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Impact Assessment of EPSRC funding on the Circular Economy

Final Report, April 2019

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1.1 Executive Summary

1.1.1 This report

The Engineering and Physical Sciences Research Council (EPSRC) commissioned Technopolis, in partnership with Clarivate Analytics, to undertake an evaluation of the socio-economic impacts of their investment in research and training relevant to the circular economy between 2007 and 2016.

The study set out to assess the outputs, outcomes and longer-term socio-economic impacts of the projects, from four perspectives, including;

1) Advances in technology and **scientific knowledge**
2) **Capacity building** and training
3) Circular economy related **environmental outcomes**
4) **Economic benefits** to industrial partners and their wider sectors.

The study used a mixed-methods approach with evidence gathered from various strands of primary research and analysis of secondary data sources. This began with an initial composition analysis of Researchfish® data on the portfolio of EPSRC research grants to provide breakdowns on what types of projects had been funded, their previously reported outcomes and to refine the programme theory of change. Subsequent strands of research included:

- **Analysis of secondary sources** – including bibliometric analysis, to assess the volume of publications arising from projects and associated citations. In addition, company finance data sources were used to search for financial information on reported spin-out companies, and the grants were matched to the REF2014 database to search for case studies of wider impacts
- **Primary research** – including an online survey of 154 Principal Investigators (PIs), plus telephone interviews with 39 PIs to explore outcomes in more depth
- **Case studies** – seven projects were selected to case study the wider benefits to businesses, based on desk research and interviews with PIs and industrial partners (24 interviews in total)
- **Interviews with directors of Centres of Doctoral Training** to explore the centres' role in addressing industry skills needs relating to the circular economy.

1.2 The need for research relating to the circular economy

The move to a circular economy is a challenge being confronted by most of the world in the drive for smart, sustainable growth. Whilst the basic concepts are easy enough to describe the complex and embedded nature of the existing 'linear' economy means it is very much less easy to progress from theory to practice and there is a need for substantial technological, organisational and institutional innovation. While the private sector is busy with these issues, there are multiple systems failures where public intervention is necessary. The UK's long-term prosperity and environmental sustainability depends heavily on progress in this space and as such public support for circular economy research is likely to become even more important in future. The EPSRC has recognised this societal challenge and has built up an active portfolio of research that looking into developing and progressing sustainability, better utilisation of resources and environmental benefits.

The EPSRC has funded research relating to the circular economy through multiple routes and at different scales (Standard Research Grants, various strategic investments and Centres for Doctoral Training), rather than one specific 'circular economy' programme.

1.3 The EPSRC circular economy portfolio

Research outcomes data from the grants gathered through the Researchfish® system was provided by the EPSRC, giving details of 223 funding awards relevant to the Circular Economy, with a total value of around £205m. The 223 grants were selected by performing a keyword search[1] on all grants which were funded by EPSRC between 1/12/2007 and 31/12/2016. The grants were then sorted for relevance to the circular economy. The shortlist of grants was chosen by taking the ten grants with the highest level of leverage committed at the start of the grant and then ten grants randomly selected from the remainder of the projects. Assessing outcomes of these awards formed the basis of this impact study.

The projects span a wide variety of different academic disciplines and thematic areas, each with their own separate project objectives. These projects ranged from relatively small-scale fundamental research to test scientific concepts, to large investments in Centres for Innovative Manufacturing, with multi-million-pound investments from several industrial partners to iteratively test, develop and commercialise new technologies and manufacturing processes.

1.4 Key findings

The study found evidence of high levels of economic and environmental impacts arising from the technologies and manufacturing processes advanced by the EPSRC funded research projects.

Economic and environmental benefits of a circular economy are interrelated, because resource efficiency benefits such as; reduced use of raw materials, energy efficient manufacturing, less waste disposal and increased recycling are often directly linked to economic benefits, including; lower production costs, energy cost savings and profits from the sale of more sustainable products.

From five of the case study projects alone, we have identified that there are approximately **£130m** of discounted benefits that can be attributable to the funding provided by the EPSRC grants, over a ten-year period. The value of the grants for the five-case studies that we have produced ROI assessments for is approximately £15m, which represents 7% of the portfolio of grants. The primary drivers of these benefits are reductions in energy use and Greenhouse Gas emissions (CO_2e) through more resource efficient manufacturing processes.

The central estimate for the aggregate ROI for the EPSRC funding of these five case studies is approximately **£9.62 per £1** of EPSRC grant funding.

1.1.1 Scientific value

The 223 individual research grants led to a high volume of publications, with 5,016 individual publications reported through the Researchfish® data gathering tool. Of these, the majority (3,563) were substantive research or peer reviewed journal articles.

The journal articles were used for bibliometric analysis. Key findings from analysis of citations of these publications include:

- The publications had an average citation impact of nearly twice the world's average, taking into account the publication year and the field of study (a normalised citation impact of 1.91). This is very much in line with the performance for all EPSRC research, and substantially stronger than the equivalent metric for all UK research
- The grants have led to publications with a relatively high proportion of highly-cited papers. Around a quarter of the papers published (26%) were among the world's top 10% of most highly cited papers, which is a very strong performance

[1] Keywords used in search include: "Sustain*" "Circular Economy" "Recycl*", "Resource Productivity", "Resource Efficiency".

- Reflecting the multi-disciplinary nature of circular economy R&D, the publications which had cited the EPSRC grant funded research papers, spanned a diverse range of fields. From engineering and physical sciences to the social sciences, agriculture, plant and animal sciences.

1.1.2 Building capability and skills

The findings from our interviews with PIs, their industrial partners and Directors of EPSRC Centres for Doctoral Training (CDT) demonstrate a range of ways in which the funding led to increased capability and skills, including; career progression of students and post-doc researchers, improved internal expertise to advance science or manufacturing processes, strengthening relationships with industrial and other academic partners to create hubs of expertise and more broadly, increasing understanding among academic communities of the challenges and skills gaps faced by industry.

Our survey results suggest the vast majority of EPSRC grants had a positive impact on; career progression, increased internal knowledge, skills and capabilities, improved visibility and awareness of their idea or technology and strengthen relations with their partner organisations. Among respondents to our survey of grant recipients:

- 91% reported that the project had a medium/high impact on career progression
- 82% reported a medium/high impact on strengthening relationships with external partners
- 69% reported that the project had either a medium or high impact on increased employment e.g. the creation of new post-doctoral positions to continue research in the area.

Projects not only strengthened existing partnerships, but also created new partnerships. Collaborations involved partners from across academia, industry, and civil society. In most cases, collaborations with new external partners continued after the initial EPSRC funded project was completed.

Collaboration with industrial partners and other academic institutions helped to raise the profile of the research outcomes. In some cases, this created ‘hubs’ of expertise that attracted additional new partners (both nationally and internationally) and helped to secure funding for follow-up projects.

1.1.3 Circular economy related environmental and economic impacts

The most common route to wider impacts was through increased levels of resource efficiency from industrial partners adopting innovative manufacturing processes. For example, one aircraft components manufacturer redesigned their maintenance and servicing operations, with a greater focus on the re-use and recycling of components, which created savings from reduced usage of raw material inputs.

The second main route to impact was where the partner incorporates new technologies in the creation of manufacturing equipment or services which they sell to their customers. For example, new chemical crystallisation technology which makes drug manufacturing more efficient. In this case, the environment benefits will be realised across the wider pharmaceutical sector, through companies who buy and adopt the technology to reduce their energy usage and minimise waste.

We found strongly positive ROIs from the case studies, which included:

1) A project which developed new processes for recycling carbon fibre – by using waste carbon fibre from retired aircraft wings and processing this to produce new carbon fibre products
2) A project which developed new forms of alloys from recycled aluminium. This was patented and adopted by a car manufacturer that collaborated in the project, leading to the production of new lightweight cars based on recycled aluminium.
3) A project which advanced technologies for developing a new type of anaerobic digestion biogas plant. This is currently being operationalised by several UK water companies.

4) The Centre for Innovative Manufacturing in Through Life Engineering services – which has led to significant resource efficiency savings in the aerospace industry

5) A project that advanced carbon capture and storage technologies. This led to the creation of a high value spin out company, which is supporting the plastics industry in reducing carbon emissions.

The total value of EPSRC grant portfolio is around £205m. The value of the grants for the five case studies that we have produced ROI assessments for is approximately £15m, which represents 7% of the portfolio of grants.

From five of the case study projects alone, we have identified that there are approximately **£130m** of discounted benefits that can be attributable to the funding provided by the EPSRC grants, over a ten-year period. The **central estimate** for the aggregate ROI for the EPSRC funding of these five case studies is approximately **£9.62 per £1** of EPSRC grant funding.

Sensitivity analysis was carried out to account for items with implicit uncertainty, such as estimates of future levels of production provided by respondents interviewed, and the level of attribution of outcomes to the projects they relate to. The sensitivity analysis produced a range of estimated discounted benefits for the total of the five case studies between **£45-447m**, representing a range of ROIs between **£3.32 to 32.73 per £1** of EPSRC grant funding.

2 Introduction

2.1 The study

The UK Engineering and Physical Sciences Research Council (EPSRC) commissioned Technopolis to undertake an evaluation of the socio-economic impacts of their investment in research and training relevant to the circular economy between 2007 and 2016.

The EPSRC has funded research relating to the circular economy through multiple routes and at different scales (Standard Research Grants, Strategic Investments, and Centres for Doctoral Training), rather than one specific 'circular economy' programme. Research outcomes data from the grants gathered through the Researchfish® system was provided by the EPSRC, giving details of 223 funding awards relevant to the Circular Economy, with a total value of around £205m. The 223 grants were selected by performing a keyword search on all grants which were funded by EPSRC between 1.12.2007 and 31.12.2016. The keywords used include:

- "Sustain*"
- "Circular Economy"
- "Recycl*"
- "Resource Productivity"
- "Resource Efficiency".

The grants were then sorted for relevance to the circular economy. The shortlist of grants was chosen by taking the ten grants with the highest level of leverage committed at the start of the grant and then ten grants randomly selected from the remainder of the projects. Assessing outcomes of these awards formed the basis of this impact study.

The 223 grants encompass a wide variety of academic disciplines and thematic areas, with multiple types of objectives across impacts on science, skills and innovation. As such, the study team has researched several distinct routes to impact, including; whether funding had led to scientific advances, increased the capacity and skills of the UK research base and delivered economic benefits to the wider economy. Crucially, the study has also explored the longer-term environmental impacts attributable to this important body of work, including reduced CO2e emissions from industrial systems. This study is focused on understanding the value of the investment EPSRC made across these diverse routes to impact.

2.2 Background – Towards a Circular Economy

A circular economy is an alternative to a traditional linear economy (make, use, dispose) in which we keep resources in use for as long as possible, extract the maximum value from them whilst in use, then recover and regenerate products and materials at the end of each service life. The UK's prosperity and national security depend heavily on access to reliable sources of resources. As such, processes, technologies and whole systems that enable the circulation of valuable resources, such as recycling, re-use and remanufacture will become ever more important.

The circular economy may be characterised by three key principles:

Life cycle thinking in the design of products, services and systems: Products are designed to be maintained and repaired to extend their life, and/or reused, refurbished, remanufactured or recycled to enter a new useful life. Services and associated systems are designed to optimise the use and value of products and ensure that the products remain in closed resource loops. Furthermore, industrial processes need to be conducted, optimised, and planned in the most resource and energy efficient way.

Customers as 'users' not 'consumers' of products and material resources: Value is directly linked to the functionality and use of products, not the transfer of ownership, i.e. to the extent possible, products are rented, leased and shared, instead of being purchased and discarded. Manufacturers and/or service providers retain the ownership of products and are thereby motivated to treat them as capital assets e.g. by being held accountable for their recycling or safe disposal.

Reconfiguration of value chains: Instead of a linear supply chain where products and materials flow in one direction, value chains in a circular economy are formed to ensure that resource loops are closed with all actors from designers, producers, service providers, users and waste handlers.

Debates on the business case for developing a more circular economy have been shaped in recent years by one of its most prominent proponents, the Ellen MacArthur Foundation. Their 2012 report, '*Towards the Circular Economy; an economic and business rationale for a circular economy,*' showcased the potential size of the prize, with estimates suggesting that adoption of circular setups in relevant manufacturing sectors could yield net material cost savings of USD 340 – 630bn per year in EU alone. In addition, a UK focused study, the Next Manufacturing Revolution (NMR) report[2] predicts a £10bn profit increase, plus 27 million tonnes of CO2 equivalent p.a. greenhouse gas emissions reductions and 300,000 jobs created from only partial implementation of circular economy approaches.

For these benefits to be realised, the transition towards a circular economy requires significant innovation ranging from adapting manufacturing processes at a company level to changing economy-wide production and consumption patterns.

In recognition of these challenges and opportunities, and as part of its delivery plan, the EPSRC has funded research and training to help the UK transform to a more sustainable society, with a focus on the circular economy: using new chemistries, materials substitutes and a whole systems approach to move towards a circular economy which includes recycle, remanufacture and remarketing of materials.

2.3 Research Questions

The study has addressed an overarching research question:

What has been the overall impact of EPSRC's investments in research and training relating to the circular economy over the last 10 years?

This was supplemented by a series sub-questions across four main routes to impact, as summarised in Table 1 below:

Table 1 Research questions

Impact pathway	Research/evaluation question
1. ***Scientific Value***	What technical and scientific advances has EPSRC funding enabled?
	What effect has EPSRC funding had on the research landscape, for example facilitating research collaborations between different disciplines?
2. Economic Impacts	What additional contributions have been leveraged through EPSRC funding and from which sources?
	Which sectors have benefitted from the research that has been enabled by EPSRC funding and how?
	What evidence is there that EPSRC-funded research and training has led to business benefits, for example, cost savings and increased turnover, profit and exports?

[2] Lavery, G., Evans, S., 2013. Next Manufacturing Revolution - report on the opportunity for profit, jobs and environmental benefits from non-human resource productivity improvements

Impact pathway	Research/evaluation question
	What impact has EPSRC-funded research and training had on innovation, for example, spin- offs, development of innovation clusters, use by business for innovation?
	Has EPSRC funding seeded significant strategic research growth in a region or institution?
3. Impact on capacity building and training the next generation	How has EPSRC funding contributed to skills training, for example, training PhD students, technicians and others?
4. Socio-environmental impact	How has EPSRC funding helped in addressing key societal challenges such as sustainability, environment, energy and health?

Source: Technopolis, 2018, summarised from the Invitation to Tender

2.4 Methods

Our research was organised across four main Work Packages (WP), as outlined below and in Figure 1.

WP1: Scoping Stage – An inception period, consisting of an initial an initial composition analysis of EPSRC administrative data on the portfolio of 223 grants awarded (see Section 2.5). Including breakdowns of the size, structure and key features of research funded, with an overview of what outcomes have been reported in Researchfish®. This was used to refine the programme logic model, evaluation framework and data collection strategy.

WP2: Further analysis of EPSRC data and secondary sources – This phase included bibliometric analysis, carried out by our partners Clarivate Analytics, using their Web of Science database to analyse levels of citations associated with publications arising from the grant funded projects. The list of publications was provided by EPSRC based on those reported by researchers via Researchfish®. Results of citation data analysis are used as indicators of the wider effects on the scientific landscape. Analysis of other secondary data sources included analysis of REF2014 case studies to summarise recorded impacts arising from research projects (see Appendix C) and use of a Bloomberg Terminal and FAME database to search for financial information on spin-out companies.

WP3. Primary data collection – The data on projects funded, derived from EPSRC's Management Information records, identified 186 individual Principal Investigators (PIs) who were recipients of funding. This formed the basis of our sampling frame for three main strands of interviews and an online survey, as follows:

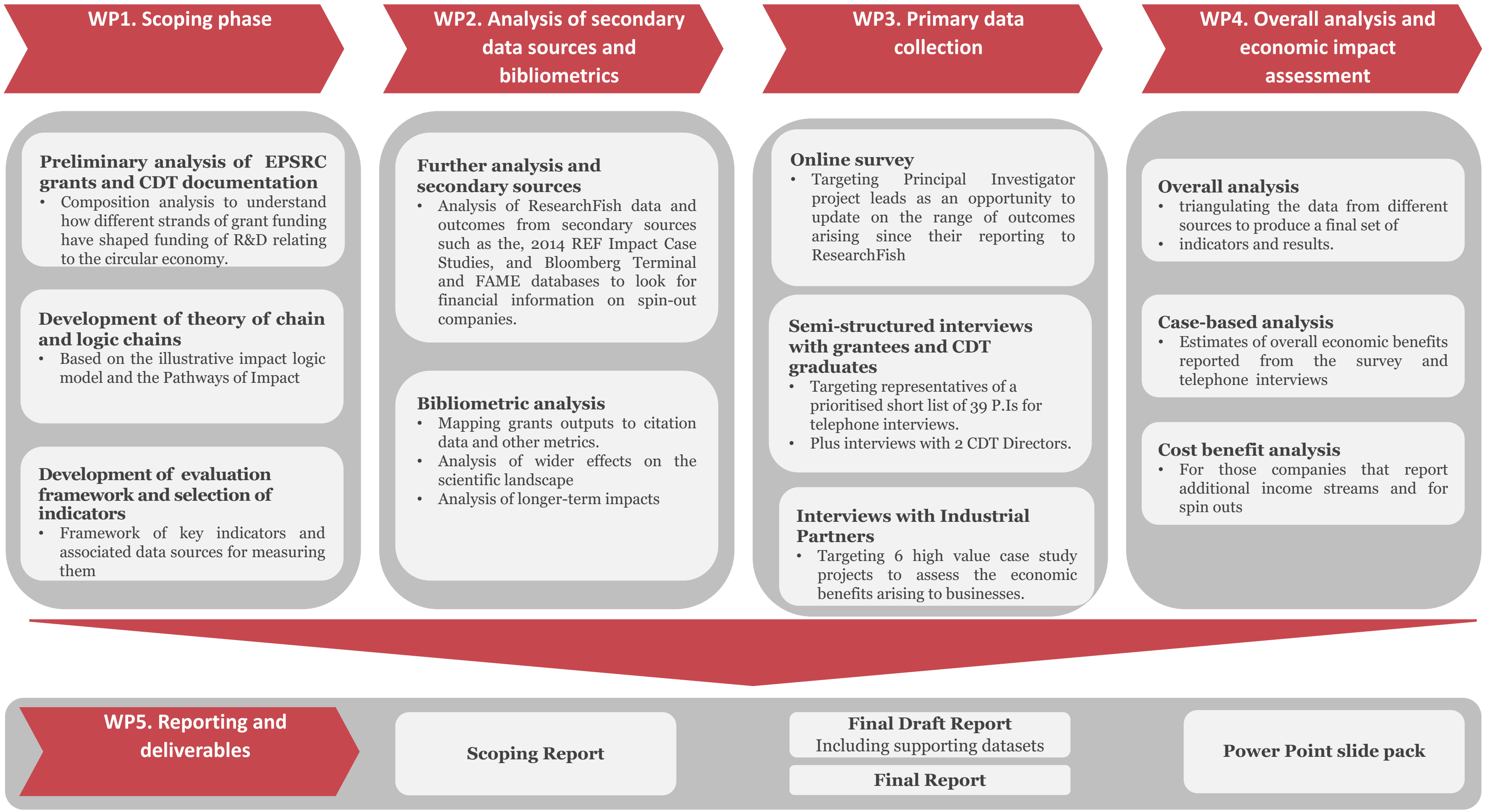
- **Online survey** – The majority of PIs (154) were sent an online survey to gather information on outcomes arising from their projects, to update information previously recorded in Researchfish®. This returned 76 responses; a response rate of 49%.
- **Telephone interviews with PIs** – A further 39 PIs were shortlisted for more detailed semi-structured telephone interviews. This short-list was broadly representative of the overall sample, although it included a slightly higher proportion of larger scale research projects (Manufacturing for the Future), where there was an interest in exploring benefits to their industrial partners. In total, 19 semi-structured telephone interviews were achieved; a response rate of almost 50%.
- **Case studies** – Seven projects were selected for case study, using qualitative research methods to develop a fuller understanding of the benefits of industry university cooperation in this area while also gathering evidence on the wider economic benefits. The case studies were selected to reflect projects led by PIs from a cross-section of academic disciplines and with outcomes for various sectors, including; plastics manufacturing, pharmaceuticals, clean energy, automotive and aerospace engineering. Semi-structured interviews were carried out with all of the PIs and 2-3 industrial partners from each of the seven projects (24 interviews in total).

- **Interviews with Directors of Centres of Doctoral Training** – The EPSRC grants data included details of three Centres of Doctoral Training (CDTs) that are training students on themes of particular relevance to the circular economy. Semi-structured telephone interviews were achieved with two of the three CDTs. These were primarily used to gather information on how the CDTs were addressing circular economy skills gaps in key industrial sectors and the destination of students.

WP4: Analysis – A final phase, drawing together and analysing the available evidence gathered through the study to estimate overall economic, social and environmental impacts.

See Annex B for further details of the Methodology and assumptions used in the analysis.

Figure 1 Overview of Approach



Source: Technopolis

2.5 Composition Analysis

This Section provides an overview of the EPSRC funding relevant to the circular economy, which formed the population that was within scope for the study. Research outcomes data from the grants gathered through the Researchfish® system was provided by the EPSRC, giving details of 223 funding awards relevant to the circular economy, with a total value of around £205m. The 223 grants were selected by performing a keyword search on all grants which were funded by EPSRC between 1.12.2007 and 31.12.2016. The composition analysis provides a breakdown of types of research and training funded through these grants, including a summary of what outcomes were previously reported in Researchfish®. These include:

- Overview of total spend by types of grant award
- Breakdowns of the amount of additional funding leveraged from industrial partners (as committed at the start of projects)
- Breakdowns of the types of outcomes reported in Researchfish® (including publications, spin-outs and patents).

Note the grants that formed the basis of this study may not cover the full population of EPSRC supported research activity relevant to the circular economy. The 'circular economy' is a broad concept and various forms science and engineering research may contribute towards it in some way even if the grants were not explicitly focused on the subject.

2.5.1 Levels of funding and private sector leverage

The £205m of total funding was allocated across three categories: 1) Standard Research Grants, 2) People Support Grants, and 3) Knowledge Exchange and Impact Grants.

As shown in Table 2, the Standard Research Grant category held the largest number of grants (140) and accounts for the largest proportion of funding (£154.1m). There were 51 Knowledge Exchange and Impact Grants which amounted to £16.6m EPSRC funding, followed by 28 People Support Grants with £14.1m funding EPSRC funding.

In total, the funding is reported to have leveraged a total of **£71,318,564** of private sector investment. Overall, this equates to an additional **£0.39 of private sector contributions for every £1 of EPSRC spend.**

The largest leverage per £1 of funding was achieved through Knowledge Exchange and Impact Grants. Within this category **every £1 EPSRC funding was matched with £0.52** of private sector funding. More than a third of total project costs in this category were funded by private sector funding (34%).

