m of investment and a commitment for a further £2m from a leading medical imaging company.

ICT

Together with sensors, ICT and Computer Science applications have an ever-increasing importance in generating positive impacts in the health field. Among the main developments are those based on data initiatives for research and diagnostics. For example, Aston University developed the Galatean Risk and Safety Tool (GRiST), a clinical decision support system to assess and manage risks associated with mental-health problems. The tool was commercialised in 2000 and has been further developed over time and is now delivered as a cloud computing service to mental-health practitioners in charities and the NHS. The tool has changed organisational and clinical processes by systematically collecting risk information, and linking it to clinical risk judgements.

Open data

Open data and applications (apps) based on 'big data' are used for improving the organisational efficiency, service provision and other peripheral aspects of the NHS outside direct patient care, which are equally important to the service's efficiency.

For example, University of Southampton played a pivotal role in launching the UK's Open Data Institute (ODI) in 2012, where one of its start-ups, Mastodon C, identified potential annual savings of £200m for the NHS by analysing drug prescription practice.

In addition, the University of Reading is researching intelligent systems incorporating automatic classification and carbon footprinting for corporate e-Procurement. These techniques have already been piloted in some NHS Trust Foundations, where they have helped save hundreds of thousands of pounds by changing procurement behaviours.

In the area of demand planning and service provision, research conducted at the University of Surrey, together with support from clinicians in Cambridge, has resulted in new algorithms to model the demand of cancer treatments. One of these models, Malthus, is now used by the NHS to predict demand for radiotherapy across England and Wales and to review / justify purchases of new equipment. Since GP commissioning of cancer services was abandoned in favour of central commissioning, it is very important that such a tool exists to accurately predict the future demand for radiotherapy regionally and nationally. As a result, Malthus contributes to a nationally-agreed and systematic way of ensuring that patient location does not have a negative impact on equal access to facilities for treatment (the dreaded 'postcode lottery').

Imaging techniques

Imaging techniques are also used in enhancing diagnostic procedures and improving the follow up of treatments. Researchers at Aston University developed several Machine-Learning based Visual Analytics algorithms that are used to develop new clinical metrics (for example, a better replacement to the widely used Body Mass Index) as well as optical measurement devices for blood glucose. These developments will bring improvements to the diagnostic of vascular diseases and make the treatment of diabetic patients more comfortable. Both developments have been in trials in the NHS and support is being provided to develop improved versions.

Imperial College London has developed improved Biomarkers using Quantitative Image Analysis techniques. Their spin-off company, IXICO, is commercialising these developments, now routinely used in clinical trials and starting to be used in healthcare diagnostics for dementias such as Alzheimer. Some of these developments have undergone trials involving 200 patients as part of new NHS brain health centres.

University of Birmingham has developed image analysis methods to provide rapid and non-invasive quantification and assessment of skin histology in cancer (SIAscopy or Spectrophotometric Intracutaneous Analysis). Large NHS trials in the 2008-10 period showed that GPs trained to use SIAscopy were better equipped to recognise suspicious lesions, with higher diagnostic accuracy and reduced assessment time, increasing the cost-effectiveness of the overall procedure.

New materials

Engineering research is also helping to develop innovative new materials and devices with a direct positive impact in the treatment and wellbeing of patients.

The Institute of Medical and Biological Engineering (IMBE) at the University of Leeds developed and contributed to the commercialisation of regenerative biological scaffolds which regenerate with the patient's own cells and are used for soft tissue repair.

These implants have demonstrated five years of successful clinical use in heart valve replacement and three years clinical use as commercial vascular patches. These developments have been commercialised via the spinout Tissue Regenix plc.[7] Further developments are underway in acellular biological scaffolds for dermal repair and in cardiac patches, acellular heart valves, vascular grafts and ligaments.

University College London also has developed a non-invasive growing prosthesis for young patients that have suffered from certain bone cancers. The prosthesis avoids costly and invasive surgical interventions of previous treatment and subsequent painful lengthening procedures. Bone reconstruction and growing costs are reduced by around £19k per patient, taking into account NHS current practice, as well as reducing the risk of infection and subsequent treatment. UCL's Centre for Biomedical Engineering spinout company Stanmore Implants Worldwide, acquired in 2008 for more than £10M when it had sales of £4M+,[8] has sold more

[7] Tissue Regenix was incorporated in May 2006 to commercialise the academic research of Professor Eileen Ingham and Professor John Fisher from the University of Leeds in the field of tissue decellularisation. Its dCELL® Technology comprises a patented process which removes cells and other components from human and animal tissue allowing it to be used without anti-rejection drugs to replace worn out or diseased body parts.

[8] http://www.ucl.ac.uk/media/library/Stanmore

than 400 devices. This new procedure saves around £10m per annum, not including other savings in terms of in-patient care and rehabilitation.

University of Southampton has used its pioneering research in acoustics of gas bubbles in liquids to develop a myriad of applications in different areas, one of which is healthcare. Some of their most notable results are: new needle-free injectors to treat migraines (with over 1 million units sold); and new sensors developed in collaboration with the NHS and used on over 200 patients undergoing kidney treatment (reducing 'patient pathways' within the system and issues such as re-treatments and overdoses). In addition, researchers at the university have also co-authored the current guidelines used for every foetal ultrasonic scan in the world since 2008 (around 700m births).

In the UK, about 1% of the adult population suffers from venous ulceration in their legs. The cost of the treatment to the NHS is around £650m per year, around 1-2% of the total healthcare expenditure. The University of Bolton has developed a novel compression therapy system for the prevention and treatment of these ulcers and a unique pressure-relieving cushion to reduce pressure sores with specific applications for wheelchair users. Baltex Ltd has licensed these developments and produces a commercial product for the global medical device company BSN medical. Revenues of Baltex Ltd are expected to ramp up in the following years and to achieve an impact in the public health system.

This case study has highlighted the contributions of recent engineering research carried out at UK's Universities to innovations in the field of life sciences in general and to improving the NHS in particular. The main outcomes of engineering research are clustered around different areas of activity, ranging from the development of new instrumentation, sensors and medical devices, to the advances possible with the use of data, ICT tools and computational resources. Together with other multidisciplinary developments and with research carried out entirely in the medical and biotechnology fields, all these developments contribute towards addressing the challenges towards the future sustainability of the NHS as well as towards solving the societal challenges posed by diseases and the ageing of populations. Their impact going forward in the system will improve health outcomes as well as provide better value-for-money for the taxpayer. Moreover, the associated creation of new intellectual property, businesses and high-value employment is another decisive contribution towards putting the UK life science industry at the forefront of global competitiveness.

6. Centres for Doctoral Training (CDT)

6.1 Postgraduate training

The EPSRC invests around £800 million annually on research and postgraduate training from areas ranging from information technology to structural engineering and mathematics to materials science. They aim to increase the number of world leading scientists and engineers working in the UK in order to keep the UK at the centre of global research and innovations. To do this, the UK needs to meet a growing need for postgraduate skills. The EPSRC has a long history of providing support for doctoral training primarily through CDTs but also by funding Doctoral Training Grants and Industrial CASE Studentships. All three routes for support provide a student-centred approach that anticipates future need.

In 1992 the EPSRC launched five Engineering Doctorate (EngD) Centres. These evolved into Centres for Doctoral Training (CDTs). CDTs are designed to train engineers and scientists, using diverse areas of expertise, with the skills, knowledge and confidence to tackle present and future challenges. Students are funded for four years and provided with technical and transferable skills training which also includes a significant research component carried out in collaboration with industry (70%+). The training and environment provided is designed to be exciting for students, supportive, to enable the creation of new working cultures and to build relationships between teams in universities and to forge long-lasting links with industry.

Following a review of the Centres in 1997, five additional Centres were established. Further Centres were added in 2001 through the Life Sciences Interface Programme and in 2006 through the Science and Innovation Call, both of which were a response to meet particular areas of identified national need.

The success of CDTs has led to continued investment by the EPSRC and in 2009 45 new Centres were funded (this also included a number of Industrial Doctorate Centres, centres focusing on EPSRC priority areas and Centres in core EPSRC disciplines) and a further £500 million of funding for a further 115 Centres was announced in late 2013. This will be complemented by a further £450 million of support from the involvement of 1000 partners. Many of the Centres will involve research that connects to key industries and technologies important for innovation and growth.

6.2 UCL Bioprocessing Leadership Industrial Training Centre

The global Industrial Biotechnology market in the chemical and pharmaceutical sectors is expected to have a value of £150-£360 billion annually by 2025, with the UK positioned to capture a £4-£12 billion share[9]. In addition, biopharmaceuticals are the fastest growing class of new medicines with a market value forecast of £125 billion per year by 2020[10] and the cell therapy industry is predicted to grow to £3 billion by 2014 from sales of £267 million in 2008[11]. These rapidly expanding industries are currently limited in the UK due to a skills need substantiated in a series of Government Innovation and Growth Team reports and industry surveys, with bioprocess training a specific need identified. This is further reinforced by the European Commission, which has identified the requirement for 'one million new research jobs' if it is too remain globally competitive with particular skills shortages related to '*fermentation*', '*downstream processing*' and the '*challenges that arise with scaling-up production using biological materials*'[12]. The lack of high quality graduates possessing these fundamental bioprocessing skills is felt across the range of UK bioprocess-using sectors:

- Chemicals and Pharmaceuticals – 90% of companies are having difficulty recruiting appropriately trained graduates[13].
- Biopharmaceuticals and vaccines – '*the difficulties experienced by companies in recruiting…is widespread and is further exaggerated by the pull from overseas*'[14]
- Regenerative Medicine and Cell Therapy – there is a '*lack of translational research*' and an inability to manufacture sufficient cells for '*large-scale clinical trials*'[15]

The UCL Bioprocessing Engineering Leadership Industrial Doctorate Centre aims to support these sectors by providing high quality EngD graduates capable of exploiting new biomanufacturing opportunities emerging from recent advances in Synthetic Biology and from novel flexible and continuous bioprocess technologies. This IDC uses a centre-based approach to provide a critical mass of researchers to establish multi-disciplinary cohorts that facilitates cross-sector and peer-to-peer learning.

Students entering the scheme spend the first year studying for an MRes; comprised of 20% generic and transferable skills modules, 20% advanced training and 60% research project. In years 2-4 up to 75% of an EngD student's time can be spent with the company partner on their research project. In addition to this, they also take a number of advanced modules which relate to the topic of their project, transferable skills training, leadership and enterprise training and more recently, develop personal career development plans with an EngD mentor to oversee their implementation. Since it was established the IDC has supported 130 projects with the

9 BERR (2009), Industrial Biotechnology 2025 – Maximizing UK opportunities from Industrial Biotechnology in a Low Carbon Economy

10 BERR (2009), Review and Refresh of Bioscience 2015

11 Mason, C et al, 2011, Regen Med, 6:265:272

12 Europe 2020, http://ec.europa.eu/research/innovation-union/index_en.cfm

13 CIA Survey (2008), Chemical Engineer, Oct, 50-51

14 BERR (2009), Review and Refresh Bioscience 2015

15 Parliamentary Office (2009), POST NOTE 333: Regenerative Medicine

involvement of 66 different companies and 97% of graduates have taken up relevant industrial or academic appointments upon graduation and 91% of these appointments are UK-based and so directly benefitting the UK economy. This helps confirm the demand for EngD graduates with these skills and the relevance of the training and research undertaken.

In addition to contributing towards the UK's skills need, EngD research has also translated into quantifiable economic benefits for companies.

- A project run with BioVex helped to realize the manufacturing process for a complex virus product resulting in a US$1bn acquisition by Amgen.
- A project run with Protherics successfully used technologies developed at the IDC to halve product development time saving an estimated £200K and triggering a manufacturing stage payment of £10million.
- Projects run in conjunction with MedImmune have created jobs valued at £300k/year and allowed products to be launched 6 months early, equivalent to sales revenue of US$50-100M and a 5% cost of good reductions valued at £5M/year.

Furthermore, EngD research has had a significant impact on sponsoring companies in terms of IP generation, knowledge transfer and improved operational efficiency and four spin-out companies have also been formed to date; Puridify, Synthace, Darwin Toolbox and Algify.

6.3 Swansea University – COATED and COATED2 CDT

The UK has more than 4 billion square meters of roofs and facades with the potential to harvest solar energy and provide twice our electricity requirements using less than 1.8% of the UK land area to do so. This will lead to reductions in CO_2 output of up to 6 million tonnes per year and create new jobs in high-value manufacturing, whilst helping the UK to achieve its target of 15% of its energy consumption from renewable sources by 2020. To help the UK to achieve this target this it is important to rapidly develop and up-scale functional coated materials on steel and glass that will transform the roofs and walls of buildings into surfaces that generate, store and release energy.

An EPSRC / Innovate UK[16] /Industry funded centre has been set up to help meet this brief called the Sustainable Product Engineering Centre for Innovative Functional Industrial Coatings (SPECIFIC) Innovation Knowledge Centre (IKC)[17]. This is an academic and industrial consortium hosted and led by the University of Swansea with Tata Steel, Pilkington and BASF as strategic partners. SPECIFIC has been supported by an EPSRC Centre for Doctoral Training (CDT) and WEFO in Industrial Functional Coatings (COATED) set up in 2012 to run until 2014 which has provided research and training in the area of functional coatings that underpins the research and scale up activities of SPECIFIC. This has led to two commercial breakthroughs, patented by the IKC, which have come directly from COATED CDT researchers that can enable the mass manufacture of low cost hybrid organics photovoltaics (HOPV).