Table 2 Economic overview by EPSRC grant scheme

Scheme Category	No. of grants funded	£ EPSRC funding	Total private sector contribution	Total project funding	Ratio of funding to leverage	Leverage per £1 EPSRC funding
Standard Research Grants	140	£154,135,699	£57,628,037	£211,763,736	73:27	£0.37
People Support Grants	28	£14,055,089	£4,995,852	£19,050,941	74:26	£0.36
Knowledge Exchange and Impact Grants	51	£16,626,001	£8,694,675	£25,320,676	66:34	£0.52
Total	219	£184,816,789	£71,318,564	£256,135,353	72:28	£0.39

Source: Technopolis, 2018, based on EPSRC data on grant awards.

The grants were also grouped into levels of funding, by the following three categories; £0-1m, £1-5m, and £5-10m. As Table 3 shows, the majority of grants (175) were below £1m, followed by £1-5m (33). Only 11 grants, all of them Standard Research Grants, were higher than £5m.

Table 3 EPSRC grants by funding volume

Scheme	£0-1m	£1-5m	£5-10m
Knowledge Exchange and Impact Grants	49	2	
People Support Grants	23	5	
Standard Research Grant	103	26	11
Total	175	33	11

Source: Technopolis, 2018, based on EPSRC data on grant awards.

The amount of funding awarded has some **correlation with the amount of leverage achieved**. The category of grants with highest levels of EPSRC funding has the highest levels of private sector contributions leveraged.

2.6 Outcomes reported in Researchfish® by types of grant scheme

In terms of previously **recorded outcomes**, Table 4 shows the number of publications, collaborators, spin outs, and patents by grant scheme. This data is based on the outcomes that project leads had previously reported in Researchfish®.

Table 4 Research outputs by grant scheme

Scheme category	Publications	Collaborators	Spin Outs	Patents
Total Standard Research Grants	4362	663	13	44
Total People Support Grants	220	31	0	8
Total Knowledge Exchange and Impact Grants	356	80	4	9

Source: Technopolis, 2018, based on information recorded in Researchfish®.

3 Scientific Value

3.1 Introduction

This section summarises evidence gathered to assess the extent of impact the funded projects have had on advancing science within their fields of study. It addresses the research question, "*What technical and scientific advances has EPSRC funding enabled*? The findings are primarily based on the bibliometric analyses carried out by Technopolis' project partner, Clarivate Analytics.

Bibliometrics is the analysis of data derived from publications and their citations. Publication of research outcomes is an integral part of the research process and is a universal activity. Consequently, bibliometric data have a currency across subjects, time and location that is found in few other sources of research-relevant data. Citations measure the volume and frequency with which a report is being referenced by other authors (including authors form separate fields of study), which gives an indication of advances in scientific knowledge, as explained further below.

Findings from the bibliometric analysis suggest that publications which resulted from EPSRC grants have relatively high levels of citation, in comparison to other publications within their field of study. The circular economy related grants had an average citation impact of nearly **twice the world average**, taking into account the publication year and the field to which they relate. This provides a strong indication that the EPSRC has funded science of high quality.

The EPSRC funding was reported to have been necessary to enable research projects to proceed and for these advances in science to occur. The majority (85%) of Principal Investigators who responded to our survey said their institution would not have carried out the research project in the absence of EPSRC funding.

3.2 Bibliometric analysis – summary of methods

The main data source used for bibliometric analysis was the Web of Science 'Core Collection,' which focuses on research published in journals and conferences in science, medicine, arts, humanities and social sciences. It covers over 27,000 of the highest impact journals worldwide, including Open Access journals and over 161,000 conference proceedings. Coverage is both current and retrospective in the sciences, social sciences, arts and humanities.

The following terms and bibliometric indicators have been used for this evaluation:

- **Citations**:[3] The citation count is the number of times that a citation has been recorded for a given publication since it was published.
- **Field-normalised citation impact**:[4] Citation rates vary between fields and with time. Consequently, the analyses take into account both field and year. In addition, the type of publication will influence the citation count. For this reason, only citation counts of papers are used in calculations of citation impact. The standard normalisation factor is the world average citations per paper for the year and journal category in which the paper was published.

[3] Research publications accumulate citation counts when they are referred to by more recent publications. Citations to prior work are a normal part of publication, and reflect the value placed on a work by later researchers. Some papers get cited frequently and many remain uncited. Highly cited work is recognised as having a greater impact and Thomson Reuters has shown that high citation rates are correlated with other qualitative evaluations of research performance, such as peer review. This relationship holds across most science and technology areas and, to a limited extent, in social sciences and even in some humanities subjects.

[4] Indicators derived from publication and citation data should always be used with caution. Some fields publish at faster rates than others and citation rates also vary. Citation counts must be carefully normalised to account for such variations by field. Because citation counts naturally grow over time it is essential to account for growth by year. Normalisation is usually done by reference to the relevant global average for the field and for the year of publication.

- **Highly cited papers**: Highly cited work is recognised as having a greater impact and Thomson Reuters has shown that high citation rates are correlated with other qualitative evaluations of research performance, such as peer review. In this analysis, publications that are in the **top 10%** in terms of citation frequency are considered to be highly cited, taking into account year of publication and field. This threshold was selected after the review of a number of previous analysis showed this to be a useful value for general management purposes.

- **Very highly cited papers**: is used in this report to refer to papers in the world's **top 1%** of most highly cited papers.

- **Hot papers**: These are papers published in the past two years that are in the **top one-tenth of one percent (0.1%)** for their field and publication period. Such papers are currently of great interest within the field to which they relate.

- **Co-authorship** of publications: the metadata associated with every research publication include the addresses of the authors. This has been used to develop an analysis of the organisations that co-author publications by extracting and examining these data.

- **Integration Index**: Porter's Integration Index[5] indicates the extent to which research papers are integrating knowledge from different research fields. The Integration Index is calculated by evaluating both a) the number of disciplines cited by a paper (represented by Journal Subject Categories (JSCs)) and b) how different the cited disciplines are (determined using the cosine measure of similarity between JSCs).

The EPSRC provided Technopolis and Clarivate Analytics with lists of the publications associated with its Circular Economy grants, as reported by researchers through Researchfish®. Of the 5,016 individual publication records provided by the EPSRC, Clarivate Analytics linked **3,563 (71%)** to research publications in the Web of Science, which form the basis of this analysis. Publications records which were not linked to Web of Science, and therefore excluded from the analysis, comprised of grey literature, conference proceedings and press articles that were not published in peer reviewed journals.

3.3 Results of bibliometric analysis.

In summary, the findings suggest these have relatively high levels of citation, providing a strong indication of advancing science in their fields of study. Key findings include:

- Overall, the grants had resulted in papers with a high average citation impact. They had an **average citation impact of nearly twice the world average**, taking into account the publication year and the field to which they relate. The normalised citation impact of 1.91 is broadly in line with the figure for the EPSRC overall (2.06) and well ahead of the figure for the UK overall (1.55).[6]

- The grants have led to publications with a high proportion of highly-cited papers (HCPs). Around a quarter of the papers (26%) were among the world top 10% of most highly cited papers.

- A total of 74 individual publications were co-authored with industrial partners. These were produced from 27 of the grant funded projects.

[5] Porter, A.et al. (2007) Measuring Researcher Interdisciplinarity. Centimetric. 72(1):117-147) https://link.springer.com/article/10.1007/s11192-007-1700-5

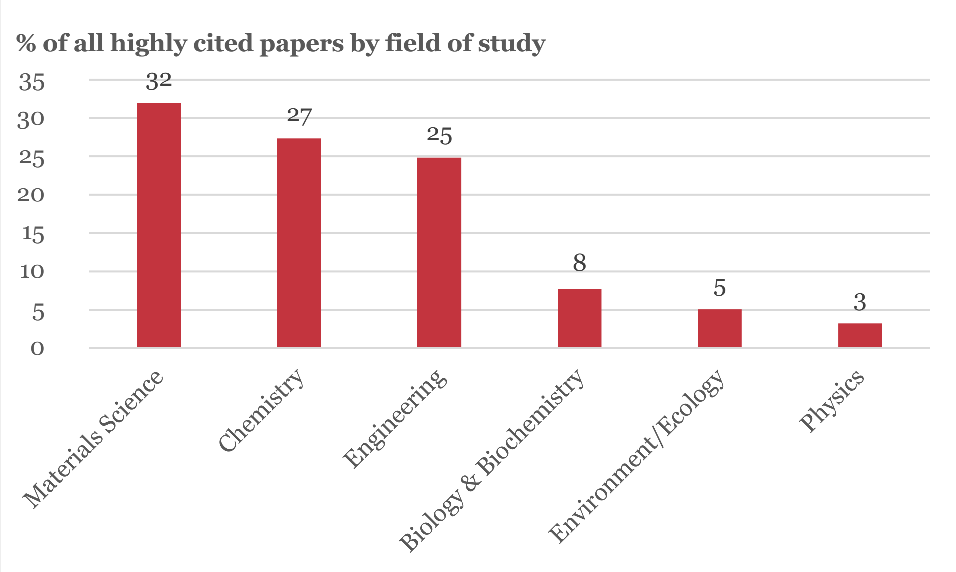
[6] See figures 1 and 2 of the EPSRC annual impact report 2016/17

3.3.1 Highly cited papers by field of study

Overall, around a quarter of all papers published were highly cited papers (26%).

The circular economy HCPs largely fall into six fields of study, within The Web of Science's '22 'Research Fields' (e.g. Mathematics, Chemistry, Engineering, Biology & Biochemistry, etc).[7] Figure 2 provides a breakdown of the percentage of highly cited papers, by field of study, based on a total of 439 highly cited papers in the six research areas where there were more than 50 publications.[8]

Figure 2 Breakdown of highly cited papers by field of study



Source: Technopolis, based on Clarivate Analytics Web of Science data.

It is of interest to note that a significant (albeit relatively small) percentage of the total population of highly cited papers come from fields of study outside the EPSRC's core areas of engineering and physical sciences e.g. Biology and Biochemistry (8%). This may reflect the multi-disciplinary nature of circular economy related research projects. For example, where engineers work alongside bio-chemists to use sewage from waste water treatment plants to develop biogas, or work alongside chemists in the pharmaceutical industry to develop more resource efficient drugs manufacturing equipment.

3.3.2 Fields of study among papers that cite the EPSRC research publications

The section above provided a breakdown of which fields of study the highly cited papers relate to. Another way of exploring the relationship between citations and fields of study is to assess the classifications of disciplines of the papers that have cited the EPSRC publications. These papers do not necessarily relate to research that was funded by the EPSRC, but rather any publications listed within the Web of Science database that have cited a paper arising from an EPSRC funded circular economy grant. This shows the fields that are citing/using the research funded by the ESPRC, and therefore gives an indication of the fields where the EPSRC's Circular Economy research is having an impact.

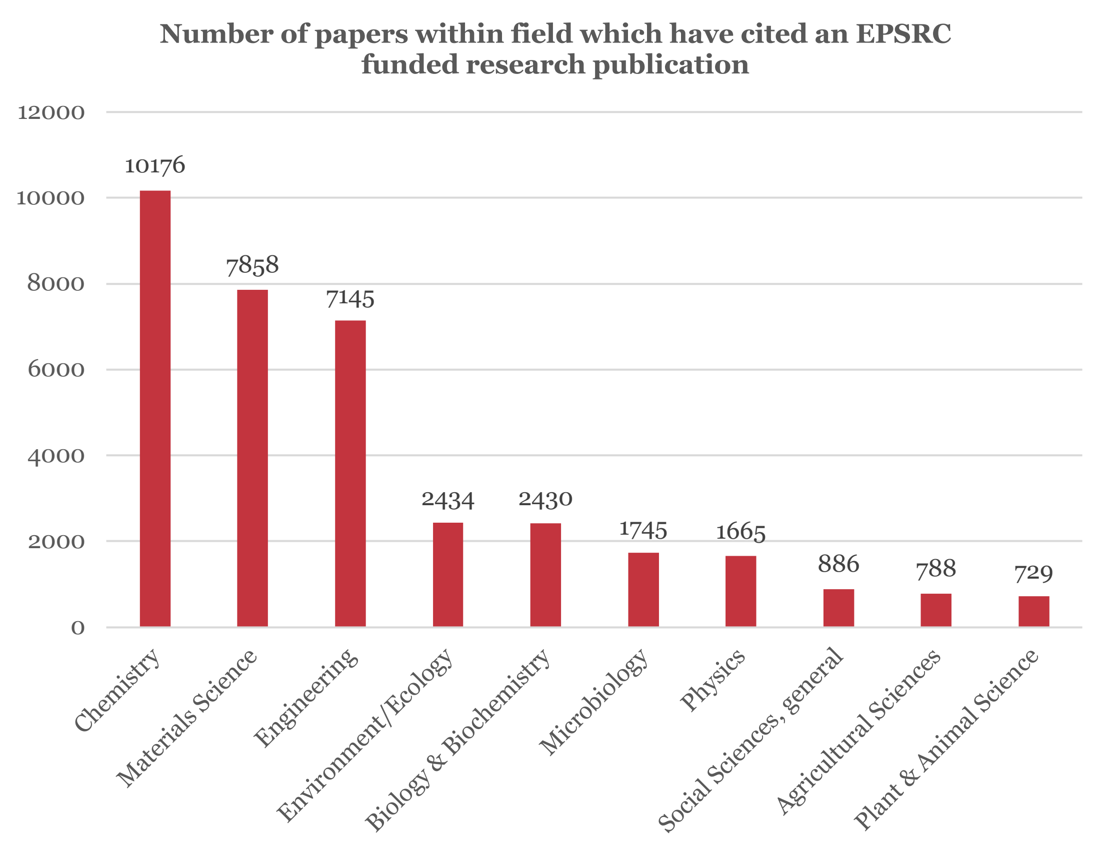
In total, **38,381** papers listed in the global Web of Science database were identified as having cited a publication of research sponsored by one of the EPSRC grants. The figure below lists the top ten fields

[7] For the full list of ESI Research Fields see website: http://ipscience-help.thomsonreuters.com/inCites2Live/8300-TRS.html

[8] The citation impact of any aggregation of sub-groups with less than 50 papers should be treated cautiously. The skewed nature of the citation distribution (lots of uncited papers and relatively few very highly-cited ones) means data for any sub-groups of fields with fewer than 50 papers have been excluded from the analysis.

of study which contain the highest number of publications that have cited the EPSRC funded projects (in order of highest to lowest).

Figure 3 Top ten fields of study with most citations of circular economy publications



Source: Technopolis, based on Clarivate Analytics Web of Science data.

3.3.3 Co-authorship with industry

Among all of the research publications matched within the Web of Science, a total of 74 individual publications were identified as being co-authored with private sector industrial partners. Note that co-authorship does not reflect the total number of research projects that have involved collaboration with industrial partners. The majority of papers published by the academic holding institution of the grant may acknowledge the contribution of partners, but the papers (mostly in academic journals) will not be directly co-authored with them. As outlined in Section 2.3 Composition Analysis, from the total 223 individual research grants funded, 107 were recorded as having leveraged financial contributions from private sector partners.

However, instances where industrial partners have co-authored the publication are of interest, as they provide an indication of papers that have been produced in particularly close collaboration or where the industrial partner has an interest in communicating the benefits of the research to them. This section provides an overview of which industrial partners of the grants have co-authored publications arising.

Among the 74 publications identified as being co-authored with private sector partners, over two thirds were co-authored by ten individual companies. These companies primarily produce products and services in the following four industrial sectors; automotive, pharmaceutical, aerospace and defence. Table 5 below lists the top ten companies which have co-authored the highest number of publications.

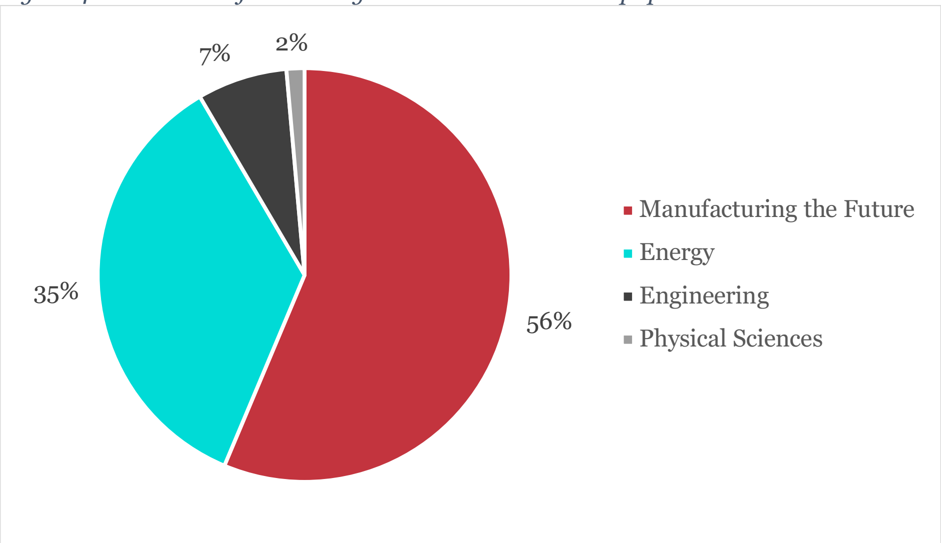
Table 5 Top ten companies with the most co-authored publications

Company Name	Sector	Number of co-authored publications
Rolls-Royce Holding Group	Automotive and aerospace	13
Airbus Group	Aerospace and defence	10
Aviation Industry Corporation of China (AVIC)	Aerospace	6
GlaxoSmithKline	Pharmaceutical	5
Unilever	Consumer goods	3
AstraZeneca	Pharmaceutical	3
Sanofi-Aventis	Healthcare	2
Boeing	Aerospace and defence	2
Eli Lilly	Healthcare and pharmaceutical	2
BMW	Automotive	2

Source: Clarivate Analytics, based on Web of Science data.

Among the 41 grants which led to publications that were co-authored with private sector organisations, the majority had recorded their lead thematic area as 'Manufacturing the Future', in EPSRC's administrative data. Figure 4 below provides a breakdown of the lead themes for each of the grants with publications co-authored with industrial partners.

Figure 4 Lead theme of research grants with co-authored papers



Source: Technopolis, based on Clarivate Analytics Web of Science data

The grant which led to the highest number of publications co-authored with industry (16 papers) related to a project based on R&D of lighter and recyclable alloys that can improve the energy efficiency of cars and aircraft. This research programme was sponsored by a range of industrial partners from automotive and aerospace sectors.

3.4 Advances in Technology Readiness Levels (TRLs)

In addition to using the bibliometric analysis to determine the extent to which the EPSRC investments had advanced scientific knowledge, we asked Principal Investigators (PIs) whether their project had led to the progression of a technology along the Technology Readiness Level scale (TRL 1 to 9). The survey asked PIs to state what the TRL of their concept or technology was before the EPSRC grant was received and what stage it had progressed to by the time the project was completed.

Just over half of respondents (52%) stated their project related to advancing a technology, which was at TRL 1 or 2 before the grant was received, with a further 15% stating it was at TRL 3-4. The remainder stated “not – applicable”. This may be the case where the research was exploratory in nature or focused on fundamental science, rather than advancing a specific technology. 44% of respondents stated the technology had advanced to TRL 3 to 4 once the project was completed, with a further 35% stating it had progressed to TRL 5 or above. This suggests the majority of research projects had supported the development of a technology up the TRL scale.

Section 5 explores the ways in which these scientific and technological advances have led to follow-up funding from both Research Councils and industry, for collaborative R&D to progress technologies further up the TRL scale, leading to eventual commercialisation of products or changes in manufacturing practices, with economic and environmental impacts across a range of sectors.

4 Capability and Skills

4.1 Introduction

This section summarises evidence gathered on the impact of the funding on training the next generation of scientists and engineers to work on circular economy related challenges. As well as more broadly building capabilities and skills among the academic institutions funded and their industrial partners. The research questions addressed include: *How has EPSRC funding contributed to skills training, for example, training PhD students, technicians and others?*

The findings from our interviews with PIs, their industrial partners and Directors of EPSRC Centres for Doctoral Training (CDT) demonstrate a range of ways in which the funding led to increased capability and skills, including; career progression of students and post-doc researchers, improved internal expertise to advance science or manufacturing process further, strengthening relationships with industrial and other academic partners to create hubs of expertise and more broadly, increasing understanding among academic communities of the challenges and skills gaps faced by industry.

4.2 Views of PIs and industrial partners on building capability and skills

Respondents to the online survey were asked to indicate the extent to which their circular economy grant had a positive impact on capability building. The results suggest that the great majority of EPSRC grants led to impacts on multiple capability dimensions: from internal knowledge to career progression and relationships with partner organisations. Key findings include;

- 95% reported a medium/high impact on improving internal knowledge, skills and capabilities
- 91% reported a medium/high impact on career progression for research students in the projects
- 82% reported a medium/high impact on strengthening relationships with external partners
- 69% reported a medium/high impact on increased employment e.g. the creation of new post-doctoral positions to continue research in the area.

The semi-structured telephone interviews with PIs probed the reasons for these impacts. Common reasons given were that the grants enabled the HEIs to fund new post-doc or PhD posts to work on the project. Also, the collaboration with industrial partners improved relationships with relevant employers, which facilitated career progression of students. As illustrated in quotes below:

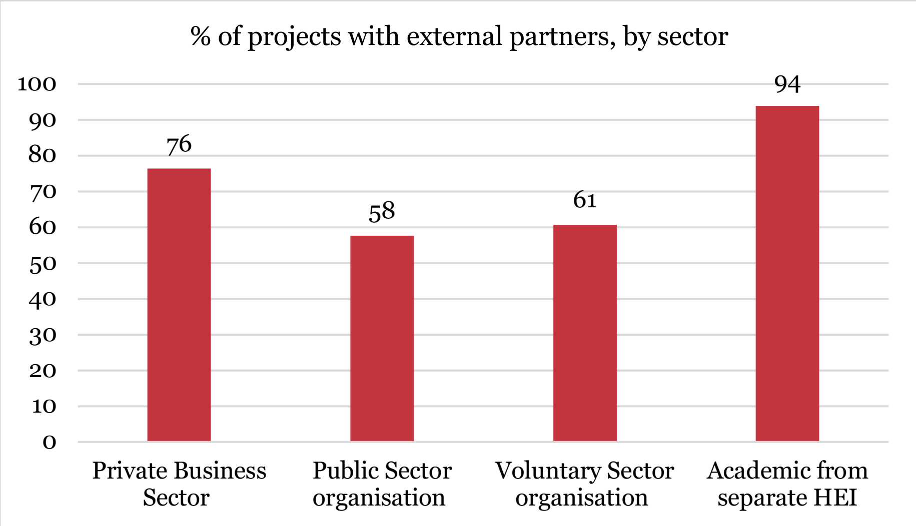
- *We trained up PhDs and are in a position to be able to retain the good ones. We have also gained fellowships. Those who left, went to high-paid industry additive manufacturing jobs. This has also given us a worldwide network of 'alumni'.*
- *We have had a lot of benefits arising from this grant. For instance, we have started a new project in the same area so new researchers have been trained. We have started a new post-doctoral training project, so more PhDs are graduating in this direction.*
- *Career progression for researchers involved with the project was a key outcome: a high percentage, 70%, of those involved in the Centre either started their own company or remained in Synthetic biology. They are a skilled workforce.*

4.3 Collaborations and Capability Building

One of the ways in which capability was increased was through a strengthening of partnerships with external collaborators. This not only strengthened existing partnerships, but also created new partnerships; often as a consequence of the application process, where applicants want to strengthen their proposal by demonstrating that industrial sponsors have committed to collaborating. Collaborations involved partners from different sectors across academia, industry, and civil society.

The online survey asked PIs which sectors their partners were from. As shown in Figure 5, nearly all respondents (94%) said they had collaborated with academics from another university (94%). Whilst 76% said their projects involved collaborations with the private sector. Collaborating with business partners was influenced by the opportunities to create a pathway to impact for the application for outcomes from the research. Other reasons included benefits arising from complementing each other's practical or technical expertise and also because of the opportunity to leverage funding (for both the public and private actors).

Figure 5 Percentage of respondents with external collaborators from different sectors



Source: Technopolis, online survey of PIs (n=76)

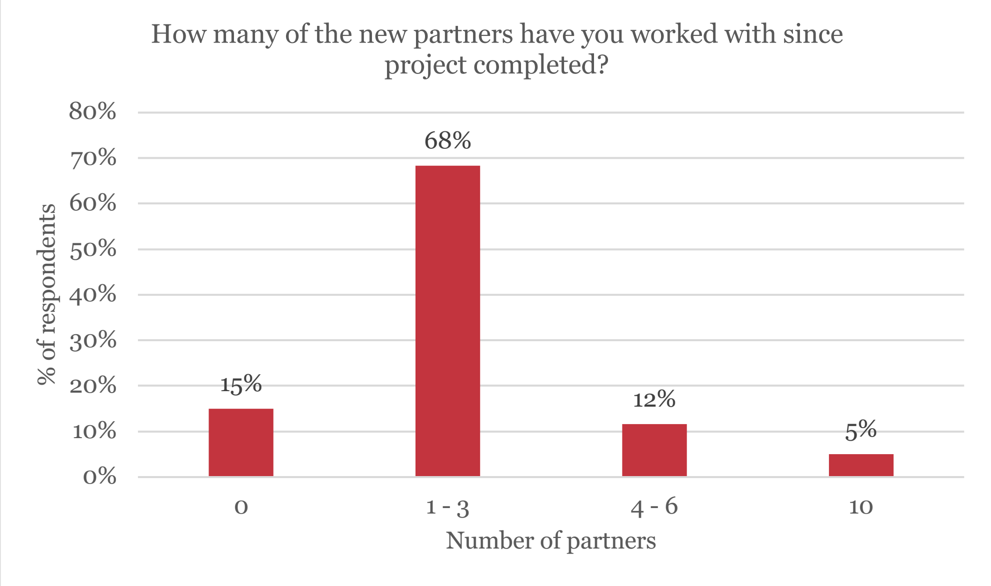
Responses to the qualitative telephone interviews reflected how addressing circular economy related challenges requires expertise from multiple disciplines:

"The project clearly had an interdisciplinary footprint in environmental management, in sociology (to understand the consumption patterns of food) and in economics to understand some parts of the network. It was very interdisciplinary: climate change, agri-environmental science, environmental management, food science, waste and resources, sociology, economics were all required".

PI lead of research grant, telephone interview

In most cases, collaborations continued after the initial EPSRC funded project was completed. Only 15% of respondents reported no further collaboration with the same partners, with the main reason given, in those cases, being a lack of further funding to develop the project together. As shown in Figure 6, in many cases the EPSRC project resulted in the creation of new partnerships which continued after project completion in follow-up collaborative research and development to progress the earlier advances through demonstrations and trials.

Figure 6 Partnerships that have continued since the end of the project



Source: Technopolis, online survey of PI project leads (n=60)

In addition, successful completion of projects helped to raise the profile of project partners and in some cases helped to create a 'hub' of expertise that would attract additional new partners for follow-on projects, both nationally and internationally.

"I think it has benefited UK's science on the international stage. The fact that the UK was leading the project has meant that people in USA, Japan, China know about our work and come to collaborate with us as a result."

PI lead of research grant, telephone interview.

"One of the benefits is strengthened collaborations with other universities in control theory research. This has become a magnet for other universities at international level.

PI lead of research grant, telephone interview.

4.4 Centres for Doctoral Training

The Grant award data provided by the EPSRC included details of three Centres for Doctoral Training (CDT) that are particularly relevant to the circular economy.[9] The three CDTs have received EPSRC funding with a combined total of £20.7m. This includes a follow-up grant for the *Doctoral Training Centre in Sustainable Chemical Technologies* at the University of Bath, which received an initial grant for the 2009 to 2018 period, and then subsequent funding for the 2014 to 2023 period.

The other two CDTs have received one round of funding each, including for the *Centre for Doctoral Training in Sustainable Materials and Manufacturing* at the University of Warwick, for the period 2014 to 2022, plus the *Centre for Doctoral Training in Sustainable Chemistry* at the University of Nottingham, also for the period 2014 to 2022.

The Directors of all three CDTs were invited to take part in a telephone interview. Interviews were achieved with the Directors of the CDTs in Sustainable Chemistry and Sustainable Chemical Technologies. Due to availability constraints, the Director of the Sustainable Materials and

[9] The EPSRC has funded more than 150 CDTs overall. These are multi-year, cohort-based training interventions in areas of adjudged national need, which complement the EPSRC's two other principal instruments for doctoral training: Industrial CASE programme (company chooses project) and Doctoral Training Partnerships (block grants to universities).

Manufacturing CDT was not able to take part in an interview. However, an overview of the Centre's aims and outcomes that are relevant to the study have been summarised based on published information.

Overall the evidence suggests the CDTs are building capability and skills to address industrial challenges. Particularly for the longer established *Centre in Sustainable Chemical Technologies* which first received funding in 2009. The other two CDTs began in 2014 and so their first cohort of students were just finalising their PhDs at time of this review (2018). Therefore, it was too early to determine the destination of the great majority of their first students. However, all the CDTs have a strong focus on **capacity building and training the next generation** of scientists and engineers by providing multi-disciplinary training in fields that are sustainability related and prioritised to address the needs of their industrial partners.

4.4.1 Doctoral Training Centre in Sustainable Chemical Technologies

Background and Introduction to CDT

The Doctoral Training Centre in Sustainable Chemical Technologies is based at the University of Bath and received funding for the 2009 to 2018 period (grant EP/G03768X/1), and then follow-up funding for the 2014 to 2023 period (grant EP/L016354/1). The original aim was stated in the grant application as being to "*place fundamental concepts of sustainability at the core of a broad spectrum of research and training at the interfaces of chemistry, chemical engineering, biotechnology and manufacturing" and to "respond to a national and global need for highly skilled and talented scientists and engineers in the area as well as training tomorrow's leaders as advocates for sustainable innovation."*

The Centre covers 4 main thematic areas of: 1) Energy and Water, 2) Renewable Feedstocks and biotechnology, 3) Processes and Manufacturing and 4) Healthcare Technologies. These four areas were considered to best articulate the needs of both EPSRC and their industrial partners. The Centre encourages students to work on projects that require multi-disciplinary input to address industry challenges, rather than formulate proposals that stick narrowly to these four themes or work only with students from the same disciplines. In practice, there is frequent overlap across these cross-cutting themes within the projects that students deliver.

Projects with the lead thematic areas of *Renewables Feedstock* and the *Manufacturing and Processes* were considered to be the most relevant to the circular economy. Projects under the other thematic areas also focus on sustainability issues, such as improving energy efficiency in industrial processes, although with fewer examples of 'circular' aims such as the recovery, reuse and recycling of resources.

The circular economy projects included one which focused on recovery of precious metals and pollutants from industrial waste streams. Plus, another which enabled carbon capture from industrial processes and then storage within renewable forms of plastic.

Engaging industry to address challenges

The aims of the Centre are very deliberately industry-focused in terms of both addressing skills gaps and through focusing students' projects to address industrial challenges. There are various mechanisms in place for engaging with industrial partners and prioritising projects in line with their needs. There is an external advisory board to steer the research programmes and thematic areas. There is also an industrial stakeholder engagement forum that meets annually, where students have an opportunity to present emerging results and exchange ideas with industrial partners. The primary aim of the Centre is to ensure their graduates are employable by industry and can address recognised skills gaps. The outcome of student-led projects in advancing scientific understanding were considered secondary, given the relatively limited resource and scope that student projects have in comparison with other academic and industry sponsored research programmes.

The total value of direct financial contributions provided by industrial partners was estimated at around £45m to date, with future contributions of around £20m expected by the time the current programme ends in 2023. These contributions were complemented by various other forms of in-kind support from industrial partners, for example; time to advise on programme prioritisation, equipment provision and use of facilities within their laboratories during secondments. The costs of becoming an industrial partner were kept as low as possible to maintain engagement and participation. The respondent described their model of industry engagement as being based *"around creating low barriers to working on competitive research. We don't want to charge them a lot of money for working on research projects."*

The funding contributions from industrial partners have been used to create additional places for students on the course, over and above the number of positions that would have been available through ESPRC funding alone. They also support the provision of resources and equipment to carry out projects that are of specific interest to partners. It was estimated that partners' funding had led to an additional 15 graduates over the first five years.

The default position of collaborative projects is that any Intellectual Property (IP) arising from a student's project will be open access in order to facilitate wider sharing of evidence, collaboration between projects and scientific advancement. However, in cases where the project relies on using commercially sensitive data provided by industrial partners, then they can choose to fully sponsor a project (rather than co-funded) in order to retain ownership of any IP arising.

Impact on skills, capability and career progression

To date, **144 places have been awarded to PhD students** within this CDT, and **53** graduated so far. The Centre follows-up with graduates to track their destination and obtain feedback from their employers. It was estimated that over half are employed by private sector businesses, around a third continue academic study in Higher Education Institutions and the rest take up posts within public sector organisations (such as Civil Service) or within charity and voluntary sector organisations. The table below gives a breakdown of destinations by broad sector for the 50 graduates where the Centre managed to obtain a response, with 56% having taken up positions in industry.

Table 6 Next destination of students from CDT in Sustainable Chemical Technologies (n = 50)

Sector	Number of graduates in employed in each
Private sector businesses	28
Academic Institutions	16
Public Sector organisations	3
Third sector (Charity/ Voluntary organisations)	3

Source: Technopolis, based on interview with CDT Director

Among those working in the private sector, most are employed by either chemical manufacturing firms or for technical research consultancy firms related to chemistry. Common public sector employers include the UK Civil Service, including the Department for Transport, while others have gone on to teaching positions. The respondent estimated that around 15% of graduates had moved abroad.

The PI interviewed received 48 letters of support from employers which mostly gave highly positive feedback. The PhD graduates were described as excellently prepared in terms of problem solving and creativity and crucially doctoral graduates have in-depth knowledge of their field, which enables companies to more readily explore potential future technological breakthroughs and devise potentially innovative (circular) products or process. This classic component of any doctorate programme – the acquisition of deep domain knowledge – is the most valued part of the CDT's capability building, expanding the total number of specialists coming into the labour market and available to industrial partners. The ability to help shape the focus of doctoral projects is also key. As the CDT Training Director has stated[10];

"Public concern about plastic microbead pollution has led to bans, but many other materials used in 'washaway', or single use, products are not sustainable either. Developing manufacturing processes and products together and underpinning this with a deep understanding of the science leads to new ingredients that our industrial partners are keen to exploit commercially".

One quote from an industrial partner of a biotech company also illustrated the value of bringing academic and industrial scientists' skills together:

"The whole idea of sustainable technologies and bringing together different capabilities are absolutely essential if we're going to build something that has impact".

The students are also trained in more general professional skills such as communication skills, project management and public engagement to prepare them for industry. A central aim of the CDT is to make students more employable by industry rather than solely to create future academics. It was explained that achieving direct, near-term economic impact was not the main purpose of the CDT. The primary aims are more around addressing longer term skills gaps of industry and to provide employment-ready graduates who can then work within relevant firms to support their own R&D departments and then create commercial opportunities, once employed. The value of this mix of technical expertise, communication skills and business acumen is illustrated by a quote from a CDT graduate who had taken up a position with a chemicals manufacturer[11]:

"On a daily basis I have to work and communicate effectively with a cross-disciplinary group whilst also quickly becoming familiar with new concepts; this is in no small part thanks to the breadth of exposure I had during my time in the CDT. Close links to industry and an understanding of the triple bottom line pays dividends when trade-offs must be made between technical curiosity and business success."

4.4.2 Centre for Doctoral Training in Sustainable Chemistry

Background and Introduction to CDT

The EPSRC Centre for Doctoral Training in Sustainable Chemistry, based at the School of Chemistry of the University of Nottingham, received EPSRC funding for the period 2014 to 2022 (grant EP/L015633/1). The grant application described the key objectives as being to *'address the shortage of PhD graduates who have the skills needed to implement sustainable technologies'* and the *'to develop new chemical and manufacturing solutions that are safe, efficient and, above all, sustainable'* through the creation of a highly interdisciplinary centre to which creates *'"industry ready" PhDs who will have an excellent understanding of sustainability for the chemicals sector'*.

The Centre focuses research on areas of industry where there is a need to; a) make industrial chemical processes more sustainable or b) where chemistry makes is more key to achieving sustainability goals.

Research projects are grouped within three broad, and often cross-cutting themes; 1) Sustainable Syntheses, 2) Continuous Manufacturing and 3) Renewables. The PI interviewed estimated that between a quarter and a third of projects could be considered as working on topics that directly relevant to the concept of circular economy. Within these, one main theme waste recovery; particularly around using waste for renewable energy.

Engaging industry to address challenges

It was explained that Industrial Partners have been involved in shaping the direction of the Centre since its inception and continue to collaborate through a variety of ways. At the start of each year, Industry

[10] From Centre for Sustainable Chemical Technologies report "Celebrating 10 years" University of Bath.2018

[11] From Centre for Sustainable Chemical Technologies website.

representatives attend workshops at the Centre to give presentations about the sustainability challenges their sector is are facing, how this impacts their businesses and where they see the main areas of future opportunity. Throughout the year, they come back for follow-up workshops to go into more detail on specific chemistry related R&D challenges that their business is interested in. The Centre does not directly assign each PhD student to work with particular partners, but these workshop sessions provide a range of options on the types of challenges they can focus their projects on, which facilitates the matching of students to industrial partners.

Partners provide funding to cover the costs of the projects they sponsor and the student's PhD placement itself. Industrial partner contributions generally range between covering 30% to 50% costs of the PhD position and their associated project costs. Direct financial contributions were estimated to have amounted to around £550,000 in total, to date. Other in-kind contributions from partners include time to attend CDT Board meetings, induction events, leading workshops, overseeing internships/placements, which was estimated to amount to around 20 to 30 days staff time per year for each partner. Additional in-kind contributions include provision of equipment or providing access to use their laboratories. However, the total value of these contributions had not been quantified.

The CDT held its first Industrial Showcase conference in September 2016 to provide a forum for students to present their emerging findings to industrial partners. The event was attended by a range of industry representatives including GSK, Croda, Synthomer, AstraZeneca, Bruker, Endeavour Chemicals, Nuplex Resins and Lubriz.

Impact on skills, capability and career progression

At the time of the research, **the CDT had recruited 52 students** so far (with recruitment spread annually across 2014 to 2018). The first years' recruits were due to graduate at the end 2018, with an **additional 17 students** starting in 2018.

It was therefore too early to determine the destination of students. Nevertheless, the information gathered from the interview and review of CDT publications suggests that the Centre is working in similar ways as the CDT in Sustainable Chemical Technologies (see above) to engage industrial partners, prioritise research according to the challenges they face, and train students to be employable and meet the skills gaps reflected by their partners. This includes completing modules on wider professional skills, such as a course on using PRINCE2 for Project Management, and one on how to communicate scientific findings.

4.4.3 EPSRC Centre for Doctoral Training in Sustainable Materials and Manufacturing

The EPSRC Centre for Doctoral Training in Sustainable Materials and Manufacturing is based at the University of Warwick and was funded by the EPSRC for the period 2014-2022 (grant EP/L016389/1). Due to availability constraints, the Director of this CDT was unable to take part in an interview, therefore, information summarised below based on a review of the Centre's publications.

The Centre is a collaboration between the Universities of Warwick, Exeter, and Cranfield, which aims to address industry-driven research challenges around sustainability, while training the research engineers to address skills gaps. Areas of focus are based around improving sustainability in materials and manufacturing, including; establishing natural or recovered materials as feed-stocks, reducing process inputs and outputs without compromising performance or economic viability, extracting high value materials from waste streams, and ultimately establishing economic and environmental sustainability.

Engaging industry to address challenges

The Centre works in similar ways to the other two CDTs described above in terms of how they engage industrial partners to prioritise the subjects of student's projects. The website explains that industrial partners submit their suggested "challenges" for students to choose from. That company then acts as the student's sponsor for the duration of the four-year programme. Industrial partners are then expected to support the researcher through provision of staff time to provide guidance and access to facilities. This 'mentor' relationship aims to give partners a 'hands-on' role in ensuring that the students' research projects are aligned to the long-term strategic goals of the business.

Impact on skills, capability and career progression

The Centre is at a similar stage to the CDT on Sustainable Chemistry: it was launched in 2014, so the first cohort of students are only completing their PhDs and graduating at the time of research (end 2018).

It is therefore too early to gather information on the destination of graduates or direct outcomes arising from completed projects. Nevertheless, the Centre's website[12] provides a series of illustrative case studies to showcase the aims of students' research projects and provides quotes from industrial partners on the added value for them in terms building their R&D capabilities.

For example, one project, titled "*Ammonia Recovery From Sewage*" aims to recover pollutants such as phosphorus, nitrogen and ammonia from Wastewater Treatment Plants (WWTPs) and then use these captured waste outputs as input resources for other industrial processes, such as the production of fertilisers. The economic and environmental impacts of EPSRC funded research in developing waste water treatment plant technology are explored further in Section 5. The benefits to industry from this collaboration in terms of building research capabilities and recruiting graduates are described by a representative of Trent Water Plc:

"The benefits to Severn Trent Water are considerable; the EngD programme allows us to advance industrially relevant research in an area we have specifically identified as important to us, it gives the opportunity to build upon our relationships with the universities involved, and provides a great route to bring top quality engineers into the water industry. We find the Engineering Doctorate a very cost-effective model for achieving our research aims, while also providing the opportunity to recruit high calibre technical staff into the business."

Many of the sponsors of CDT programmes are large industrial firms. However, another published case study[13] illustrates the benefits for smaller firms, in terms of building their R&D capabilities where they have less internal R&D resources. Their collaboration with the CDT was based around sponsoring a project to advance techniques for recycling carbon fibre.

"The Eng D programme has allowed ELG Carbon Fibre to expand its R&D portfolio to address areas of technology that are important in the medium to long term. As an SME, internal R&D resources are often focussed on short term needs, and this ability to plan and carry out work aimed at longer term developments is an important part of the company's growth strategy. A further benefit that derived from the Eng D programme is access to high quality academic input and excellent R&D facilities across a range of leading universities, which an SME would not normally be able to fund on a commercial basis".

[12] http://www.sustainablematerialsmanufacturing.com/case-studies/

[13] http://www.sustainablematerialsmanufacturing.com/case-studies/

5 Economic and Environmental Impacts

5.1 Introduction

This section addresses the research questions on what longer term economic and environmental impacts the grants are expected to have, including;

a. *How has EPSRC funding helped in addressing key societal challenges such as sustainability, environment, energy and health?*
b. *What evidence is there that EPSRC-funded research and training has led to business benefits, for example, cost savings and increased turnover, profit and exports?*

These questions are interrelated, because the environmental benefits of growing a circular economy, such as; reduced use of raw materials, energy efficient manufacturing, less waste disposal and increased recycling are often directly linked to economic benefits, such as; lower production costs, energy cost savings and profits from the sale of more sustainable products. The societal benefits from reduced greenhouse gas emissions (CO2e) can also be valued. Our analysis of economic impacts is therefore primarily based on the valuation of these linked environmental and resource efficiency benefits which the grant funded developments in technology and manufacturing processes have led to.

This section begins with a brief summary of findings from our survey of funding recipients to gain insight on the range of different types of environmental and economic benefits that they expect their projects to achieve. It then explores these types of benefits across different sectors in more depth, through a series of seven case study projects. This provides estimates of the economic benefits arising for their industrial partners and the extent of wider societal impacts.

From five of the case study projects alone, we have identified that there are approximately **£130m** of discounted benefits that can be attributable to the funding provided by the EPSRC grants, over a ten-year period.

The value of the grants for the five-case studies that we have produced ROI assessments for is approximately £15m, which represents 7% of the portfolio of grants. The **central estimate** for the aggregate ROI for the EPSRC funding of these five case studies is approximately **£9.62 per £1** of EPSRC grant funding.

Our analysis has conducted sensitivity analysis to account for items with implicit uncertainty such as the responses provided by case study interview respondents, and the level of attribution of outcomes to the projects they relate to. The sensitivity analysis produced a range of estimated discounted benefits for the total of the 5 case studies between **£45-447m**, representing a range of ROIs between **£3.32 to 32.73 per £1** of EPSRC grant funding.

5.2 Principal Investigators' (PI) views on economic and environmental benefits

Results from our survey of PIs were positive in terms of high proportions stating that socio-economic and environmental outcomes were *expected to* be achieved. However, few PIs were able to provide evidence of quantifiable estimates of the extent of these economic or environmental benefits. This is partly because the majority of projects related to R&D of technologies that were still at mid TRL stage and not yet been commercialised. In addition, in cases where technologies/processes had been adopted by industrial partners, the PI did not necessarily have access to precise information on the commercial benefits to these partners. Indeed, it was often suggested that we would have to obtain information on commercial benefits from the industrial partners themselves. This is the focus of the section 5.4 below, where our case studies include finding from interviews with a range of industrial partners to gather this evidence.

The survey and telephone interview with grant recipients was useful for gaining insight on explaining *how* their research led to advances in new technology or manufacturing process had achieved, and *why* this was expected to achieve a range of different forms of circular economy related benefits.

5.2.1 Overview of types of economic impacts achieved

For a number of industrial partners, the involvement in the EPSRC project has led to significant changes in their manufacturing or business processes. Some clear examples of how economic impacts to businesses have arisen were reported. Through semi-structured telephone interviews, industrial partners described how their collaboration with the EPSRC funded project was instrumental in opening up avenues of R&D; through the pathway from collaboration in exploratory research to implementation of changes in their company's internal manufacturing process. The most common ways in which economic benefits were achieved were through:

- Cost savings deriving from increased efficiencies in production processes (less inputs and resources used to achieve the same or better products)
- Additional revenue streams created from selling innovating technologies to other businesses
- Higher profit margins deriving from the manufacture of better performing products.

Evidence suggests that the most common economic impact on businesses were from increased productivity and cost savings brought about by efficiencies in manufacturing processes. Respondents reported quantifiable estimates of economic impacts for five out of the seven case studies. For the remaining two some anecdotal or qualitative explanations of why economic benefits had been achieved were described, but they were unable to quantify these.