A newly funded CDT, COATED2, will extend and enhance doctoral training provision provided by COATED until 2018. This additional support is worth £2.5 million, provided by the EPSRC and will fund a further 40 EngD research engineers in four cohorts from 2015. In addition, the CDT will be expanded to support the EPSRC Centre for Innovative Manufacturing (CIM) in Large Area Electronics of which the Welsh Centre for Printing Coating at Swansea University is a key partner. The CIM will be key in the development of large scale printing process for the functional coating technologies that are being developed by SPECIFIC. The work of COATED research engineers will underpin both the recently funded EPSRC projects focused on the scaling up of functional devices.

[16] Formerly the Technology Strategy Board

[17] IKCs have been set up to nucleate new industries by closing the gap between scientific research and its commercial exploitation.

Students funded through COATED and COATED2 undertake four years of study with a taught component providing advanced theoretical training on coatings as well as providing students with the opportunity to develop business, entrepreneurial and communication skills, and a large, 4 year research project defined by industry. Research projects are embedded in the participating company's business plan and focus on existing industrial problems. Students are assigned an industrial supervisor responsible for steering the project as well as an academic supervisor based at the CDT.

Appendix B : Estimating economic impact

B.1 Broad economic sectors

Figure 26 – Information on SIC codes

Sectors	SIC 2007	SIC 2007 Definitions	UK GVA (2011) (£million)
High-tech Manufacturing	21, 26	• Manufacture of basic pharmaceutical products and pharmaceutical preparations • Manufacture of computer, electronic and optical products	£22,399
Computing & Telecommunications	61, 62	• Telecommunications • Computer programming, consultancy and related activities	£59,793
Med-High tech Manufacturing	20, 27-30	• Manufacture of chemicals and chemical products • Manufacture of electrical equipment • Manufacture of machinery and equipment n.e.c. • Manufacture of motor vehicles, trailers and semi-trailers • Manufacture of other transport equipment	£41,334
Med-Low tech Manufacturing	19, 22-25, 33	• Manufacture of coke and refined petroleum products • Manufacture of rubber and plastic products • Manufacture of other non-metallic mineral products • Manufacture of basic metals • Manufacture of fabricated metal products, except machinery and equipment • Repair and installation of machinery and equipment	£33,348
Utilities	35-39	• Electricity, gas, steam and air conditioning supply • Water collection, treatment and supply • Sewage • Waste collection, treatment and disposal activities; materials recovery • Remediation activities and other waste management services	£33,289
Construction	41-43	• Construction of buildings • Civil engineering • Specialised construction activities	£86,789
Business Services	68-75	• Real estate activities • Legal and accounting activities • Activities of head officers; management consultancy activities • Architectural and engineering activities; technical testing and analysis • Scientific research and development • Advertising and market research • Other professional, scientific and technical activities • Veterinary activities	£240,296
Finance & Insurance	64-66	• Financial service activities, except insurance and pension funding • Insurance, reinsurance and pension funding, except compulsory social security • Activities auxiliary to financial services and insurance activities	£116,363

Sectors	SIC 2007	SIC 2007 Definitions	UK GVA (2011) (£million)
Low-tech Manufacturing	10-18, 31, 32	• Manufacture of food products • Manufacture of beverages • Manufacture of tobacco products • Manufacture of textiles • Manufacture of wearing appeal • Manufacture of leather and related products • Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials • Manufacture of paper and paper products • Printing and reproduction of recorded media • Manufacture of furniture • Other manufacturing	£43,458
Media & Publishing	58-60, 63	• Publishing activities • Motion picture, video and television programme production, sound recording and music publishing activities • Programming and broadcasting activities • Information service activities	£28,242
Other Services	94-97	• Activities of membership organisations • Repair computers and personal and household goods • Other personal service activities • Activities of household as employers of domestic personnel	£25,730
Public Admin & Defence	84	• Public administration and defence; compulsory social security	£70,400
Agriculture & Mining	01-09	• Crop and animal production, hunting and related service activities • Forestry and logging • Fishing and aquaculture • Mining of coal and lignite • Extraction of crude petroleum and natural gas • Mining of metal ores • Other mining and quarrying • Mining support service activities	£40,818
Transport & Storage	49-53	• Land transport and transport via pipelines • Water transport • Air transport • Warehousing and support activities for transportation • Postal and courier activities	£59,179
Retail & Wholesale	45-47	• Wholesale and retail trade and repair of motor vehicles and motorcycles • Wholesale trade, except of motor vehicles and motorcycles • Retail trade, except of motor vehicles and motorcycles	£151,785
Education	85	• Education	£84,556
Arts & Entertainment	90-93	• Creative, arts and entertainment activities • Libraries, archives, museums and cultural activities • Gambling and betting activities • Sports activities and amusement and recreation activities	£20,410
Support Services	77-82	• Rental and leasing activities • Employment activities • Traveling agency, tour operator and other reservation service and related activities • Security and investigation activities • Services to building and landscape activities • Office administrative, office support and other business support activities	£62,126
Health & Social Services	86-88	• Human health activities • Residential care activities • Social work activities without accommodation	£104,026
Accommodation & Food	55-56	• Accommodation • Food and beverage service activities	£36,554
Total			£1,360,925