In the two cases where it was not feasible to provides estimates of what level of economic or environmental impacts may be attributable to the grants (case studies 6 and 7 below), it was explained that large scale manufacturers in sectors such as pharmaceuticals of aerospace will typically make use of several strands of external scientific evidence when deciding to implement changes to design or manufacturing of products. They then carry out further testing and development through their own internal R&D processes before these are operationalised. The findings from the original EPSRC projects may then be viewed as one strand of evidence, that played some role in helping progress technologies or processes to mid-range TRL or MRL, which are then further developed as part of wider R&D programmes, making it difficult to attribute directly quantifiable outcomes to the initial project.

The most common route to circular economy related impacts was through increased levels of resource efficiency, due to industrial partners adopting innovative manufacturing processes. For example, one aircraft components manufacturer redesigned their maintenance and servicing operations, with a greater focus on the re-use and recycling of components, which created savings from reduced usage of raw material inputs. The second main route to impact was where the partner incorporates new technologies in the creation of manufacturing equipment or services which they sell to their customers. For example; new chemical crystallisation technology which makes drug manufacturing more efficient. In this case, the environment benefits will be realised across the wider pharmaceutical sector, through companies who buy and adopt the technology.

5.2.2 Survey responses – circular economy related outcomes

The survey of grant recipients asked PIs whether they expected their project will achieve a range of different resource efficiency circular economy related benefits. The most common types of **environmental benefits** where respondents stated their project would have an impact were;

- A reduction in Greenhouse Gas Emissions from relevant sectors (e.g. CO_2e) – 67% of respondents
- A decrease in waste outputs from relevant sectors – 61%
- A reduction in the use of fossil fuels in relevant sectors – 58%
- A reduction in energy usage among relevant businesses or consumers – 55%

- Reduced use of raw materials for manufacturing in relevant business sectors – 51%.

In the qualitative telephone interviews, respondents were asked to explain the reasons why they expected these environmental benefits to be achieved. The following quotes illustrate examples of how their projects were expected to achieve circular economy related environmental benefits;

"We demonstrated the principles of a circular economy … Instead of using oil-based inputs we use bio-based stocks [for plastics manufacturing]. This has an environmental implication: not using oil produces less carbon residuals [CO2e emissions]. Part of our strategy is also the use of waste, which we extract from landfill. One of the key components is to use it [waste] as a source. Landfill has become a source of materials rather than a sink."

PI with lead theme: Engineering.

"The project was aimed at developing a continuous process of manufacturing nano-crystals using biomass. …where organic waste could be used as a raw material and that would have an impact on environment as well as reducing costs of the materials. The product is a good insulator that could be utilised as a building material. This may have an impact on energy consumption in heating…"

PI with lead theme: Manufacturing the Future

"We have developed a home compostable material made out of straw wastes to replace paper and plastics for food packaging. The environmental outcomes are evident. The manufacturing process can be based in a farm and this can generate employment in rural areas."

PI with lead theme: Manufacturing the Future

5.2.3 Attribution of outcomes to the EPSRC grant

To obtain a measure of attribution of outcomes to the EPSRC funding, PIs were asked what the probability was that their institution could have attributed these outcomes via other means, such as alternative forms of funding. 80% said there was either No or Low probability that these outcomes could have gone ahead without the EPSRC grant.

Respondents were asked to explain why the EPSRC funding was needed for their projects to have gone ahead. Most common reasons were that the EPSRC is the only viable route for funding research projects that are within their field of study, whilst at an exploratory research stage. Commercial funding may be feasible, but only once the technology or process has been de-risked and developed to a more advanced TRL or MRL stage. It was noted that EPSRC funding had been strategic in enabling researchers to progress science in areas where private sector funding was not available and not fall behind international competitors:

Quotes from telephone interviews with PI help to elaborate on these points:

- "*Because we embarked in something new, it would have been hard to get it funded from other sources. We wanted to establish a defined new lead in an important new avenue of additive manufacturing."*
- *"It would have been more difficult to do it without the EPSRC. Back in 2008, there was a lot of question marks over whether synthetic biology would become an important field. It is now recognised as an important theme. EPSRC demonstrated strategic vision in this sense."*
- *"It would have been extremely difficult without the EPSRC, it would have happened five years later. We would have been way behind everybody else*".
- *"We would have been working in a crowded marketplace and would need to do incremental research, such as practical work, and applied activities which would have been less effective and less impactful on society and the environment."*

5.3 Spin out companies

The grant award data provided by EPSRC included details of spin-out companies that were reported to have been created as a result of the project (where project leads had reported this outcome in Researchfish®). This listed 17 companies, including basic information such as the Company registration number and website (where known), but not financial information such as annual turnover or company valuation. Our survey/interviews with PIs asked questions on whether spin-out companies have arisen that were attributable to their project. We also asked for additional financial information on their estimated annual turnover and number of employees.

Respondents to the survey provided details of nine spin-out companies (see Table 7 below). Of these, six were new companies that had not previously been recorded in Researchfish®. Giving a combined total of **23 spin-out companies**[14] being reported to have been created as a result of the grants funded research projects. The table below provides a list of company names, alongside estimates of their turnover and number of employees in the cases where these were provided through the survey with PIs.

Table 7 Spin-out companies reported through survey of PIs

Name of the company created	Source of reporting (Survey of PIs or Researchfish®)	Their estimated annual £ turnover (from survey with PIs)	Number of employees (from survey with PIs)
ABIL Ltd	Survey		
Absolute Maximum	Survey		2
CM Digital Innovations	Survey	60,000	1
Membranology ltd	Both Survey and Researchfish®	250, 000	3
OXHEX	Survey	100,000	3
Perlemax Ltd.	Both Survey and Researchfish®	5,000,000	10
Plasmagy	Survey		
Prospective	Survey	2,000,000	10
Added Scientific LTD	Both Survey and Researchfish®		10
8power Ltd	Researchfish®		
Bentham 3D Limited	Researchfish®		
Bento.Lab (Bento.Bioworks)	Researchfish®		
BIPV Co	Researchfish®		
Contextualised	Researchfish®		
E.I.I.S. LIMITED	Researchfish®		

[14] Note the table lists 22 companies rather than 23. For one of the grants, it was reported in Researchfish that a spin-out company had been created, but the name of the company was not given.

Econic technologies	Researchfish®		
Hexigone Inhibitors Ltd	Researchfish®		
Insignia Technologies Ltd	Researchfish®		
MUREX ADVANCED MATERIALS LTD	Researchfish®		
SPECIFIC Innovations Ltd	Researchfish®		
Synaptec Ltd	Researchfish®		
Utterberry Ltd	Researchfish®		

Source: Technopolis Survey/ interviews and Researchfish®

The figures above on annual turnover and number of employees are based on the PIs own estimates. To try to verify this information, searches for of all spin-out companies listed in both Researchfish® and the survey/interviews were carried out using a number of secondary databases which record publicly listed financial information, including; FAME (by Bureau Van Dyke), the Bloomberg Terminal, and other online sources including; Pitchbook and Owler. These searches found details of estimated annual turnover and private equity investment deals for four of the companies, as shown in Table 8 below.

Table 8 Company Financial Information obtained from secondary sources

Company name	**Estimated £Annual Turnover**	**£value of publicly disclosed private equity investment**
8power Ltd		700,000
ABIL Ltd		700,000
Econic technologies	3,801,728	7,000,000
Insignia Technologies Ltd		870,000

Source: Bloomberg Terminal and Owler

5.4 Case Study projects – economic and environments impacts

1.1.4 Introduction

A range of projects were selected for more in-depth case study to understand what benefits have arisen from the projects for partners who collaborated in the research programmes and the extent of wider economic and environmental impacts. These seven case studies are not intended to be representative of the wider population of all grants awarded in a statistical sense. However, they were selected to broadly reflect a range of different types of businesses and sectors that commonly collaborate with EPSRC funded research relating to circular economy. This provides evidence to build the theory of change on how different types of environmental and economic impacts can be attributed to the original research grants. The case studies are used to provide estimates of Return on Investment estimates from the value of EPSRC grants, at both case study level.

In summary, the main criteria used to select the cases studies included;

a) where the aims of the research project are relevant to the concept of the circular economy. Across the different case studies we reflect different 'points of the circle', for example; design for longer lifespan of products, use of less resources in manufacturing processes, less waste at end of product life and increased recovery of materials for recycling.

b) to reflect projects across a range of academic disciplines and with outcomes for various industrial sectors, including; plastics manufacturing, pharmaceuticals, clean energy, building construction, food and drink, automotive, aerospace and defence, and;

c) where the project summaries include more explicit aims around addressing challenges of industrial partners or suggest that routes to commercialisation of products were actively explored as part of the project.

These case studies, therefore, can be considered examples of the types of research programmes that are most likely to have achieved environmental and economic impacts. We have therefore not extrapolated level return in investments estimates from these seven projects to all 223 grants.

1.1.5 Summary of Case Studies

The seven case studies that have been selected for in-depth study, are:

Case Study 1: Low Carbon Wastewater Treatment

Case Study 2: Recycling Carbon Fibre using a Fluidised Bed Process

Case Study 3: Low Carbon Vehicle Structures (TARF-LCV)

Case Study 4: Through-life Engineering Services (TES Centre)

Case Study 5: Catalysts to reduce carbon dioxide in production of carbon-based fuels (Econic)

Case Study 6: EPSRC Centre for Innovative Manufacturing in Continuous Manufacturing and Crystallisation (CMAC)

Case Study 7: EPSRC Centre for Innovative Manufacturing in Additive Manufacturing

A summary of each Case Study is presented in Table 9 below:

Table 9 Summary of Case Studies

#	Name	Period	Grant Size	Aims	Key Benefits (to circular economy)	ROI range
			£000			£ per £ of EPSRC grant (central case)
1	**Low Carbon Wastewater Treatment**	2008 – 2009	199	Develop an energy neutral pilot wastewater treatment plant Examine potential for increasing the energy production capacity of the generated renewable biogas.	Reduction of energy required to run a typical wastewater treatment plant serving 50k customers Conservative 6000 MWh of electricity saved per year per plant.	4.94-12.06 (8.23)
2	**Recycling Carbon Fibre using a Fluidised Bed Process**	2011 – 2012	101	Provide an assessment of the potential commercial opportunities and market applications of a small-scale 'fluidised bed process' for recycling carbon fibre composite materials With Boeing providing additional finance to extend the project and develop a scaled up pilot plant, representative of a commercial scale operation.	Reduction of energy required to produce virgin carbon fibre Conservative reduction of 8000 GJ of energy and 400 tonnes reduction in CO2e emissions.	0.86-18.04 (5.37)

3	**Low Carbon Vehicle Structures (TARF-LCV)**	2011 – 2016	4,221	Develop closed-loop recyclable aluminium and magnesium alloys Improve recyclability of scrap aluminium	Reduction of energy required to produce virgin aluminium Conservative reduction of 8000 GJ of energy and 400 tonnes reduction in CO2e emissions.	5.06-85.93 (16.54)
4	**Through-life Engineering Services (TES Centre)**	2011-2015	5,834	Develop the knowledge, technologies and processes to improve design and manufacture of complex engineering products. Improve reliability of complex engineering products through their lifecycle, to reduce whole life costs associated with their servicing.	Reduction in costs associated with 20% improvement in asset availably, across £20b of output	3.35-6.71 (5.03)
5	**Catalysts to reduce carbon dioxide in production of carbon-based fuels (Econic)**	2010-2013	1,675	Develop catalysts to enable the reduction of carbon dioxide to produce carbon-based fuels Enable capture and storage of carbon dioxide in the production of other products.	Create 'value' for polyol producers Reduced CO2e emissions savings as part of polyol production,	5.59-61.44 (27.37)
6	**EPSRC Centre (CMAC)**	2011-2016	6,060	Development of continuous manufacturing processes for powders, particles and crystals Improvement in the precision of crystal formation through continuous processing	Reduces equipment Smaller production facilities with lower building and capital costs. Shortening supply chains. Possible manufacture, smaller quantities of customisable of drugs for users Less chemical waste	n/a
7	**EPSRC Centre (Additive Manufacturing)**	2011-2012	5,973	Research multi-material additive manufacturing (AM) processes, materials and design systems, and potential industry applications.	Makes manufacturing processes shorter, smaller, more localised, and more collaborative Reduces material consumption and energy consumption Reduced waste disposal Reduced transportation in the supply chain	n/a

Source: Technopolis, based on EPSRC grant administrative data.

The remaining sections of this chapter provide further detail for each Case Study, with the descriptions structured as follows:

- Introduction
- Aims of the Research
- Relevance to the Circular Economy
- Economic and environmental impacts
- Estimates of Return on Investment (Case Study 1-5 only)

It was not possible to provide robust return on investment estimates for Case Study 6 and 7. These case Studies include qualitative descriptions of the relevance to the circular economy and wider benefits.

The following generic assumptions have been made regarding the estimated benefits associated with all Case Studies, where applicable.

Table 10 Generalised assumptions across case studies

Assumption	**Unit**	**Value**	**Source**
Base Year		2009	Technopolis
Discount rate	%	3.5	Treasury Green Book
Industrial Electrical Tariff	£/kWh	0.08	BEIS DUKES
Carbon Intensity of Grid	gCO2 / kWh	225	BEIS DUKES
Carbon Emissions Cost (EUA)	EUR/ tCO2e	20	EEX.com EUA price (Feb 2019)

Source: Technopolis, and others

The individual Case Study descriptions also provide specific assumptions relevant to the identification of benefits.

A key consideration in the identification of the economic returns for the EPSRC grants is the extent to which the funding provided by EPSRC is responsible for the benefits identified in the analysis.

5.5 Case Study 1: Low Carbon Anaerobic Wastewater Treatment and Renewable Energy

EPSRC Grant title	**Delivering Low Carbon Anaerobic Wastewater Treatment and Renewable Energy Production**
Principal Investigator	Professor E. Cartmell, School of Applied Sciences, Cranfield University
Time scale	01/04/2008 to 30/09/2009
EPSRC Investment	£199,108
Industry Investment	£110,400
Other grants	EU Horizon 2020 grant (£500k)
Industry Partners	Anglian Water, E.On, PAQUES B.V., United Utilities, Yorkshire Water

5.5.1 Introduction

Since the water industry was privatised in 1989, it has invested over £130bn in water and wastewater infrastructures, which is generally considered to have improved environmental standards and customer service.[15] The water industry, however, remains the fourth most energy intensive industrial sector in the UK and uses approximately 2-3 % of net UK electricity, releasing approximately four million tonnes of greenhouse gas emissions (carbon dioxide equivalent) every year.[16] Energy is used to abstract, treat and distribute drinking water; collect, treat and discharge sewage and manage sewage sludge.

The conventional method of treating waste water in large water companies in the UK consists in forcing air, blown from a compressor, into the wastewater (aerobic treatment). This is an energy intensive process, with only some companies managing to recover a portion of the energy needed for this process by using energy produced by anaerobic digestion of sludge. This EPSRC funded project enabled researchers to study an anaerobic treatment for wastewater using a bio-reactor, which not only is less energy intensive (given that there is no need to blow air) but has also the potential to reduce the production of carbon dioxide and recapture waste methane gas for usage in energy projection, becoming energy neutral overall.

5.5.2 Aims of the research

The aim of the EPSRC funded project was to develop a pilot plant at Cranfield University, in which an energy neutral sewage treatment could be developed. The research is a pilot-scale feasibility study to examine the fundamental operation of an anaerobic bioreactor for the treatment of wastewater and to examine the potential for increasing the energy production capacity of the generated renewable biogas. An added benefit of the new water treatment was the potential to introduce nutrient recovery technologies, to recover Nitrogen and Phosphorus. In conventional wastewater treatment processes these environmentally and economically important nutrients are removed but not recovered.

The research project made use of a reactor imported from The Netherlands for initial investigations so as to be able to develop an anaerobic Membrane Bio Reactor as well as developing technologies improving the efficiency of the biogas conversion process.

5.5.3 Relevance to the Circular Economy

Research into low carbon wastewater treatment and production of biogas has the potential to offer benefits to the UK's energy system by triggering a circular economy in this sector. By reducing the

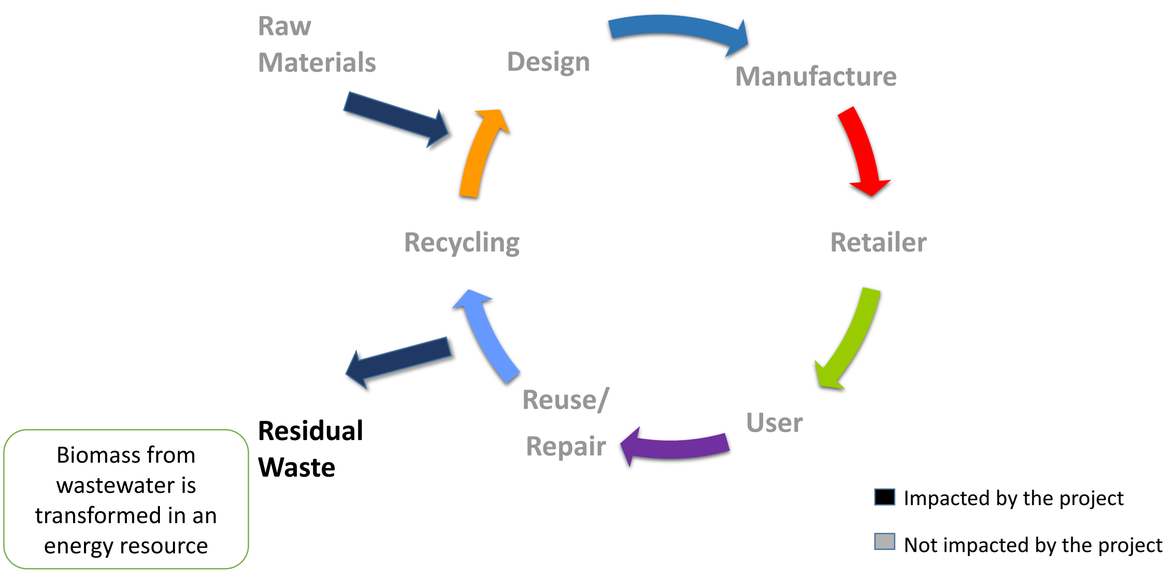
[15] MBA Group. Available at: http://www.mba-group.com/media-centre/mba-blog/facing-up-to-water-industry-challenges-5

[16] EPSRC, details of grant. Available at: https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/F062052/1

amount of energy required to treat sewage whilst at the same time producing renewable biogas, the new technologies can bring economic and environmental benefits as follows:

- recovering nutrients from waste sewage
- cutting the cost of running energy-intensive water treatment by replacing it with low carbon anaerobic treatment
- self-generating energy through the anaerobic digestion of the sludge produced; splitting the biomethane from the carbon dioxide and injecting the methane into the gas grid.

Figure 7 Circular economy of energy production from wastewater



Source: Technopolis

5.5.4 *Economic and environmental impacts*

The aim of the EPSRC project was to establish fundamental knowledge with regards to the development of an anaerobic waste water treatment by developing a pilot plant, designed to cater for a population of 400-500. This was pioneering work at the time. According the PI of the original grant, Professor Cartmell, technological developments up to TRL 5 are attributable to the EPSRC funds.[17] Prof Cartmell has since moved to Scottish Water to take up a post as their Chief Scientist. Research on anaerobic waste water treatment and energy production has been continuing at Cranfield University under the supervision of Professor Ewan McAdam.

Professor Cartmell said:

"Since I wrote the bid, the project has moved from being highly speculative, to realistic, and now very soon, realised. It was the EPSRC funds that made this leap possible."

Anglian Water and Severn Trent plc were industry partners and the current PI continues to collaborate with a group of UK water companies. For example, Professor McAdam's research group is currently

[17] Interview with Professor McAdam

involved in the demonstration phase of an anaerobic water treatment plant at Severn Trent and is co-partner with them on an EU NextGen project which co-funds the plant.

5.5.5 Outcomes for Industry

The interest from implementing the new technology among both water and electricity industries is strong, with the former aiming at implementing the new treatment and the latter focussing on its output (buying bio-methane to pump directly into the gas grid). Scottish Water, together with Anglian Water and Severn Trent, formed a peer group, with an interest in continuing to build on the work done at Cranfield with the aim for furthering the development and implementation of reactors.

A representative of Scottish Water said:

"Scottish water wants to embed a circular economy approach into all our activities, from generating energy (biogas) and value (nutrients) from waste streams, to reducing carbon dioxide emissions by cutting out energy intensive processes from our waste water treatments."

The group is working on developing a 'Membrane bioreactor' (MBR) treatment plant, building upon the technology advanced by Cranfield since 2008. Although this project is now independent from Cranfield University, the group shares knowledge with the research group at Cranfield and taps into their scientific expertise on methods for recovering methane from the reactor. A representative from Scottish Water said that once their pilot study is running, they will be able to assess scalability, gas production rates, potential for other lines of revenue coming from, for example, the formation of bioplastics, and the recovery of nutrients or metals. These assessments will inform their business model.

A representative of Scottish Water estimated that, once implemented, the value of energy production from this MBR treatment plant would be around £250k per year:

"If aerobic treatments catering for a population of 50,000 were converted to anaerobic treatments, this work would be worth £250k per year, depending on the technology used. To give an idea of scale, the value of the original EPSRC grant of £200k would be recovered by one plant in one year."

It was explained that in the last 15 years alone the water industry has invested around £1.5bn in aerobic waste water treatment, using older technology. Water companies will therefore prefer to introduce the new MBR technology gradually as older plants (eg prior to 1995) need to be upgraded.

Severn Trent plc is a UK water company responsible for removing and cleaning 1.4 billion litres of waste water per day. Severn Trent's collaboration with University of Cranfield is aligned with the two strategic objectives the company has set out:

- to become carbon neutral
- to maximise the opportunity to recover valuable material from waste.

The collaboration between Severn Trent and Cranfield dates back to the time of the original grant, as Severn co-sponsored the first PhD student working on this topic. They remain sponsors of the PhD programme. A representative of Severn Trent said:

"The collaboration with Cranfield is as strong as ever. We are building a new plant based on the technology developed in 2008 as part of the EPSRC funded project."

Severn Trent is now in the process of completing the development of a Demonstration Plant at one of their water treatment sites that will enable the implementation of the anaerobic MBR technologies related to the biogas production. EU-funds from a Circular Economy programme (400k) are also contributing to support the building work.[18]

[18] Watershare. Available at: https://www.watershare.eu/watershare-news/start-of-new-h2020-project-nextgen/

The purpose of the demonstration plant is not yet to generate revenue, but rather, to validate the technology, and to move it up the TRL, in order to prepare for commercialisation. The plant will be completed by December 2019 and is expected to become the largest anaerobic MBR in the world.[19] Throughout 2020 the plant will be generating biogas to measure its quality and quantity. This will be on a small scale (500mc3 per day). A representative of Severn Trent said:

"Receiving the EPSRC funding meant that we could reduce the risk of us investing in early stage research. Given the risks involved, it is very likely that we would not have carried out the research, so the contribution of the EPSRC was vital."

With regards to the timescale, the switch to anaerobic treatment will be gradual. It is estimated that there may be 5-10 plants every five years where upgrades are necessary and where new technology can therefore be introduced. Severn Trent is also exploring the possibility to retrofit the technology to existing tanks by removing the diffusers and converting the tanks to the anaerobic process. Although this conversion would speed up the implementation, this scenario would require capex investment.

Implementation at full scale is predicted for the water company's next investment period (2025-2030). From 2025, with the implementation of the activated anaerobic technology, Severn Trent estimate they can become **energy neutral and save £10m per year in energy costs.**

There are a number of reasons why this new water treatment aids the circular economy. Although initially the renewable energy generated by the anaerobically digested sludge will be absorbed by its internal demand, when all the aerobic wastewater treatment plants will be substituted with anaerobic treatments, there will be a reduced internal demand for energy, which may result in Severn going from being energy neutral to energy positive and so will be in a position to sell the biogas.

Another advantage of the anaerobic treatment is that nutrients will be in greater concentration in the waste water and so they will be easier to recover. There are other products attainable through the process of the biogas clean up, such as Ammonium Bicarbonate. Other opportunities for recovery are under investigation.[20]

In addition, anaerobic bacteria are much slower-growing and produce less sludge. As a result, there is a reduction in carbon footprint: given that an anaerobic reactor can produce 10-20% less waste water sludge,[21] there is less of it to dispose or transport to land. The carbon directly emitted in the production of the sludge is reduced; and the carbon indirectly emitted from transporting it is also reduced.

5.5.6 Estimates of Return on Investment

Our ROI analysis is based on the replacement of 'standard' waste water treatment (WWT) plants serving approximately 50k customers and using aerobic waste water treatment technology, with plants of a similar size that use anaerobic digestion.

The two key streams of benefits for the Case Study are:

- value of avoided energy required to operate WWT plants
- value of CO2e emissions associated with the provision of energy to WWT plants from the UK national grid

For the Case Study, in addition to the assumptions described above in Table 10, the following assumptions for the baseline have been made:

- Energy requirements for wastewater treatment plants remain constant over time, and that current WWT plants will be used to treat waste water.

[19] Interview with industry partner

[20] Interview with industry partner

[21] Interview with industry partner

The following assumptions for the central 'with-grant' case have been made:

- All energy requirements for a 'standard' plant will be met by the anaerobic digestion and therefore all energy (and associated CO2e emissions) currently used for the WWT will be saved, as per the case study narrative, where WWT plants can become 'energy neutral'.
- The 'standard' plant is based on usage data from Scottish Water's 2017-2018 annual report and assumes annual energy consumption for a WWT plant of approximately 13 kWh per person per year, equating to a 650 MWh energy consumption per year.
- Replacement of the Scottish Water WWT assets is assumed to occur at the speed of 1.5 plant per year in line with the information provided by Scottish Water.22
- Assumptions relating to carbon intensity of the grid and the value of carbon are described in Table 10 above.
- Benefits will be realised, per year, for a ten-year period from 2019 to 2028.

Sensitivity analysis has been undertaken for this Case Study to test the robustness of outputs. The sensitivity of the analysis to the following assumptions has been included.

Table 11 Case Study 1 – Sensitivity Analysis assumptions

		Central	High	Low
Number of replacement plants per year	No.	1.5	2	1
Total WWT Energy Consumption, per standard plant	GWh	0.648	0.713 (+10%)	0.583 (-10%)

Source: Technopolis

Our central case scenario estimates that there will be a **total electricity demand reduction of up to 9,720MWh** for a projected portfolio of 15 WWT plants in 2028 (the final year of the study), equivalent to approximately **£780k reduction in electricity costs** and reduced **CO2e emissions of 2,100 tonnes** in 2028, equivalent to an approximate **£40k reduction in CO2e costs**.

As EPSRC provided 64% of the funding for this project (EPSRC £199k vs Collaborative Investment £110k), we have assumed that 64% of the benefits can be attributed to the EPSRC funding. We have not included any contribution of the £500k of funding provided by Horizon 2020 in the analysis.

The central case estimates discounted benefits, attributable to EPSRC of approximately £1.6m over the period of ten years. The ROI estimate for the central case is approximately **£8.23 per £1** of EPSRC grant funding, with the results of the sensitivity analysis producing a range between **£4.94 – £12.06** per £1.

[22] This assumption reflects that in any given year,the first plant is commissioned at Jan 1, and a second plant is commissioned at July 1, and therefore only a half year of electricity and emissions are saved with this 2nd plant during this year.

5.6 Case study 2: Commercialisation of a fluidized bed carbon fibre recycling process

Project title	Development of markets for the commercialisation of a fluidized bed carbon fibre recycling process
Principal Investigator	Prof Pickering, University of Nottingham
EPSRC Grant Reference	EP/I502009/1
Timescale	October 2011 to 2012
EPSRC Investment	£100,767
Industry Investment	Technical Fibre Products Ltd £35000, Advanced Composites Group Ltd £15000
Further funding	Boeing, £115,723

5.6.1 Introduction

Carbon fibre reinforced plastic (CFRP) is being used in increasing quantities in aerospace and automotive industries as a replacement for steel and aluminium due to its lightweight properties and potential to increase fuel efficiency of vehicles. In the 10 years prior to 2017, the annual global demand for carbon fibre (CF) has been estimated to have increased from approximately 16,000 to 72,000 tonnes and is forecast to rise to 140,000 tonnes by 2020[23]. However, the production of carbon fibre is a relatively high cost and energy intensive process. While substituting metals with carbon fibre may result in energy efficiency at the end-use stage for vehicles, some studies[24] which have taken a full Life Cycle Assessment (LCA) have found that improved fuel economy during the vehicle life are compromised by the energy intensity of the virgin carbon fibre (vCF) production process, resulting in minimal net benefit in terms of overall greenhouse gas emissions (CO2e).

Using recycled carbon fibre (rCF) as a replacement for virgin carbon fibre, offers opportunities to significantly reduce waste and CO2e emissions in the production of carbon fibre-based products.

5.6.2 Aims of the research

Across the USA and Europe, 6,000–8,000 commercial aircraft are expected to come to their end-of-life by 2030, generating an estimated 3,000 tonnes of waste Carbon fibre reinforced plastic (CFRP) per annum[25]. The high cost and energy intensity of virgin carbon fibre (vCF) manufacture provides an incentive to recover substantial value from carbon fibre waste. The University of Nottingham developed a small-scale ‘fluidised bed process’ for recycling carbon fibre composite materials. Its unique feature is that it is capable of processing contaminated and mixed waste from end-of-life components. The aim of this EPSRC funded research project was to provide an assessment of its potential commercial opportunities and market applications.

The support provided by EPSRC for the assessment of commercial opportunities project led to the engagement of Boeing Company, who then provided additional financial contributions to extend the project and develop a pilot plant scaled up to be representative of a commercial scale operation. Boeing also provided input materials in the form carbon fibre taken from retired aircraft wings. The fluidised bed process separates the waste carbon fibres from other incombustible materials, such as metals, then recovers the remaining clean carbon fibres, which can be reconstituted for the manufacturing of a range

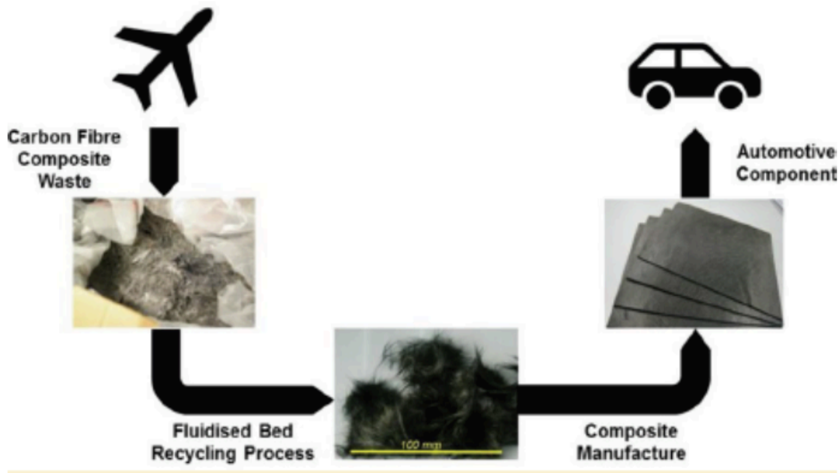
[23] Energy and environmental assessment and reuse of fluidised bed recycled carbon fibres. Pickering et al 2017a. Composites: Part A 100 (2017) 206–214

[24] Environmental Aspects of Use of Recycled Carbon Fiber Composites in Automotive Applications. Environ. Sci. Technol. 2017, 51, 12727-12736. Pickering et al 2017b

[25] Pickering et al 2017b

of other products. For example, manufacturing carbon fibre components for cars, or aircraft seats, based on recaptured carbon fibre from aircraft wings. As illustrated in Figure 8 below.

Figure 8 Carbon Fibre recapture



Source: Environment, Science and Technology. 2017, 51, 12727-12736.

5.6.3 Economic and environmental impacts

The pilot fluidised bed plant developed by University of Nottingham has not yet begun commercial operation. Industrial partners in the carbon fibre manufacturing sector that were interviewed as part of this case study explained the while the work carried out by University of Nottingham can be regarded as pioneering and advanced science to demonstrate the potential for using recycled carbon fibre, other manufacturers of carbon fibre have since recognised this opportunity and in recent years have developed their own independent processes for producing recycled carbon fibre.

The leading supplier of recycled carbon fibre in the UK and Europe (ELG Carbon Fibres Ltd) currently use their own pyrolysis process[26] for recycling carbon fibre. One of the industrial partners who collaborated in the ESPRC funded research project with University of Nottingham explained that while the pyrolysis process is very cost effective (around 50% cheaper to buy than virgin carbon fibre), the quality is lower. This industrial partner procures carbon fibre materials for production of a variety of CF based products that they sell to customers across sectors including; Automotive, Aerospace Defence, Consumer Electronics, Construction and Healthcare markets.

The respondent explained that while they are increasingly using recycled carbon fibre in their manufacturing, there are some products for which it is not suitable and so virgin carbon fibre is still procured and used. The main benefit to them from Nottingham's fluidised bed process for recycling was that the end product is of higher quality, offering potential opportunity to use it across their range of products, and displace a higher proportion of virgin carbon fibre. As explained;

"The project demonstrated that that recycled carbon fibre produced through the fluidised bed process that they (Nottingham) developed can produce fibres at sufficiently high quality. The properties of recycled carbon fibre are not an exact match to virgin carbon fibre, but they are sufficiently high quality to use in our manufacturing. It also helped to understand the potential for cost savings".

Respondents interviewed explained that negotiations are underway for Nottingham University to license the fluidised bed technology to an existing producers of recycled carbon fibre. If implemented, the respondent estimated that the new fluidised bed plant would produce recycled carbon fibre with a sales

[26] ELG's process uses reclaimed carbon fibres that have been obtained through pyrolysis of scrap prepreg materials or cured laminates. For further details see company website: http://www.elgcf.com/technology/process-capability

value of around **£1m per year**, with the expectation being that production will begin within the next five years.

Previous Life Cycle assessment (LCA) studies[27] have demonstrated the environmental benefits of manufacturing products using recycled carbon fibre (rCF) over virgin carbon fibre (vCF), in terms of both reductions in energy usage overall CO2e emissions. The fluidised bed recovery of CF and use of rCF to displace vCF-based composites provides substantial savings in energy demand (65–330 MJ energy savings per kg of CFRP), offering an order of magnitude greater net energy savings compared to waste CFRP produced that is otherwise incinerated. Estimates of avoided GHG emissions range from 3 to 19 kg CO2e per kg of CFRP waste processed by fluidised bed, depending on the precise type of vCF material displaced.

If Nottingham Uni's fluidised process is implemented and produces around £1millon worth of rCF per annum, we estimate this would equate to around 100 tonnes of rCF produced per year (as carbon fibre currently sells for around £10,000 per tonne[28]).

5.6.4 Estimates of Return on Investment

Our ROI analysis is based on the manufacture of around £1millon worth of rCF that will replace an equivalent volume of vCF in the market.

The two key streams of benefits for the Case Study are:

- value of avoided natural gas used in the manufacture of vCF.
- value of CO2e emissions associated with the use of natural gas

For the Case Study, the following assumptions for the baseline have been made:

- Natural gas is the sole source of energy for the manufacture of vCF
- There will be no reduction in the energy intensity of the processs for manufacture of vCF
- There will be no reduction in the price of Natural gas
- Higher quality rCF is used in the manufacturing of products that displaces vCF,
- rCF will replace vCF-only

The following assumptions for the central 'with-grant' case have been made:

- A plant producing £1m of rCF will produce approximately 133 tonnes of rCF, at the current price of approximately £7,500/ tonne (midpoint of prices ranging between £5,000 – 10,000/tonne)
- 133 tonnes of rCF will displace vCF in every year of analysis.
- The price of Natural Gas is 50 p/therm.
- Benefits will be realised, per year, for a ten-year period from 2019 to 2028.
- Assumptions relating to value of carbon are described in Table 10 above.

Sensitivity analysis has been undertaken for this Case Study to test the robustness of outputs. The sensitivity of the analysis to the following assumptions has been included.

[27] Pickering et al 2017b

[28] *New research into carbon fibre recycling*. Additives for Polymers. Volume 2009, Issue 4, April 2009

Table 12 Case Study 2 – Sensitivity Analysis assumptions

Sensitivity	Units	Central	High	Low
Value of rCF produced per annum	£m	1.0	2.0	0.5
Energy savings by using rCf vs vCF	MJ / kg	197.5	330.0	65.0
Avoided GHG emissions	kg CO2 per kg of Cf waste	11.0	19.0	3.0

Source: Technopolis and others[29]

Our central case scenario estimates that there will be a total energy demand reduction of up to 26,000 GJ per year equivalent to an approximate £125,000 reduction in natural gas fuel costs, per year and reduced CO2e emissions of 1,400 tonnes per year, equivalent to an approximate **£25,000 reduction in CO2e costs, per year.**

As EPSRC provided 67% of the funding for this project (EPSRC £101k vs Collaborative Investment £50k), we have assumed that 67% of the benefits can be attributed to the EPSRC funding.

The central case estimates discounted benefits, attributable to EPSRC, of approximately £540k over the period of 10 years. The ROI estimate for the central case is approximately **£5.37 per £1** of EPSRC grant funding.

However, due to the wide range of values for the potential energy savings in manufacture of rCF vs vCF and the associated GHG emissions, the results of the sensitivity analysis produced a range between £0.86 – £18.04 per £1.

[29] Pickering et al 2017a

5.7 Case study 3: Towards Affordable Recyclable Future Low Carbon Vehicles

Grant title	Towards Affordable, Closed-Loop Recyclable Future Low Carbon Vehicle Structures TARF - LCV
Principal Investigator	Professor Z. Fan, College of Mechanical and Aerospace Engineering, Brunel University
Time scale	01/12/2011 to 31/05/2016
EPSRC Investment	£4,221,482
Industry Investment	£506,000
Other follow-up funding	£10m to fund LiME; follow-on EPSRC grants; £40m from industry partners to fund Future LiME; RACE From £4.7m
Industry Partners	Jaguar Land Rover, Aston Martin, Bentley Motors Ltd, Lotus Engineering Ltd, Ricardo Group, SAIC Motor UK Technical Centre Ltd

5.7.1 Introduction

The aim of the project "Towards Affordable, Closed-Loop Recyclable Future Low Carbon Vehicle Structures" (TARF-LCV) was to research the development of Low Carbon Vehicles (LCVs), vehicles that are built with lightweight materials, which are recycled in closed-loops from End of Life Vehicles (ELVs) and then manufactured with processes that are low on carbon emissions. As a whole, this results in lower carbon footprints attributable to these vehicles compared to conventional vehicles.

Vehicle light weighting is an effective route to achieving lower greenhouse gas emissions, given lighter cars will be more fuel efficient. Until 2011, the most common process was to incrementally reduce the mass of specific vehicle parts piece-by-piece, with little consideration given to the carbon footprint of input materials and closed-loop recycling of end of life vehicles. The EPSRC funds allowed the possibility to explore a more rounded approach, including the consideration of the carbon footprint of input materials and their provenance and closed loop recycling of end of life vehicles.

5.7.2 Aims of the research

The research programme was organised in **six work packages** over four years:

1) Development of closed-loop recyclable aluminium and magnesium alloys
2) Development of metal matrix composites (MMCs)
3) Development of recyclable polymer matrix composites (PMCs) for body structure and powertrain applications
4) advanced low carbon manufacturing technologies for casting, forming and effective vehicle assembly and disassembly
5) mass-optimised design principles
6) specific life cycle analysis methodology for future LCV development.

Alloy development has been identified as central to solving the big challenge facing the global manufacturing industry and presents many opportunities to build the car of the future. For example, Magnesium is the lightest available structural metal, with a density approximately 35% lower than that of aluminium. Therefore, it has great potential to become a primary material used in future low carbon vehicle structures. However, its manufacture presents some difficulties, such as low ductility and formability, particularly at low temperatures. Hence, a series of experiments was conducted to demonstrate the feasibility of using Heat treatment, Forming and in-die Quenching (HFQ) as a method of producing complex shapes from a sheet of magnesium alloy.

Aluminium alloys used for shape casting presented challenges in terms of ductility and strength; however, through intensive research in this area, an aluminium casting alloy characterised by sufficient ductility to allow cast vehicle body component to be more readily joined by self-piercing riveting was developed.[30] A novel technology to improve the recyclability of scrap aluminium through the removal of deleterious iron impurities was also developed.

5.7.3 Relevance to circular economy

This project aims to stimulate the development of a number of circular economy practices. The manufacture of a vehicle represents 20% of its total carbon footprint (the other 80% being the use of the vehicle over its entire lifespan).[31] This means that any efficiencies in manufacturing can contribute significantly to lowering its carbon footprint overall.

Optimum **design**, for example, ensures efficient performance which reduces consumption of fossil fuel and CO2 emissions in manufacture.

Vehicle **light weighting** is an effective way to reduce CO2e emissions, since by reducing the weight of a vehicle's body and components, cars can improve fuel efficiency by up to 30%[32]. This can translate into cost savings for users too.

The development of closed-loop low carbon vehicle structures minimises the use of virgin raw materials. Metal extraction to build a car body is energy intensive. For example, 1/3 of the cost of aluminium is attributable to the cost of energy to extract it:[33] for one kilogram of aluminium 12 kilowatts of electricity are required, and this corresponds to 12kg of CO2.[34] By reusing materials from end-of-life vehicles in a closed loop/full metal circulation, the amount of waste sent to landfill is reduced. Furthermore, aluminium already buried in landfills can be up-cycled in order to create a sustained circulation of **recycled aluminium.**

[30] LiME. Available at: https://www.brunel.ac.uk/research/Institutes/Institute-of-Materials-and-Manufacturing/Liquid-Metal-Engineering/What-is-LME

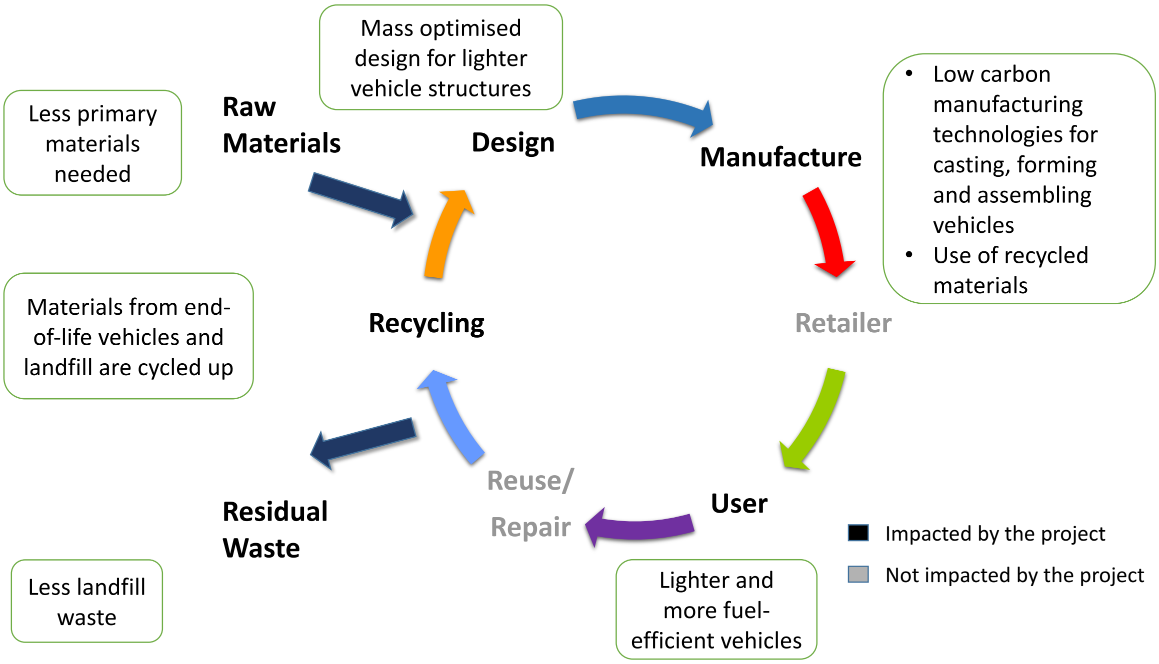
[31] Interview with Professor Fan

[32] El Fakir, O., Das, S., Stone, I., Scamans, G., Fan, Z. et al (2014) *Solution Heat treatment, Forming and in-die Quenching of a commercial sheet magnesium alloy into a complex-shaped component: experimentation and FE simulation.* Available at: https://www.researchgate.net/publication/269037110_Solution_Heat_Treatment_Forming_and_In-Die_Quenching_of_a_Commercial_Sheet_Magnesium_Alloy_into_a_Complex-Shaped_Component_Experimentation_and_FE_Simulation (accessed 16 January 2019)

[33] Metal Miner, sourcing and trading intelligence for global metals markets. Available at: https://agmetalminer.com/2015/11/24/power-costs-the-production-primary-aluminum/

[34] Interview with Professor Fan

Figure 9 Circular economy model of TARF-LCV



Source: Technopolis

5.7.4 *Economic and environmental Impacts*

Professor Fan at Brunel University was the Principal Investigator of the EPSRC original project. He formed a consortium involving a total of 51 academics belonging to eight different research teams in order to bring excellence to the TARF-LCV project. Professor Fan said that the EPSRC funding of early-stage research in a pioneering territory, such as alloy development and full metal circulation, has resulted in a significant contribution to create capability in this field in the UK.

The TARF-LCV project is still active to date and additional commercial contracts and follow up funding are likely to continue to happen on the back of the EPSRC-funded project. The aims of the research are long term and so the industry partners who joined this collaboration approached the work with vision, i.e. preparing core low carbon technologies to build 2030-2040 cars, and commitment to decarbonise. Professor Fan describes the car of the future as follows:

"2030-2040 cars will consist of a number of large pieces; at the end of the vehicle life, the car can be dissembled into the same number of large pieces.[35]*"*

This research has already resulted in significant outcomes from the initial funding period, with a number of technologies having been licensed to industry.