B.2 Field level impact economic assessments

'Assessing the economic returns of engineering research and postgraduate training in the UK' sits along other studies exploring the economic impact of the engineering and physical sciences (EPS), with studies having estimated the economic returns to research and training in each of three fields: chemistry, mathematics and physics.

The table below summarises the approach undertaken by the different field-level studies.

Field	Estimations	Method

Engineering
 	
"Assessing the economic returns of engineering research and postgraduate training in the UK"
 	
Technopolis, 2014
	£280 billion in direct contribution to UK GVA (20% GVA, 2011)	GVA calculations include:
		• GVA of economic sectors tightly linked to engineering such as high-tech manufacturing and computing & telecommunications (in this case we account for 100% of GVA in those sectors):
		  • Construction
		  • Computing & Telecommunications
		  • Med-High-Tech Manufacturing
		  • Med-Low-Tech Manufacturing
		  • High tech Manufacturing
		  • Architectural and engineering activities
		• GVA contribution of graduate engineers across all other others economic sectors (in this case the we account for a % of GVA in those sectors, based on the percentage of graduate engineers in relation to the total workforce as show in

Chemicals "The economic benefits of chemistry" Oxford Economics, 2010	£258 billion in direct contribution to UK GVA (21% GDP, 2007) for 'Chemistry-reliant industries'	The GVA calculations take into account the GVA generated by the 'Upstream' and 'Downstream' chemical sector • The upstream sector entails the chemical-producing industry and the estimates account for 100% of its GVA • The downstream (or enabled industry) includes 15 industries that are identified as 'chemical-using'. In this case the study team makes a 'qualitative' assessment of the extent to which the sector relies on chemicals for its production process. For instance, Aerospace: 100%, Automotive: 100%, Food & Drink:95%, Printing: 30%. • There are clear overlaps between the estimations for 'chemistry' and 'engineering'.
Physics "The importance of Physics to the UK Economy" Deloitte, 2012.	£77 billion in direct contribution to UK GVA (2010) by physics-based businesses Taking account of indirect and induced effects (through the use of standard multipliers), the total GVA contribution rises to more than £220 billion in 2010	• "Physics-based sectors are defined as those sectors of the UK economy where the use of physics – in terms of technologies and expertise – is critical to their existence, i.e. if there was no physics, these sectors would not exist" • Physics-based sectors include 74 classes (four-digit IPC code).

Mathematics
 	
"Mathematical science research. Leading the way to UK economic growth"
 	
Deloitte, 2012.
	£208 billion in direct contribution to UK GVA (16% GVA in 2010)	• "Mathematical sciences occupations were those which either entail maths or which directly require mathematics-derived tools and techniques"
		• The study follows three steps:
		  • Identify occupations directly involved in the generation and application of mathematics science research ('MSR occupations'). This includes from Financial managers & chartered Secretaries; to Management consultants, actuaries, economists & statisticians; and senior officials in national government
		  • Identify how these MSR occupations' were distributed across the 600+ sectors of the economy.
		  • Use UK Input-Output to calculate GVA attributable to MSR.

Appendix C : Text mining of REF case studies

Overview

Engineering research and training delivers many types of social and economic benefits that cannot easily be monetised and captured, case by case, within the overarching economic analysis. These benefits however amount to a powerful argument for the substantial and continued public support for engineering research and training. This study also aims to provide this qualitative insight, by means of a selection of success stories that complement the financial analysis.

The EPSRC sent a formal request to UK Universities asking them for the impact case studies that were submitted by each of the institutions to the UK's Research Excellence Framework (REF) and that showcased contributions of engineering research. REF impact case studies provide the basis for a wide-ranging cross sectional analysis, using text mining and semantic analysis tools, in order to be able to code the material and then carry out segmental analyses by type of research outcome / impact.