5.7.4.1 Collaboration with Jaguar Land Rover

The objective of producing new recyclable aluminium and magnesium alloys was achieved, with the development of three new alloys for industry which have all been patented, one of which by Jaguar Land Rover (JLR), that has already introduced it to their production line.[36]

Jaguar Land Rover is the UK's largest automotive manufacturing business. Technological improvements, such as aluminium body structures, have been initially introduced to the Jaguar range

[35] Interview with Professor Fan

[36] Intellectual Property Office, *GB2500825* - Alloy and method of production thereof. Available at: https://www.ipo.gov.uk/types/patent/p-os/p-find/p-ipsum/Case/PublicationNumber/GB2500825(accessed 16 January 2019)

(reducing the weight by around 40%)[37] and are now being introduced to Land Rover models. Building upon the recyclable alloy technology advanced by the research project, they created a new lightweight modified aluminium alloy that allows for a higher proportion of recycled content and uses 95% less energy to manufacture, as well as producing less waste than virgin material[38].

These changes have made JLR a leader in using recycled aluminium for light weighting, with a current use of 50% recycled aluminium in their car manufacturing, corresponding to approximately 350,000 vehicles per year.[39] Their target is to raise this percentage to 85% by 2020. These low carbon vehicles contain materials which reduce the carbon footprint of at least 10-15% (compared to all other vehicles), as demonstrated in the life cycle analysis, conducted on each vehicle, and audited by the British Standard Institution.

They work on achieving optimal material utilisation during manufacture by using aluminium scrap from production lines as well as post-consumer aluminium scrap.[40] The use of secondary (or recycled) aluminium uses 92% less energy than is required to make new aluminium,[41] and 10% increase in aluminium end of life recycling rates decreases industry greenhouse gas emissions by 15%.[42] One of the aluminium recyclable alloys first developed with the EPSRC research group was used for the JLR's REALCar.[43]

By collaborating on the research programme and then commercialising low carbon vehicles, JLR established its role as an early adopter of sustainable car manufacturing, de-risking environmental technologies and making them open knowledge in the automotive industry. A representative from JLR described the benefits of collaboration in this application-focussed research.

"A benefit of collaborating for TARF-LCV was that value was being put on the synergy between research bodies, original equipment manufacturers and tier 1 suppliers. More publicly funded fundamental research focussing on production processes and infrastructures would be good news."[44]

5.7.5 Estimates of Return on Investment

The two key streams of benefits for the Case Study are:

- value of avoided energy used in the manufacture of aluminium.
- value of CO_2e emissions associated with the provision of energy to produce aluminium from the UK national grid
- For the Case Study, the following assumptions for the baseline have been made:
- Electricity, provided by the UK is the sole source of energy for the manufacture of aluminium
- There will be no reduction in the energy intensity of the process for manufacture of aluminium
- The manufacture of cars would use virgin aluminium for the length of the study (2016-2025)

The following assumptions for the central 'with-grant' case have been made:

- 25% of the benefits from the REALcar /Novelis cited in the case study is attributable to the TARF-LCV.

[37] Jaguar Media, Lighter, Stronger, Cleaner. Available at: https://media.jaguar.com/en-gb/2016/lighter-stronger-cleaner?q=&start=0&brand=jaguar (accessed 16 January 19)

[38] Land Rover, *Product Responsibility*. Available at: https://www.landrover.co.uk/explore-land-rover/responsibility/product-responsibility.html (accessed 16 January 2019)

[39] Interview with Professor Fan

[40] Interview with industry partner

[41] The Aluminum Association. Available at: https://www.aluminum.org/industries/production/secondary-production

[42] The Aluminum Association. Available at: https://www.aluminum.org/industries/production/secondary-production

[43] Interview with industry partner

[44] Interview with industry partner

- 50,000 tonnes of recycled aluminium will displace virgin aluminium in every year of analysis.
- 500,000 tCO_2e will be avoided by using the recycled aluminium.
- Benefits will be realised, per year, for a ten-year period from 2016 to 2025.
- Assumptions relating to value of carbon are described in Table 10 above.

Sensitivity analysis has been undertaken for this Case Study to test the robustness of outputs. The sensitivity of the analysis to the following assumptions has been tested. The values for the sensitivity are designed to demonstrate that there are key factors that drive the extent to which benefits can be monetised and attributed to the EPSRC. The assumptions used in the analysis are shown below.

Table 13 Case Study 3 – Sensitivity Analysis assumptions

Sensitivity	Units	Central	High	Low
Electricity requirements for virgin aluminium	kWh/ kg	10	12	8
Reduction in Energy used to manufacture rAl vs Val	%	80%	92%	70%
% of REALCAR gains attributable to TARF-LCV[45]	%	25%	100%	10%

Source: Technopolis

The central case scenario estimates that there will be a total electricity demand reduction of up to 400 GWh per year, of which the 25% attributed to the TARF-LCV is a 100 GWh per year electricity demand reduction. This demand reduction is equivalent to an approximate **£8m reduction in electricity costs, per year.**

Our central case scenario included a total reduction in CO_2e emissions of 500k tonnes per year of which 25% attributed to the TARF-LCV grant is a 125 tCO_2e per year. This reduction in CO_2e emissions is valued at approximately £2.1m per year.

As EPSRC provided 89% of the funding for the TARF-LCV project (EPSRC £4.2m vs Collaborative Investment £506k), we have assumed that 89% of the TARF-LCV project benefits can be attributed to the EPSRC funding.

The central case estimates discounted benefits, attributable to EPSRC of approximately £60m over the period of 10 years. A key difficulty in this analysis is attributing the contribution of the TARF-LCV project to the gains observed in the REALCAR project. The low case estimate for discounted benefits is approximately £18m over a period of 10 years. Whilst the estimated discounted benefits using high case assumptions is as high as £315m over a period of 10 years.

Given the difficulty in assigned the benefits of the REALCAR to the TARF-LCV, there is a large range in return on investment. The central case estimate is approximately **£16.54 per £1 of** EPSRC grant funding. The sensitivity analysis produces a range of between £5.06 – £85.93 per £1.

[45] The attribution of the benefits of the JLR REALCAR project to the TARF-LCV project is a significant area of uncertainty related to this case study. The casual link between the execution of the TARF-LCV project and the development of the JLR REALCAR project is clear but the maginitude of that link is not known. As stated in the case study narrative (page 36) *"producing new recyclable aluminium and magnesium alloys was achieved, with the development of three new alloys for industry which have all been patented, one of which by Jaguar Land Rover (JLR), that has already introduced it to their production line"* and the PI (Prof. Fan) of the TARF-LCV project was jointly named on the patent of process ('Alloy and method of production thereof') used in the development of JLR's REALCAR project. Technopolis have identified a broad spectrum of values for the causal link, with 100% of the benefits realised in the high case (REALCAR could not have been accomplished, had it not been for TARF-LCV), a central case of 25% (other factors, aside from TARF-LCV were responsible for the delivery of REALCAR) and a low case of 10% (TARF-LCV had very little to do with the eventual delivery of REALCAR). These assumptions reflect the uncertainty that is present in identifying the causal link. "

5.8 Case study 4: EPSRC Centre for Through-life Engineering Services

5.8.1 Introduction

Through-life Engineering Services involve the maintenance, repair and overhaul of complex engineering systems, which are carried out throughout the life cycle of high-value products, such as aircraft engines. Complex engineering products are referred to as 'Coupled Whole Systems', since they combine five major domains (structural, mechanical, electrical, electronic and software sub-systems) to achieve the required functionality and performance. Better design and manufacturing processes can improve the predictability and reliability of Coupled Whole Systems and reduce their whole life cycle cost. This type of innovation can be applied to a range of UK high value manufacturing companies.

Whole system product design and manufacturing with through-life support is a growing business for the UK aerospace, energy, railways, high-end automotive and defence companies. The EPSRC TES Centre report on the international market for Through-life Engineering Services estimates that by 2025, the global market for maintenance, repair and overhaul (MRO) services in civil air will be worth $89bn, whilst in the UK the repair and maintenance (RAM) industry as a whole will be worth in excess of £35bn[46].

5.8.2 Aims of the research programme

The aim of the EPSRC Centre for Innovative Manufacturing in Through-Life Engineering Services (TES) was to develop the knowledge, technologies and processes needed to improve the design and manufacture of complex engineering products. Research undertaken at the TES Centre aimed to improve the availability, predictability and reliability of complex engineering products through their lifecycle, in order to reduce whole life costs associated with their servicing.

Complex engineering systems (Coupled Whole Systems) are present in high value products, such as aircraft engines, high-end cars, railway vehicles, wind turbines and defence equipment, which are typically technology intensive, expensive and reliability-critical. Competitiveness of producers is thus dependent on design innovation, added value through the services and minimisation of whole life cost. TES integrates manufacturing, engineering and technology with new service-based business models such as leasing and benefit sharing, to ensure that the manufacturer and, or maintainer is incentivised to provide great user value at reduced cost.

Specifically, the Centre undertook three types of projects over the course of the six years. The first type of project aimed to identify challenges in the systems design across multiple sectors. The challenges were identified through a scoping review of the research space, which was completed in the first year. Projects of the second type addressed three major industrial challenges for engineering services across the aerospace, defence, railways and electronics sectors. They aimed to develop technology and process demonstrators, design rules and standards to evaluate the system design in order to reduce the engineering services cost later in the life cycle (TRL 2-3). The studies focused on the following topics:

- The reduction of the no-fault found (NFF) problem through system design. This relates to reduction in the scrappage of equipment where faults have become apparent, but their root cause cannot be determined to enable repair.
- The characterisation of 'in-service' component feedback for system design. This project used technologies such as 3D imaging for verifying component geometry and infrared thermography to identify wear and sub surface damage such as cracks, delamination, and corrosion. The goal was to develop a technology demonstrator that can autonomously capture and analyse data on component degradation that might lead to failure.
- The development of self-healing technologies for electronic and mechanical components and subsystems. This project was conceived with a more long-term scope (TRL 1-2) since it aimed

[46] EPSRC TES Centre (2015) Annual Report. Available at https://www.through-life-engineering-services.org/downloads/27058_EPSRC_Annual_report_final_low_res_web.pdf (accessed 11 January 2019)

to develop new technologies that could reduce the need for maintenance and therefore reduce the whole life cost of a high value product.

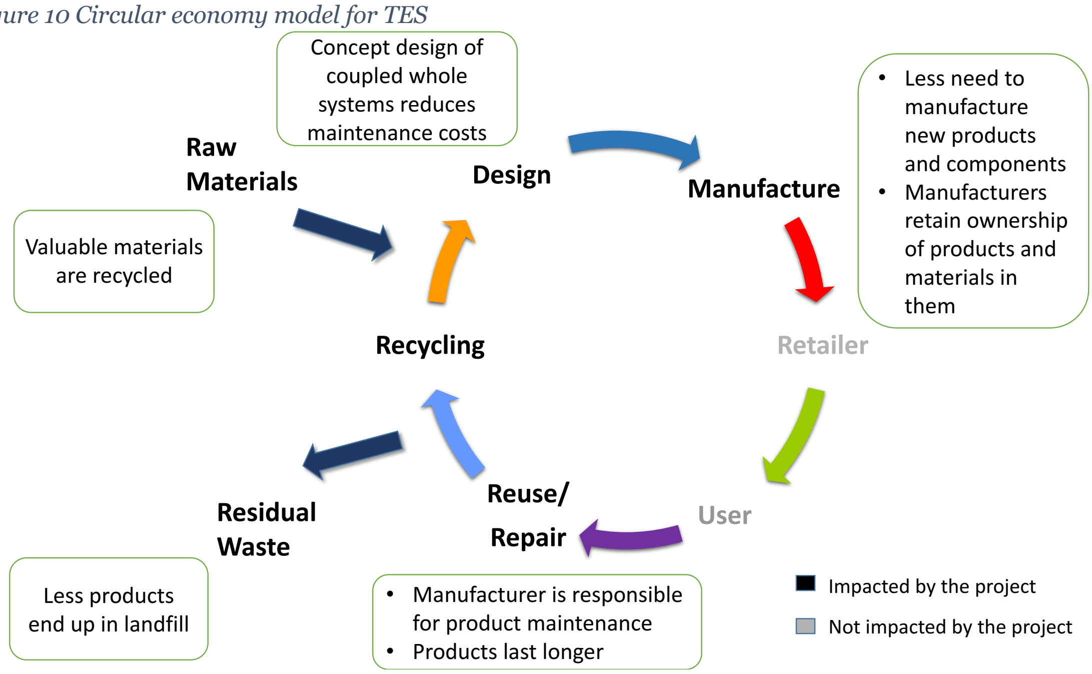
5.8.3 *Relevance to the Circular Economy*

Increasingly, UK companies are providing end-user services which require Through-life Engineering Services. An example is the Rolls-Royce 'Power by the Hour' TotalCare system with which the company provides maintenance to customers for their own aircraft engines. According to Rolls-Royce, providing through-life engineering services decreases the service intervals between engine overhauls by around 25%[47]. Resource efficiency is also optimised because demand for new expensive and resource intensive products and components is decreased by keeping engines in use for longer.

Residual waste is reduced because Rolls Royce has access to end-of-life products, components and their materials, 95% of which can be recycled. Around half of the materials recovered are of such high quality that they can be safely remanufactured for use as new aerospace components, which also reduces the need to procure virgin raw materials. A Rolls Royce representative interviewed estimated that, by improving Through Life Engineering services, manufacturing costs were reduced by around one third, through reducing manpower, machinery, energy and fuel requirements[48].

The provision of similar end-user services by manufacturers represents a shift in the traditional asset-ownership model in which users are also owners of high value products, to a service-based model in which manufacturers retain ownership over their products and the valuable materials contained in them. Effectively, manufacturers do not just make the assets, but remain responsible for timely maintenance and on-going improvements. This gives users more certainty whilst manufacturers gain access to a growing market of high value engineering services. Ultimately this brings to better product value and durability, which are central elements in manufacturing for a circular economy.

Figure 10 Circular economy model for TES



Source: Technopolis

[47] Rolls-Royce plc Power by the hour. Available at: https://www.rolls-royce.com/media/our-stories/discover/2017/totalcare.aspx

[48] Interview with industry partner

5.8.4 *Environmental and economic impacts*

EPSRC funding enabled Cranfield University to set up the Through-life Engineering Services Centre and build the critical mass to become a centre for excellence in the subject. The TES Centre established a wide business partnership across the following sectors: aerospace, defence, railways, electronics, defence, information technology (IT), machine tool, and energy sectors. Rolls-Royce, BAE Systems, Bombardier Transportation and the Ministry of Defence (MoD) were business partners with full membership, taking part in the Centre Executive and Advisory Boards and steering the direction of research.

The Centre created its own spin-out consultancy, The Cranfield Manufacturing Consultancy, whose expertise on Through-life Engineering Services benefited a number of business partners. For example, supporting BAE systems to reduce initially high rejection rate of components in operational aircraft at BAE Systems. This was part of the Centre's core project on the **no-fault found (NFF)** problem.

According to one project partner[49], the NFF problem is very common but many of companies do not want to publish NFF cost impact to their business because it is a sensitive topic, as it is related to safety and reliability. Moreover, the problem involves supply chain costs, which are harder to estimate. At BAE Systems, over 40% of rejected components were classified as NFF in successive tests, which constituted a major loss of time and money for the company. The changes implemented at BAE Systems as a result of the intervention of a Cranfield team brought to an 80% reduction of the NFF rate[50].

One of the project partners recognised the value of implementing the TES tools to make sure products and components are built to last and reducing after sales costs. According to this project partner,

"The rule of thumb for us is that we sell an aircraft, but it costs 3 times to maintain it after sale services. the Tornado aircraft, for example, was built to last 25 years but has lasted 40 years and has just come out of service. We need to provide leaner and meaner services and make the aircrafts last more".

The company has not yet implemented TES across their supply chain but intend to and expect significant costs savings. The impact is expected to be significant because 60% of the company's core business is support and maintenance of aircrafts; "*we employ 1,700 engineers. TES will help support all of this. We are planning to Start to embed the TES DOTES system in 2022, with a full set of tools available*'.[51]

Business partner Rolls-Royce benefitted from the collaboration with the TES Centre through a project focused on integrating spare parts planning with engine health monitoring. **Rolls-Royce** currently employs a specific technology that allows it to diagnose engine failures on the go. The TES project proved that this technology could also be used to predict which spare parts will be needed in the future. Results showed that the inventory made through use of this technology was 15% better aligned to demand than the currently used processes for prediction[52].

According to company representative interviewed, 52% of their company revenue comes from engineering services and support and, as such, they have a strong interest in staying ahead in the research in this field[53]. The respondent estimates the annual turnover coming from after sales repair and maintenance services to be £14bn[54]. The respondent explained that adopting innovative processed advanced by the TES has saved the company around one hundred million a year in this area of the

[49] Interview with industry partner

[50] TES Centre *The Cranfield Manufacturing Consultancy*. Internet, available at https://www.through-life-engineering-services.org/index.php/tes-consultancy (accessed 10 January 2019)

[51] Interview with industry partner

[52] EPSRC Annual Report 2013. Available at: https://www.through-life-engineering-services.org/downloads/epsrc_annual_report_2013_pages_Online_version.pdf p. 19

[53] Interview with industry partner

[54] Interview with industry partner

business. According to their own estimates, at least £1m of this cost saving can be attributed to their collaboration with the EPSRC TES Centre.[55].

5.8.5 Estimates of Return on Investment

The approach to determine a projected return on investment for the TES Centre is divided into two phases:

- 1. Identification of the possible volume of business that Rolls Royce and BAE currently undertake that could be improved by the results of research undertaken by TES Centre.
- 2. Identification the size of the company R&D budgets assigned to those areas and the relative size of the TES Centre (and by extension, the EPSRC grant) in relation to the R&D work undertaken by the companies as part of their normal business practices.

The key stream of benefits for the Case Study is:

- The reduction in costs associated with implementing processes made possible by the TES Centre.
- For the Case Study, the following assumptions for the baseline have been made:
- Costs for services provided by Rolls Royce will remain constant and will only be reduced as a result of R&D activities to achieve improvements in their asset utilisation and availability56.
- Spend on R&D at Rolls Royce and BAE is in direct proportion to the size of the business (measured in turnover).
- The following assumptions for the central 'with-grant' case have been made:
- In the case of Rolls Royce and BAE, both companies will achieve 15% improvements in the 'service engineering' sectors. These 15% improvements will result in an equivalent reduction in the cost of the services.
- 15% improvements57 are assumed to begin in 2019 until 2028 (3 years later58 than the strategy).

The TES aspirational strategy of 20% reduction in cost with a 20% improvement in asset availability, across more than £20b of UK economic output by 2025 is achieved. This figure is used in the high case (see sensitivity below)

The identification of the possible volume of business for Rolls Royce and BAE that could from TES Centre is shown in Table 14 below. There is approximately £4bn of activity in the Rolls Royce service sector and up to £11.4bn of activity in BAE, that has the potential to be improved by work conducted by the TES.

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[55] Interview with industry partner

[56] In reality, there may be other factors that affect the cost of RR services (such as increases in labour and/or raw materials). For simplicity of modelling, we have assumed a reasonable casual link between R&D spend and reduction in costs.

[57] The case study highlighted that the 15% inventory improvements could be realised as a result of the TES project funded by EPSRC. The TES strategy document used a figure of 20% reduction in cost and a 20% increased in asset avialbility. The 20% strategy figure was considered to be an aspirational target, and therefore was identified as the high case (to account for Optimism Bias), with the 15% figure highlighted in the cast study interview as forming the basis of the central case. We then used 10% to represent a low case. (See Table 13, page 48).

[58] The 3 year lag is because there is no evidence to suggest any specific benefits were realised between 2016 and 2019. The full cost reductions are assumed to be realised in 2019, and last for 10 years.The central case assumes that full cost reductions appear in 2019. This full cost reduction may not reflect the exact profile of cost reduction and can be considered a modelling simplification in the absence of more concrete data. The rationale being that the full cost reduction may overstate the reduction in early years, but may understate the reduction by 2028. (3 years later than the TES strategy).

Table 14 Volume of Business potentially benefitting from TES Centre

Company	Item	Units	Value	Source
Rolls Royce				
	Civil Aerospace Revenue	£bn	8	RR 2017 Annual Report
	% of Civil Aero that is service industry	%	52%	RR 2017 Annual Report
	Civil Aerospace – Services Revenue	£bn	4.16	
BAE				
	Revenue	£bn	19	BAE 2016 Annual Report
	% of core business is services	%	60%	Case Study Respondent
	Services in BAE	£bn	11.40	Services in BAE

Source: Technopolis using Rolls Royce, BAE and interview with PI

Table 15 below shows the size of the company R&D budgets and attribution of benefits to TES Centre.

Table 15 R&D budgets and attribution of benefits to TES Centre

Company	Item	Units	Value	Source
Rolls Royce				
	Total company R&D	£mil, per annum	1,400	RR 2017 Annual Report
	Civil Aerospace as % of RR Revenue	%	53%	RR 2017 Annual Report
	Service as % of Civil Aerospace revenue	%	52%	RR 2017 Annual Report
	Est. RR Civil Aerospace Service R&D	£mil, per annum	388	
	TES Centre funding	£mil, per annum (2011-2015)	1.87	
	% TES Centre Funding (as propotion on RR CA Serv R&D)	%	0.48%	
BAE				
	Total company R&D	£mil, per annum	1,400	BAE 2016 Annual Report
	Service as % of Civil Aerospace revenue	%	60%	Case Study Respondent
	Est. BAE Service R&D	£mil, per annum	840	
	TES Centre funding	£mil, per annum (2011-2015)	1.87	
	% TES Centre Funding (as propotion on BAE R&D)	%	0.22%	

Source: Technopolis using Rolls Royce, BAE and Case study interview

Sensitivity analysis has been undertaken for this Case Study to test the robustness of outputs. The sensitivity of the analysis to the following assumptions has been tested.

Table 16 Sensitivity Analysis assumption

Sensitivity	Units	Base	High	Low
Reduction in Cost through adoption of TES	%	15%	20%	10%

Source: Technopolis, TES Centre, Case Study Interview

The central case uses a figure cited a respondent to an interview as part of the case study, whereas the high case is the TES aspirational target of 20% as per the TES Centre Strategy.

The central case scenario estimates that there will be an improvement in asset availability and associated cost reduction that will equate to approximately **£2.23bn per year**. The value that is attributed to the TES Centre is approximately £6.8m per year.

As EPSRC provided 67% of the funding for the TES Centre project (EPSRC £5.8m vs Collaborative Investment £3.5m), we have assumed that 67% of the TES Centre project benefits can be attributed to the EPSRC funding.

The central case estimates discounted benefits, attributable to EPSRC of approximately £25.5m over the period of ten years. The low case estimate for discounted benefits is approximately £17m over a period of ten years whilst the estimated discounted benefits using high case assumptions is £34m over a period of ten years.