Each of the REF case studies follows a standard template, containing information on the institution, REF assessment panel, title, underpinning research, details of the impact and supporting sources and evidence. In order to sift through and extract valuable insights from this large volume of unstructured data we processed all the documents received using text extraction, text mining and semantic analysis tools. The set of case studies was then turned into a database form, and different classifications were added. This final resource comprises one of the outputs of this study, and has been used both to obtain a bird's eye view of the contributions of engineering research in the UK and to identify for this study a set of success stories that illustrate specific types of impacts in specific economic sectors. To this end, we devised an analytical framework (Figure 27) with three main dimensions of analysis that will allow us to classify and identify the relevant information.

Figure 27 - REF impact case studies: analytical framework

Economic Sectors	REF Units of Assessment	Impact Categories
• Aerospace and satellites • Automotive • Construction • Life Sciences • Wind power	• (11) Computer Science and Informatics • (12) Aeronautical, Mechanical, Chemical and Manufacturing Engineering • (13) Electrical and Electronic Engineering, Metallurgy and Materials • (14) Civil and Construction Engineering • (15) General Engineering • Others	• International and domestic increases in competitiveness and productivity • Importance of research-based skills • New or increased economic activity • Better provision of public services and support to citizens

Source: Technopolis (2014)

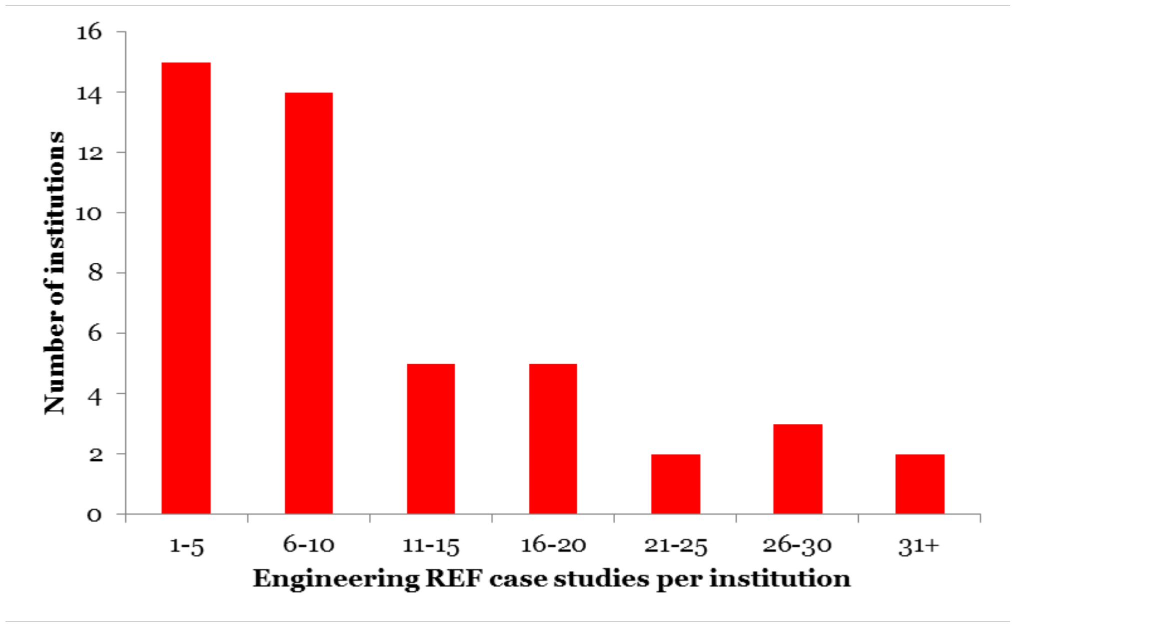
This analytical framework serves us to classify the case studies and to group those that are related in order arrive at a compelling set of engineering impact success stories for this study. Our selection makes sure that we have a good coverage across all the different dimensions, and each of them covers at least one or more of the elements in each dimension of analysis. Finally, we also carried out an identification of the companies involved in these case studies in order to understand which industrial players are most supported by the overall contribution of UK engineering research in the UK.

The REF Case studies

The response to the request for impact REF Case Studies related to engineering research was very positive. Up to 514 case studies were received from 46 different UK institutions. Each case study has a length of 5-7 pages, totalling more than 3,000 pages of high quality written material. It is important to remind the reader that researchers and institutions invest a great deal of time and care in the crafting of these case studies, as their evaluation influences part of the resources received from the Government by the institutions in the period following the REF assessment. The cases highlight some of the most notable achievements of engineering research in UK's universities during the past two decades and are properly referenced and backed by evidence. As a result, they can be safely regarded as a useful body-of-work that contributes to our assessment of the impact of engineering research carried out in the UK.

Figure 28 shows the distribution in the number of case studies received per institution. Institutions were given the freedom to select as many contributions as they wanted to send to the study team. More than half of them (29 out of the 46) selected between 1 to 10 engineering impact case studies for the study team to consider. Because of their size and focus on engineering disciplines, other institutions facilitated a larger volume of material to analyse, with three of them sending in 30 or more impact cases each. Confidentiality issues were one of the main reasons given for some institutions to decide not to participate or to only participate partially in this exercise. Also, some other institutions opted for providing redacted versions of the case studies with the most sensitive information removed.[42]

Figure 28 – Number of Engineering REF Case Studies per institution (frequency)



Source: Technopolis (2014)

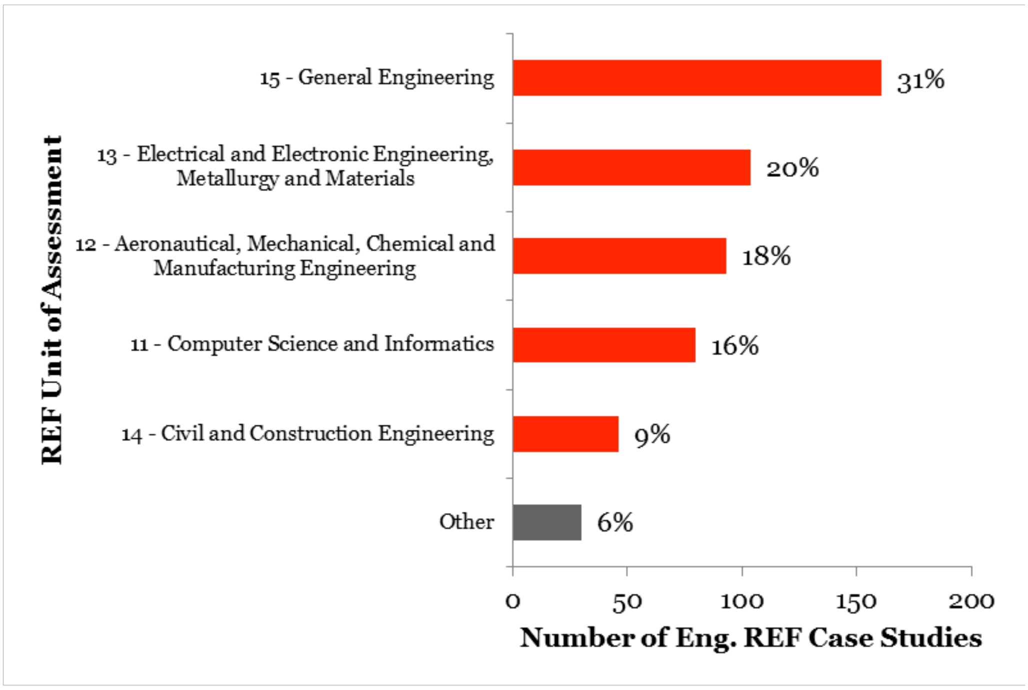
Units of Assessment

The received case studies contain an initial thematic classification that was directly obtained during the text extraction phase. The REF Units of Assessment determine the panels that will evaluate each of the specific submissions to the REF and the specific descriptors and boundaries of each UoA can be consulted on the REF's official website[43]. The impact cases studies that we received span across 15 out of the 36 different Units of Assessment (UoA) of the REF exercise.

[42] The study team requested access to the case studies on a confidential basis several months before HEFCE provided feedback on its REF funding decisions and HEIs chose to publish them openly, which is why some institutions considered this a highly sensitive material at the time.

Participating institutions selected these as those with a greater contribution from engineering research. As a result, the majority of case studies fall into the engineering REF UoAs (11 to 15), as seen in Figure 29. Case studies from other UoAs were also received from areas ranging from mathematical sciences to agriculture, veterinary and food Science. Note that the large number of cases in the 'general engineering' category highlights the multidisciplinary nature inherent to most engineering work.

Figure 29– Number of received engineering impact REF Case Studies per UoA



Source: Technopolis (2014)

Categories of Impact

The 'Unit of Assessment' information was contained in one of the fields of the REF case studies and was a direct result of our text extraction process. However, for the other dimensions of analysis (the categories of impact and the impact target sectors) this information is contained in the descriptions of the impact. In order to extract this information we have resorted to text analysis tools that match patterns of text[44] in order to assign case studies to categories. Using textual patterns instead of rigid keyword sets helps us match things such as:

- Spelling variations (e.g. spin out, spinout, spin-out)
- Plurals (e.g. saving/savings)
- Different verbal tenses (e.g. patented/patenting)
- Related words and words that occur together in a specific context (e.g. increase in sales)