The central case estimate is approximately **£5.03 per £1** of EPSRC grant funding. The sensitivity analysis produces a range of between **£3.35- 6.71 per £1.**

5.9 Case study 5: Nano-structured Catalysts for CO_2 Reduction to Fuels (Econic spinout)

Grant Title:	**Research Grant: Nano-structured Catalysts for CO_2 Reduction to Fuels**
Principal Investigator	Prof Charlotte Williams, Imperial College London.
Dates of grant funding	May 2010 - Apr 2013
EPSRC Funding Value	£1,675,521
Value of industrial partner contributions	£35,200
Sector of respondents interviewed	Plastics manufacturing

5.9.1 Introduction

Fossil fuels are society's major energy sources and the primary raw materials for the chemicals industry. However, there are significant concerns associated with their sustainability, depletion and cost. One solution is to use carbon dioxide itself as the fuel and feedstock material. The solution proposed by this project was to react CO_2 with H_2 or water, using chemical, photochemical or electrochemical catalysts, to produce liquid transport fuels, such as methanol. This project aimed to develop novel nanostructured catalysts to enable the reduction of carbon dioxide to produce carbon-based fuels, and enable their capture and storage into the production of other chemical and polymer based products. In effect, this is the reverse process to the combustion of fossil fuels.

The focus of this case study is not the wider outcomes of the original research programme, but rather, a spin-out company (Econic) that emerged from the technologies and process that were tested, developed and then patented as a result of this research grant. The processes and services developed by Econic enable manufacturers to capture carbon emissions from one industrial process and use it as an input for another e.g. plastics manufacturing, resulting in high potential for both economic and environmental benefits. As explained by a representative of the company who was interviewed;

"Econic is a catalyst company that enables plastic manufacturers to use waste CO_2 to replace a portion of their petrochemical feedstocks, up to 50% of it. They can replace up to 50% of the existing petrochemical raw material with waste CO_2. In this way we enable companies to create value out of a waste, locking that CO_2 for a long time into products that have a long-life span, such as insulation foams and foams for plastic. This is our circular economy".

The respondent explained that there were a range of economic gains for customers of their technology (primarily in plastics manufacturing).

"A traditional petrochemical polyol that may cost ~$2500/tonne would be made from raw materials that cost ~$2000/tonne. If you replace 50% of the raw material with CO_2 you can save on raw material costs by up to $1000 and generate significant added value for the manufacturer.

There is another added value. The manufacturer might sell the final product for a higher price, because the performance of the product is better than the 100% oil based produced product".

The respondent (and their company website) claim that if their targets on 30% market penetration of the wider plastics manufacturing sector are achieved. This would result in total economic gains for their clients of **around $1bn.**

5.9.2 Estimates of return on investment

The approach to identifying the return on investment for the Case Study focuses on quantifying Econic's own published claims on the economic and environmental impacts of their products, found on its website.

The two key streams of benefits for the Case Study are:

- value to polyol producers from the use of nano-catalysts in the polyol production process.
- value of reduced CO2e emissions associated with use of nano-catalysts in the polyol production process.

The following assumptions for the baseline have been made:

- Polyol producers carry on with current methods to produce their product, using existing methods until 2029.[59]

Econic's published estimates on their website for the impacts of their products and services include:

- 30% market penetration of Econic catalysts would create $1bn in value to polyol producers. We have assumed that this claim is the total value to polyol producers for a ten-year period, 2020 to 2029.
- 30% market penetration of Econic catalysts would create 3.5 Mt savings in CO2e emissions per year, by 2026.
- The following assumptions for the central 'with-grant' case have been made:
- We have used Econic's claims to identify value creation (£m) and emissions savings (tCO2e) on a percentage-market-penetration basis. The assumptions that have used to identify the potential added value of Econic are as follows:

Table 17 Indicative value to polyol producers and reduced emissions per % of market penetration

Item	Units	Value	Source
Value to polyol producers from 30% market penetration	$bn	1	Econic
Value to polyol producers from 30% market penetration	£bn	0.78	
Value to polyol producers, per % penetration	£m/ % market penetration	26	
Reduction in CO2e emissions 30% penetration by 2026	tCo2e	3,500,000	Econic
Reduction in CO2e emissions per % penetration	tCo2e	26	
Value to polyol producers, per % penetration	tCo2e % market penetration	116,667	

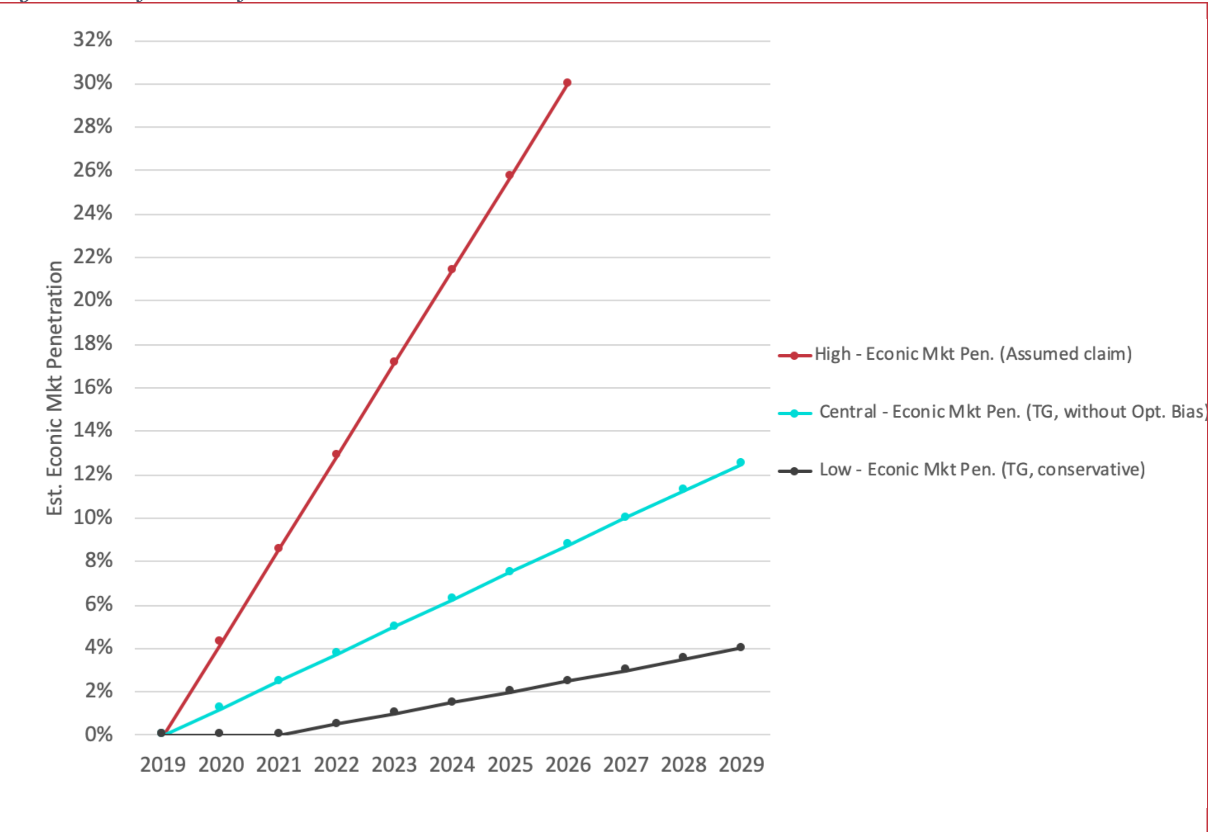
Source: Technopolis, using Econic

- As Econic is a new business, we have adjusted their claimed values to account for optimism bias. We have a market penetration profile such that Econic reaches a market penetration of only 12.5% in 2029, increasing year on year by 1.25% for ten years, beginning in 2020.
- Assumptions relating to value of carbon are described in Table 10 above.
- 25% of the creation of Econic is attributable to Nano-crystal project.

The graphic below shows the penetration profiles for the three sensitivity cases, representing our central, high and low cases.

[59] It is prudent and reasonable to accept that Optimism Bias is very likely to be present in the claims of Econic. In order to use Econic claims in an appropriate manner, Technopolis have identified the probable baseline that Econic have used (however this is not confirmed). The central case assumptions provide a conservative estimate of the eventual market penetration of Econic, that is anticipated to mitigate some or all of the optimism bias present in the Econic claims.

Figure 11 Projections of Econic Market Penetration



Source: Technopolis, using Econic

Our analysis also tests the sensitivity to the attribution of the gains from Econic to the Nano-crystal project. The table below shows the assumptions used in the analysis.

Table 18 Sensitivity Assumptions

Sensitivity	Units	Central	High	Low
Market Penetration[60]	-	Blue line	Red Line	Black Line
% of Econic benefits attributable to Nano-crystal project	%	25%	30%	20%

Source: Technopolis andEconic

Our central case scenario estimates that Econic could provide up to £175m of discounted value to polyol producers in total by 2029. Of this, £76m is estimated to be in the discounted value of approximately 8MtCO2e avoided carbon emissions.

The central case assumption is that the Nano-crystal project contributed to approximately 25% of the formation of Econic. As such, our central estimates approximately £44m of discounted value can be attributed to the Nano-crystal project.

[60] The specific assumptions underpinning the market penetration sensitivity assumptions are:

- High (Econic website assumptions)
- Central (market penetration increases by +1.25% per year, for ten years, starting 2019)
- Low (no market penetration occurs until 2022, +0.5% market penetration per year (3% total in 2027, 4% in 2029).

As EPSRC provided 98% of the funding for the Nano-crystal project (EPSRC £1.67m vs Collaborative Investment c.£35k), we have assumed that 98% of the benefits can be attributed to the EPSRC funding.

The central case estimates discounted benefits, attributable to EPSRC of **approximately £43m** over the period of ten years. The ROI estimate for the central case is approximately **£27.37 per £1** of EPSRC grant funding.

However, due to the wide range of values for the potential market penetration and attribution of benefits from Econic, the results of the sensitivity analysis produced a range between **£5.59 – £61.44 per £1.**

5.10 Overall assessment of return on investment across the case studies

Our analysis has estimates that there are positive ROIs from the case studies.

The value of the grants for the five case studies that we have produced ROI assessments for is approximately £15m, which represents 7% of the portfolio of grants. We have assumed that benefits will be realised, per year, for a ten year period.

We have estimated that there are approximately **£130m** of benefits that can, or will, be attributable to the funding provided by the EPSRC grants from the five case studies. The aggregate ROI for the EPSRC funding of these five case studies is approximately **£9.62 per £1** of EPSRC grant funding.

We have applied sensitivity analysis to each of the case studies. The range of estimated discounted benefits for the total of the 5 case studies is **between £45- 447m**[61], representing a range of ROIs between **£3.32-32.73 per £1** of EPSRC grant funding.

[61] At the high end of this estimate, Case Study 3 is responsible for £314m of the £447m discounted benefits, and as stated in detailed description of Case Study 3, this assumes that 100% of the benefits identified as part of the REALCAR project conducted by JLR and Novelis are attributable to the TARF-LCV project. The central case assumes a 25% attribution.

5.11 Case study 6: EPSRC Centre for Innovative Manufacturing in Continuous Manufacturing and Crystallisation (CMAC)

Grant title	**Centre for Innovative Manufacturing in Continuous Manufacturing and Crystallisation**
Principal Investigator	Professor A. Florence, Institute for Pharmacy and Biomedical Science, University of Strathclyde
Time scale	01/10/2011 to 31/12/2016
EPSRC Investment	£6,060,701
Industry Investment	£1,845,000
Industry Partners	AstraZeneca, Novartis, Bayer, AstraZeneca, British Salt, Croda Group, Fujifilm, Genzyme Corporation, GlaxoSmithKline plc, NiTech Solutions Ltd, Pfizer, Syngenta, Phoenix, Solid Form Solutions

5.11.1 Introduction

The aggregate global emissions of the Pharmaceutical sector amounted to about 52 MMt-CO2e in 2015, which was higher than the emissions caused by the global automotive sector in the same year (46.4 MMt-CO2e)[62]. Research into continuous manufacturing and crystallisation can make an important contribution to addressing global CO2 emissions.

'Batch production' is a traditionally used form of manufacturing that happens in stages. Batch production of pharmaceuticals, for example, involves a series of stages (synthesis, crystallisation, blending, granulation and sizing) which are distinct and may take place in different facilities, with the need to transport products between them and sometimes, with some months passing between each stage.

In the 'continuous processing' form of manufacturing, raw materials are transformed into a final product in the same facility and with no need to shut down the equipment. This reduces the need for heating or cooling down a reactor and reduces the discharging of waste chemicals after each batch63. Continuous manufacturing of powders, particles and crystals is applicable to the chemicals and pharmaceutical industry (for production of drugs, inks and pigments, paints, computer screens) and to future products such as nanomaterials.

5.11.2 Scientific aims of the research programme

The aim of the EPSRC Centre for Innovative Manufacturing in Continuous Manufacturing and Crystallisation was to research the possibility to move from batch production of powders, particles and crystals to the development of continuous manufacturing processes for these substances. One more specific aim of the research conducted at CMAC was to improve the understanding of the ways in which the molecules that make up crystals pack together. Controlling crystal formation in the pharmaceutical industry is crucial because the wrong crystal form could affect the amount of drug released by a tablet into the body after it is swallowed. Improvements in the precision of crystal formation through

[62] Lotfi Belkhir & Ahmed Elmeligi (2019) *Carbon footprint of the global pharmaceutical industry and relative impact of its major players,* Journal of cleaner production (214). Pp. 185-194.

[63] Novartis. Available at: https://novartis-mit.mit.edu/ (accessed 24 January 2019)

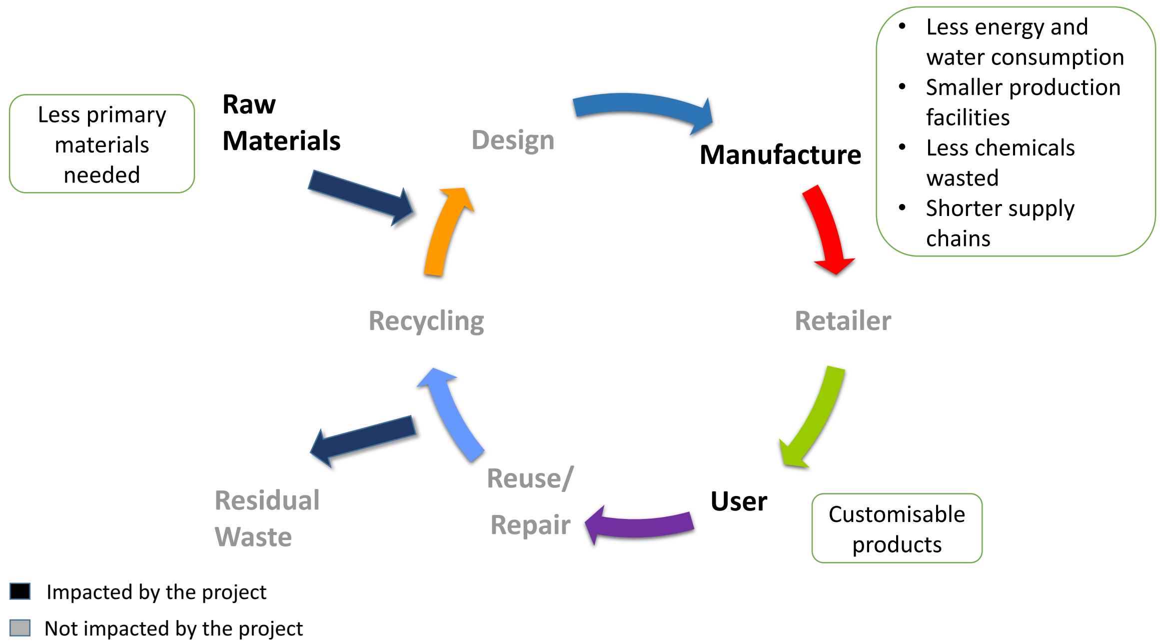
continuous processing can achieve more consistent quality and controllable performance of drug products. As explained by the PI interviewed:

> *"If we can produce particles that behave consistently, then we can save a great deal of money in manufacturing, as the first attempt will deliver the right result. This will be more efficient and will save resources, removing the need for reworking or more complex operations. Lots of energy goes into the process to manage the material properties so getting it right first time and designing for the intended purpose is energy saving"*[64].

5.11.3 Relevance to circular economy

Continuous manufacturing also reduces the size of equipment needed to manufacture a product because the same equipment aggregates different manufacturing steps that in batch manufacturing are carried out in separate stages and at different scales. Reducing the equipment needed means that production facilities can be smaller, thus with lower building and capital costs. Moreover, aggregating different manufacturing steps in one process could enable significant shortening of supply chains. Finally, it is possible to manufacture smaller quantities of drug using continuous crystallisation and achieve precise control or customisation over the material as well as enable scalable supply.

Figure 12 Circular economy for continuous processing



EPSRC funding enabled Strathclyde University to set up the Centre for Innovative Manufacturing in Continuous Manufacturing and Crystallisation. In particular, it enabled the Centre to achieve the critical mass and the investment needed to identify specific research questions and establish a collaborate, multidisciplinary team to address them[65].

A UK Research Partnership Investment Fund (UK_RPIF) capital award secured in 2013 allowed CMAC to invest £11.4M in a suite of continuous processing platforms, PAT and control technologies and

[64] Interview with Professor Florence

[65] Interview with Professor Florence

advanced characterisation tools creating a world class facility for continuous manufacturing research. Strathclyde University recruited a team of staff to support the CIM research team and our partners working on the Centre's projects[66]. At present, the activities of the centre are continuing with renewed EPSRC funding for a Future Manufacturing Research Hub from 2017 until 2023, with a particular focus on manufacturing of pharmaceuticals. CMAC currently employs more than 130 staff, researchers (academics, post docs, and about 45 PhD students) and benefits from an experienced support team. CMAC has helped to leverage a £100m funding portfolio spanning university and industry led awards from a mix of; EPSRC, EU and AMSCI projects[67],

5.11.4 Economic and Environmental impacts

In 2011, the chemical and pharmaceutical sectors were worth £113 billion annually to the UK economy in terms of sales[68]. Introducing continuous manufacturing on a larger scale could bring a number of benefits to the chemical and pharmaceutical industries, such as accelerating the introduction of a new range of products, enhancing process reliability and flexibility to respond to market needs and monitoring product quality on a continuous basis rather than through post-production, batch-based testing[69].

CMAC's initial Tier 1 partners were: AstraZeneca, GSK and Novartis with Bayer joining during the CIM[70]. Four other tier 1s have joined CMAC since then including Roche, Pfizer, Lilly and Takeda. These companies are major pharmaceutical companies and end users for the advanced manufacturing technology and research outputs. Moreover, CMAC has collaborated with 17 Tier 2 technology provider companies. Tier 1 partners all have a seat on the CMAC Industry Membership Board, which gives them the opportunity to inform the direction of research and support training and translational activities of the Centre. Moreover, this precompetitive partnership approach has allowed the Centre to develop strategy and accelerate progress across all of its key areas of research, training, translation and facilities development.

One Tier 2 partner company during the CIM, **NiTech Solutions,** is a developer and supplier of new crystallisation technology equipment. NiTech's technology was one of the early platforms investigated during the initial phase of CMAC[71] and the company provided early stage technological equipment to the Centre to support further research and development. Later generations of the equipment have been sold to companies in the pharmaceutical and fine chemicals sector. One pharmaceutical company that has applied it to their operations reported; 10% less waste disposal of chemicals[72], reduced water consumption by 83% and reduced solvent use by 42%, with an overall reduction of 52% of the manufacturing carbon footprint.

Swiss agrochemical multinational **Syngenta** and CMAC collaborated on a project which applied learning from a continuous crystallisation feasibility study to a Syngenta batch process for fungicide production, resulting in an improvement of the process. Referring to the project, Syngenta expressed the following: "*Overall it was a very valuable collaborative experience. I was really impressed that all the experiments in all equipment scenarios gave meaningful results. The project has led to insights which have changed the way we think about our crystallisation*"[73].

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[66] Interview with Professor Florence

[67] CMAC (2017) Annual Review *2017*. Internet, available at: https://www.cmac.ac.uk/files/media/18-198_CMAC_Annual_Review_2018.pdf (accessed 23 January 2019)

[68] Science Daily (2011) Center to revolutionize chemical manufacture is open for business. Internet, available at: https://www.sciencedaily.com/releases/2011/04/110408075035.htm (accessed 23 January 2019)

[69] Novartis. Available at: https://novartis-mit.mit.edu/ (accessed 24 January 2019)

[70] CMAC (2016) Annual Review 2015-2016. Internet, available at: https://www.cmac.ac.uk/files/media/Annual_Reveiw_2015-2016.pdf, p. 13

[71] NiTech Solutions. Available at: http://www.nitechsolutions.co.uk/about-us/

[72] Interview with industry partner

[73] CMAC (2016) Annual Review 2015-2016. Internet, available at: https://www.cmac.ac.uk/files/media/Annual_Reveiw_2015-2016.pdf (accessed 16 January 2019)

5.12 Case study 7: EPSRC Centre for Innovative Manufacturing in Additive Manufacturing

Project Title	**EPSRC Centre for Innovative Manufacturing in Additive Manufacturing - EP/I033335/1**
Principal Investigator	Professor R. Hague, School of Engineering, University of Nottingham
Time scale	01/10/2011 to 30/06/2012
EPSRC Investment	£5,973,220
Industry Investment	£3,175,000
Other grants & industry investments	Nottingham University grant, follow up EPSRC grants and industry investments.
Industry Partners	3T, the Atomic Weapons Establishment, BAE Systems, Boeing, Delcam International plc, Delphi Diesel Systems, Econolyst Ltd, EOS GmbH - Electro Optical Systems, MTT Technologies Ltd, National Physical Laboratory, Objet Geometries Ltd, Printed Electronics Limited, Renishaw, Smart Fibres Ltd, Solidica Corp, TWI Ltd., Coherent Inc., Physik Instrumente, Laser Quantum.

5.12.1 Introduction

As a manufacturing technology, Additive Manufacturing is based on the principle of fabricating a product layer-by-layer by adding material to '3D print' three dimensional objects. Multi-material additive manufacturing enables the manufacture of geometrically complex, low to medium volume production components in a range of materials, with little need, if any, of fixed tooling (such as moulds). It offers opportunities to create more lightweight components, whilst reducing material consumption and energy consumption in manufacturing processes. This sustainable and value-adding manufacturing process is applicable across multiple sectors.