We have compiled lists of textual patterns that would signal that the case study concerns a specific category of impact. If the detailed description of impact of a case study matches any of the patterns, we assign it to that category of impact. However, more generic expressions also yield more mismatches. As a result, time spent in calibration and ironing out 'false positives' directly depends on the resources at hand. In this case, we aimed to classify 60 to 80% of the

[43] REF Panel criteria and working methods. January 2012. Available at: http://www.ref.ac.uk/pubs/2012-01/#d.en.69569

[44] See Regular Expressions: http://en.wikipedia.org/wiki/Regular_expression

case studies within the proposed categories of our analytical framework, with error rates in the classification of no more than ±5% in the number of cases classified to a particular category. Text analysis methods usually have this fuzzier aspect, which implies that the classification obtained as a result will be of an orientative nature, as achieving 100% accuracy is never possible.

As per REF rules, a submitted case study can only be assigned to one UoA. However, for the other categories, the options are not mutually exclusive. A new development can have a simultaneous impact in the aeronautic and automotive fields (e.g. advances in computational fluid dynamics simulation), or ICT and life sciences (e.g. the development of a new sensor to measure oxygen levels). In the case of impacts, the same case study may highlight both the creation of a new spinout (new economic activity) and the impact of the procurement of a new innovation by the NHS (impact on public services).

The impact of engineering research in supporting industrial champions

Having such a broad collection of engineering impact REF case studies also allows us to realise that several of the UK industrial champions repeatedly benefit from the impact of engineering research conducted across UK universities and in a variety of disciplines. In order to illustrate this broad and complementary effect and to assess the contribution from engineering research to such companies, we need to extract mentions of impact in these companies from the text in a structured way.

To this end, we have passed the descriptions of the impact in the case studies through a Named Entity Recognition (NER) engine. NER algorithms take text and tag it with specific metadata, locating and classifying expressions in different sets of predefined categories or entities. Some of these algorithms are pre-trained with large volumes of textual data and use advanced techniques to detect names in the text, and to classify them by type of entity[45]. For this study we have used one of the codes developed by the Stanford Natural Language Processing research group[46]. Using a 3-class model for English language, the model tags the organisations, locations and person names present in a text. For example, the text

> *"Working with Synopsis Inc he developed interfaces for the Glasgow simulation tools. Asenov and Millar joined Gold Standard Simulations (GSS) as CEO and COO when it was spun out of the University of Glasgow"*

when processed becomes annotated as follows,

> *Working with [Synopsis Inc][ORGANISATION] he developed interfaces for the [Glasgow][LOCATION] simulation tools. [Asenov][PERSON] and [Millar][PERSON] joined [Gold Standard Simulations][ORGANISATION] (GSS) as CEO and COO when it was spun out of the [University of Glasgow][ORGANISATION]*

This type of analysis, while quite experimental in nature, has some interesting advantages. The main one is that we do not interrogate the text with a pre-assumed or expected list of companies and count the amount of mentions, but we let the data tell us who is mentioned in the text and to what extent (number of cases). This bottom-up text analysis with a lack of predefined search targets allows us to just see what emerges from the data, avoiding missing out on unanticipated or important topics/trends.

For this study, we take the processed versions of the case study impact descriptors and, when a specific company name is mentioned, we attribute one point to that company (but not if it is repeated several times within the same case study). Before arriving at the final results, several other aspects are taken into consideration:

- A manual clean up was done to homogenise spelling variations in company names.

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[45] Manning, Christopher D., Surdeanu, Mihai, Bauer, John, Finkel, Jenny, Bethard, Steven J., and McClosky, David. 2014. The Stanford CoreNLP Natural Language Processing Toolkit. In Proceedings of 52nd Annual Meeting of the Association for Computational Linguistics: System Demonstrations, pp. 55-60.

[46] Available at: http://nlp.stanford.edu/software/CRF-NER.shtml

- Redacted versions of some of the confidential case studies may intentionally omit mentions to specific companies, and as a result these will not be picked up by our analysis.
- The names of Universities, Government Departments and other government organisations and networks were omitted, as this analysis focuses on the most mentioned companies. However, while not technically companies, we left mentions to organisations such as NASA, the European Space Agency, NHS, etc. also featuring in this list as important targets for engineering research impact.
- Even with this more sophisticated analysis type, interpretation of the final results in relation to their context is as important as ever. For example, the BBC, Google and YouTube featured as company names mentioned frequently in the case studies. However, one can quickly realise that this is because the authors mention these organisations as communication channels that 'prove' their impact in the media, rather than to explain how their research contributed to these companies. This situation has been identified and these names removed from the final results, as they do not match the original intent of the analysis.

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