5.12.2 Scientific Aims of the research programme

The aim of the EPSRC Centre for Innovative Manufacturing in Additive Manufacturing (CIM AM) was to research multi-material additive manufacturing (AM) processes, materials and design systems, and its potential industry applications. The research group led by Professor Hague conducted pioneering research in this area. Until 2011, research in AM had mainly focused on single-material, homogenous structures. In this respect, the EPSRC funding allowed the Centre to redirect basic research away from established, single material AM and explore multi-material, 'active' AM and its new and more sustainable solutions. Professor Hague, described the EPSRC funds as contributing in a major way to achieving their scientific and in commercial aims:

"The grant pump-primed us to work on multi-material additive manufacturing and to establish ourselves as a world leader in AM; we developed a new capability for the UK, and now are beginning to see its commercial exploitation."[74]

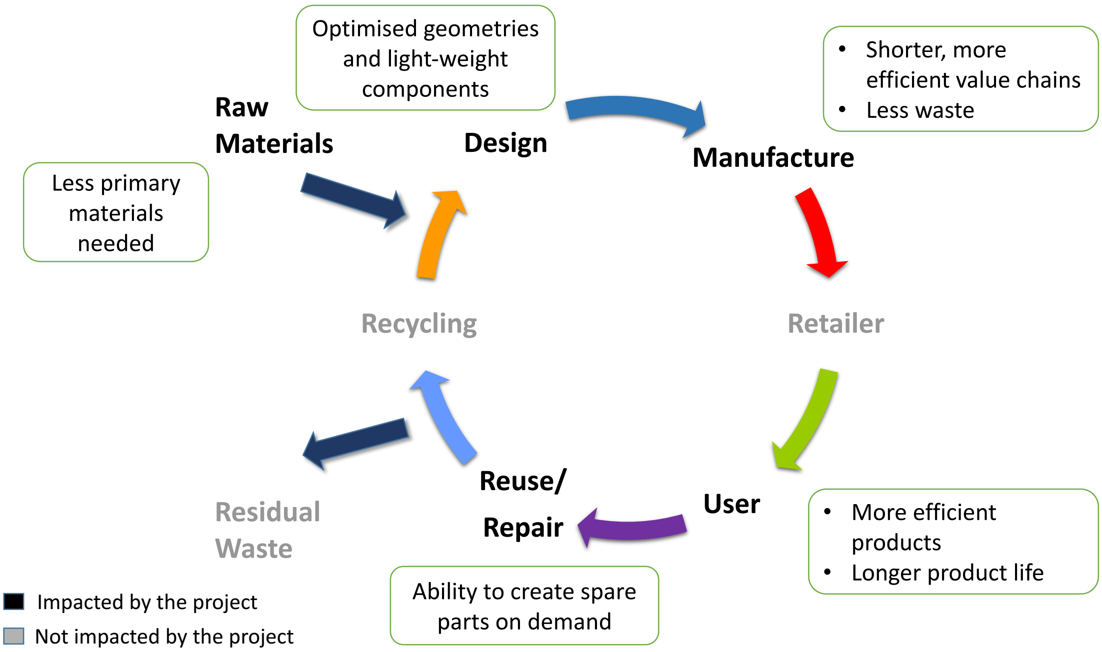
5.12.3 Relevance with the Circular Economy

The 'next generation' of Additive Manufacturing contributes to the circular economy by reducing industry's impact on the environment and by creating cost savings along the supply-chain. Additive manufacturing processes have the potential to improve the sustainability of manufacturing processes by making them shorter, smaller, more localised, and more collaborative. As illustrated in Figure 13, the capability to optimise geometries and create lightweight components reduce material consumption and

[74] Interview with Professor Hague

energy consumption in manufacturing, plus reduced waste disposal. There is also a subsequent reduction in transportation in the supply chain due to the ability to create spare parts on-site'[75].

Figure 13 Circular economy for additive manufacturing



Source: Technopolis

The EPSRC funds enabled the Centre to grow from 20 to 100 people and to attract a large number of additional grants and investments, both from the public and the private sectors. After one year from the start of the funding period, the Centre moved from the University of Loughborough to the University of Nottingham, where the CIM secured a £24m building (financed by the University of Nottingham, and in smaller parts by the Local Enterprise Partnership and the Wolfen Foundation), state of the art equipment and funding for further five years of research. Professor Hague said that the CIM has leveraged a total of £30m in additional funding.[76]

5.12.4 Outcomes for industrial partners

The CIM in AM has had several industry partners across sectors including Aerospace, Defence and Marine, Transport Systems, Electronics and Pharmaceuticals, with the latter two being new areas of applications. Industrial partners have engaged with the CIM in various ways.

In the period 2013-2014, the EPSRC Centre collaborated with **BAE Systems**, the UK's largest defence and security company. One of its core businesses consists in manufacturing military defence aircrafts. The collaboration with Professor Hague's CIM led the company to develop internal processes so as to start streamlining their production processes and integrate AM into their integrated manufacturing facilities.A project representative from BAE Systems' Additive Manufacturing explained the environmental and economic efficiencies brought about by AM:

"Because the additive manufacturing process is shorter, there is evidence for a reduction in the usage of energy (in particular of fossil fuel) and a reduced need for human labour; there is also a reduction

[75] Ford S. & Despeisse M. (2016) *Additive manufacturing and sustainability: an exploratory study of the advantages and challenges,* Journal of Cleaner Production 137. Available at: https://www.sciencedirect.com/science/article/pii/S0959652616304395 (accessed 11 January 2019)

[76] Interview with Professor Hague

in the usage of raw materials and in disposal waste, including landfill waste. This reduction in production costs results both in cost savings and in environmental benefits. AM also leads to more efficiently designed parts, which are lighter and better performing. Lighter-weight aircraft components are 'greener', as they require less consumption of fuel, although this is a smaller scale saving".

BAE Systems see the collaboration with the EPSRC as one of the factors that contributed to the successful application of additive manufacturing technologies. BAE Systems' own internal R & D, the collaboration with other industries and with other universities were all fundamental in achieving the outcome. BAE Systems said:

"Thanks to our involvement in Professor Hague's CIM, BAE Systems was able to widen the range of processes and the uses of materials. It made a significant difference to us."

BAE Systems continued to collaborate with many different research groups based at various universities in the UK and thus it is not feasible for them to attribute quantitative estimates of the value of this to the initial EPSRC collaboration.

For its collaboration with the UK's **Atomic Weapons Establishment** (AWE) in 2011, the EPSRC Centre provided contract research support to work on a number of projects based on AM. These initial projects have led to AWE becoming a formal partner of the Centre for Doctoral Training in AM and sponsoring internships for PhD students carrying out dissertation projects with industry relevance.

More recently, AWE's funding contribution to the EPSRC Centre for AM supported the following projects: '*Jetting of Polydimethylsiloxanes*', aimed at expanding the use of this material with properties such as high flexibility, gas permeability and biocompatibility which make it ideal for use in the biomedical, automotive, aerospace and defence industries; '*Laser Sintering and Stereolithography of Syntactic Foams*' aimed at producing customised, low density components for industrial applications which are more sustainable.

There are many examples of major industries investing significantly in early stage research for new AM techniques. In these cases, the expected environmental and economic benefits resulting from the collaborative research cannot yet be quantified. However, this level of interest and commitment from international industrial partners is an indicator that longer-term economic benefits are expected.

6 Conclusions

The study set out to assess what the overall impact has been of EPSRC's investments in research and training relating to the circular economy. This was considered from four perspectives, including;

1) What technical and scientific advances has EPSRC funding enabled?
2) What has been the impact on capacity building and training the next generation of scientists and engineers?
3) How has EPSRC funding helped in addressing key societal challenges around sustainability, environment, energy and health?
4) What evidence is there that EPSRC funded research has led to economic benefits to industrial partners and their wider sectors?

The evidence gathered shows high levels of impact have either already been achieved or are expected to be, within a ten-year period, across all four of these areas, as outlined below.

Advances in technology and scientific knowledge – the grants led to a high volume of publications in peer reviewed journal articles. These publications had an average citation impact of nearly twice the world's average, taking into account the publication year and the field of study. They also contained a relatively high proportion (around a quarter) that were among the world's top 10% of most highly cited papers. This is a strong performance and provides a good indicator of having advanced scientific knowledge in their relevant fields.

The industrial partners which had most frequently co-authored papers with grant recipients primarily represented the following industrial sectors; automotive, aerospace and defence and pharmaceuticals. Our case studies have explored examples of how initial scientific advances made by research in each of these sectors was subsequently progressed through follow-up collaborative R&D. For example, where scientific advances in creating new alloys based on recycled aluminium led to joint patents with an industrial partner, then follow-up R&D to test and develop manufacturing processes at scale, before reaching an operational phase and commercialisation.

Capability building and training – The award of a grant was commonly described as having a direct and near-term impact on building the capability of recipients to progress their field of study. For example, through providing resource to recruit post-doc research posts. In addition, capability building often follows as a result of publication of successful research results and the awareness this raises, leading to interest from new industrial partners and follow-up funding to provide resources for progressing the technologies along the TRL scale. For example, where an initial EPSRC funded project to develop new processes for recycling carbon fibre led to engagement with Boeing Company, who (although not a partner in the original research) provided follow-up funding and material resources to develop a pilot commercial scale carbon fibre recycling plant.

Aside from the benefits of increased collaboration, another route to building capability is through funding training, such as Centres for Doctoral Training (CDT). These demonstrated how engaging business partners to address the skills gaps and challenges faced by industry is core to shaping the aims of student's research. Our research with the one CDT which has been established long enough to report on next destination of students, also suggests that their training on wider professional skills (in addition to specialist subject area expertise) has proven successful in enabling them to obtain employment in relevant sectors.

Economic and environment impacts – Economic and environmental benefits of a circular economy are interrelated, because resource efficiency benefits such as; reduced use of raw materials, energy efficient manufacturing, less waste disposal and increased recycling are often directly linked to economic benefits, including; lower production costs, energy cost savings and profits from the sale of more sustainable products.

Our survey with PIs found that most could not provide evidence of quantifiable estimates of economic or environmental benefits having been already achieved. This reflects the early to mid TRL stage of technologies that most projects were at the time of this research, with their future pathways to commercialisation not yet certain. However, the case studies of selected grants that were awarded 5 to 10 years ago illustrate how the pathways to growth of a circular economy can be achieved, across a range of sectors, leading to high levels of economic and environmental impact.

Industrial partners described how their collaboration with the EPSRC funded project was instrumental in opening up avenues of R&D; through the pathway from collaboration in exploratory research to implementation of changes in their company's internal manufacturing process. The most common ways in which economic benefits were achieved were through:

- Cost savings derived from increased efficiencies in production processes (less inputs and resources used to achieve the same or better products)
- Additional revenue streams created from selling innovating technologies to other businesses
- Higher profit margins deriving from the manufacture of better performing products.

These improvements to products and services will also lead to wider social, environmental and sustainability benefits for consumers and the general public. For example, the production of lighter, more fuel-efficient cars will lead to cost savings for owners, whilst contributing towards improved air quality and associated public health benefits. Innovation in medicines manufacturing will reduce costs in the supply of drugs for healthcare, whilst also contributing towards reduced chemical waste.

From five of the case study projects alone, we have identified that there are approximately **£130m** of discounted benefits that can be attributable to the funding provided by the EPSRC grants, over a ten-year period. The primary drivers of these benefits are **reductions in energy use and Greenhouse Gas emissions (CO2e)** through more resource efficient manufacturing processes.

The value of the grants for the five case studies that we have produced ROI assessments for is approximately £15m, which represents 7% of the portfolio of grants. Whilst the high levels of return on investment from these case studies (**£9.62 per £1 per £1 invested**) may not be representative of all 223 grants, the value of economic benefits from these 5 projects alone provides a strong indication of positive impact from EPSRC's investment in circular economy research.

Appendix A Logic chain

Based on our assessment of stated outputs and outcomes from analyses of EPSRC's administrative data, we updated the initial **logic model** that was provided in the project invitation to tender. This sets out the logical sequence and causal relationships between; the funding (inputs) used and the activities undertaken to carry out research, the outputs arising from projects, intended changes (outcomes) and longer term impacts (based on the stated pathways to impact).

Table 19 Logic Chain

Inputs: Primarily EPSRC funding, plus networking and dissemination opportunities.

Impact pathway	Activities	Outputs	Intermediate Outcomes	Impacts
Knowledge (research excellence)	Research carried out relevant to CE	New research reports provide new evidence and scientific knowledge.	Improvement of research quality	Growth in body of knowledge relating to circular economy. Internationally leading research UK research capacity and expertise increased.
	Existing or new Research Centres supported	Research centres established/supported	Strategic growth in a region or institution	
	Research carried out in call-targeted fields	Publications & Citations in targeted area	Growth in targeted research community	
	Research carried out involving multi-disciplinary collaborations	Multidisciplinary publications	New areas of research emerging	
Economy (knowledge exchange, early stage commercialisation)	Research projects carried out with business collaboration	New or strengthened direct partner leverage	New investment created	Increase in sector productivity, value, exports, jobs, innovation Emergence of industrial symbiosis clusters Inward investment deals Increased turnover from sales of new products
		Greater collaboration on publications between Academia and Industry	New or improved products and services are informed by/based on CE R&D New Products, tools and services enter to the market and deliver value	
		Increased Intellectual Property and patenting		
	Research carried out focused on commercialisation-relevant R&D	New Spin-outs and JVs		
		Follow-on activity, e.g. proof-of-concept projects		

Impact pathway	Activities	Outputs	Intermediate Outcomes	Impacts
	Knowledge exchange events held	New or strengthened Demonstrators	Better/more relevant products/services for users which follow a CE approach Reduced costs of production from reduction in raw material inputs. Reduced costs of production from minimising expenditure on waste processing. Increased business to business collaboration through industrial symbiosis.	Increased profit margins from reduced costs of production
		New or strengthened connections between academia and private sector relevant to CE	Strengthened network of connections between CE-relevant academia and private sector	
People and Skills	Staff - research / other participating in CE research grants'	Career development supported	Improved researcher's career development Better prepared labour force supplied to the CE sector	Increase in UK's research capacity UK's leading position in the CE sector
	Research grants funded to support Doctoral students	Doctoral completions supported		
	Research grants funded to support Masters students	Masters completions supported		
	Research grants funded to develop courses or to enable researchers' attendance to relevant courses	Training completed		
	Existing or new Centres for Doctoral Training (CDT)	**CDT doctoral students' career development supported**	**Strategic growth in a research field**	UK's national/regional research capacity Enhance UK's position in the CE sector **Increased employment opportunities for CDT graduates.**
	Employers sponsor CDTs		**Students obtain PhD**	
			Expertise in industry relevant research subjects	

Impact pathway	Activities	Outputs	Intermediate Outcomes	Impacts
				Increase in skills and innovation among businesses **employing CDT graduates** or from collaborating in research projects.
		New or strengthened connections between academia and industry	Better prepared labour force supplied to the market, based on sector's demands	Highly skilled industrial labour force in CE sector
Society / Environment	Research carried out, which held public engagement events / activities held as part of project's activities	Public engagement or events carried out	Increase in public awareness of and perceptions about CE	More sustainable use of resources through increase in products designed to be reused, recycled or re-manufactured. Societal, e.g. consumer behaviour change and increased recycling. Environmental impacts, e.g. reduced CO_2e emissions, pollutants and waste to landfill. Health benefits from less pollution.
	Research initiated to address challenges around sustainable use of resources Stakeholder involvement and consultations – research considers industrial and Government R&D needs	New research evidence produced to inform future Government policy development and support	Public policy, standards and regulatory standards influenced	
		Projects adapted or developed	More relevant projects for public/consumer Products and processes informed by research results	
	Research carried out, which considered dissemination of results to policy audience	Citations and references to publications in policy documents	Policy instruments/programmes informed by research results	

Source: Technopolis

Appendix B Methodology

B.1 Overview of Research Strands

The approach to gathering evidence from various strands of primary research and analysis of secondary data sources was organised around four main Work Packages, summarised below

B.1.1 **WP1: Scoping Stage**

A short inception period, consisting of an initial an initial composition analysis of EPSRC data on the portfolio of research grants. Including breakdowns of the size, structure and key features of research funded, with an overview of what outcomes have been stated in ResearchFish®. This was used to refine the programme logic model and framework of methods to guide the evaluation.

Research outcomes data from the grants gathered through the Researchfish® system was provided by the EPSRC, giving details of 223 funding awards relevant to the circular economy, with a total value of around £205m. The 223 grants were selected by performing a keyword search on all grants which were funded by EPSRC between 1/12/2007 and 31/12/2016. The composition analysis provided a breakdown of types of research and training was funded through these grants, including summary of what outcomes were previously reported in Researchfish®.

The £205m of total funding was allocated across three categories: 1) *Standard Research Grants, 2) People Support Grants, and 3) Knowledge Exchange and Impact Grants*. These three high level categories grants each comprised of a number of different individual types of funding award. The table below provides a breakown of the composition of each of the three categories of funding.

Table 20 Composition of funding awards

Higher Level Category of Grants	**Individual types of funding within these categories.**
Standard Research Grant:	Standard Research
	IDEAS Factory Sandpit
	Standard - NR1
	Programme Grants
People Support Grants:	Leadership Fellowships
	Career Acceleration Fellowship
	EPSRC Fellowship
	Postdoctoral Mobility
	Platform Grants
	Research Chairs
	First Grant Scheme
Knowledge Exchange and Impact Grants:	Science and Innovation Awards

	Network
	Follow on Fund
	PPE
	RCUK PER Catalysts
	Technology Programme

B.1.2 WP2: Further analysis of EPSRC data and secondary sources

This phase included bibliometric analysis, carried out by our partners Clarivate Analytics, using their Web of Science database, to assess the volume of publications arising from the grant funded projects and associated citation data to map out the wider effects on the scientific landscape (further details given in section B.3 below). Analysis of secondary data sources also included case study analysis of REF2014 to summarise recorded impacts arising from research projects and use of a Bloomberg Terminal and FAME databases to search for financial information on spin-out companies.

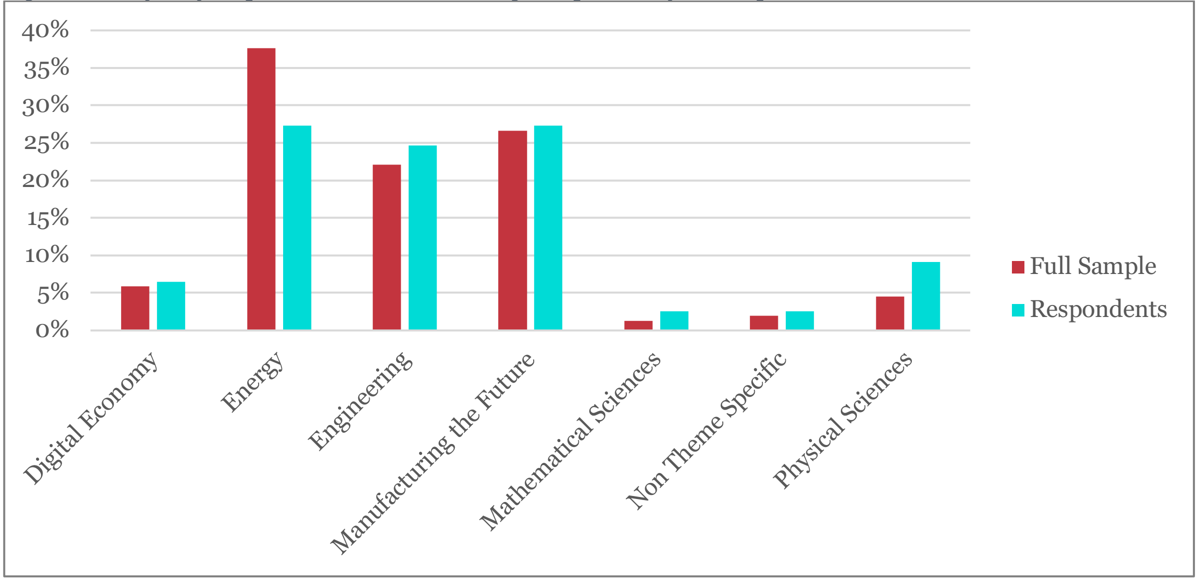
B.1.3 WP3. Primary data collection

The EPSRC's administrative data on grant awards provided contacts for a list of 186 individual Principal Investigators (PIs) who were recipients of funding. This formed the basis of our sampling frame for three main strands of telephone interviews and an online survey, as follows:

Online survey - The majority of PIs (152) were sent an online survey to gather information on outcomes arising from their projects, to update information previously recorded in ResearchFish®. This returned 76 responses; a response rate of 50%.

The profile of respondents to the survey generally provided a good reflection of profile of the full sample selected for the survey. Figure 14 below provides a comparison of proportions of lead thematic area for each research grant, between the full sample (shown in red bars) and the profile of respondents (in turquoise bars).

Figure 14 Profile of respondents to online survey compared to full sample



Source: Technopolis.

Telephone interviews with PIs - A further 39 PIs were shortlisted for more in-depth semi-structured telephone interviews to explore what range outcomes of outcomes had arisen from their projects in more detail. This short-list was selected to broadly reflect of the profile of the overall sample of research grants provided, in terms of proportions of grant by lead thematic areas of study, the amounts funded and types of grant. In total, 19 semi-structured telephone interviews were achieved; a response rate of almost 50%.

Interviews with Directors of Centres of Doctoral Training - The grant administrative data included details of three Centres of Doctoral Training (CDTs) which had been identified by the EPSRC as training students on themes that were particularly relevant to the circular economy. The Directors of all three Centres were invited to take part in semi-structured telephone interviews to gather information on how the CDs were addressing skills gaps in relevant industrial sectors and what the next destination of students are. Interviews were achieved with two out of the three CDTs, with one Director declining the invitation to take part due to a lack of availability. Across all three CDTs, a brief desk-based review of publications relating to their outcomes was carried out. For example, the CDT annual reports, reports on next destinations of graduates, and other information available via the CDT websites such as descriptions of the ways in which they collaborate with industrial partners.

Follow up interviews with industrial partners - Seven case study research programmes were selected to gather evidence on the wider economic benefits to businesses. The seven case studies were selected to reflect projects led by PIs from academic disciplines and with outcomes for various sectors, including; plastics manufacturing, pharmaceuticals, clean energy, automotive and aerospace engineering. Interviews were achieved with industrial partners from each of the seven case studies. The approach to selection and analysis of the case studies to estimate economic and environmental impacts is discussed further in section B.2. below.

B.2 Case Study Methodology

A range of projects were selected for more in-depth case study to understand what benefits have arisen from the projects for industrial partners who collaborated in the research programmes and the extent of wider economic and environmental impacts.

These 7 case studies are not intended to be representative of the wider population of all grants awarded in a statistical sense. However, they were selected to broadly reflect a range of different types of businesses and sectors that commonly collaborate with EPSRC funded research relating to circular economy. This provides evidence to illustrate the theory of change on how different types of environmental and economic impacts can be attributed to the original research grants. The main criteria used to select the cases studies included;

a) where the aims of the research project are relevant to the concept of the circular economy. Across the different case studies we reflect different 'points of the circle', for example; design for longer lifespan of products, use of less resources in manufacturing processes, less waste at end of product life and increased recovery of materials for recycling

b) to reflect projects across a range of academic disciplines and with outcomes for different industrial sectors where businesses commonly collaborate on EPSRC research projects, including; pharmaceuticals, clean energy, building construction, food and drink, automotive, plastics manufacturing, aerospace and defence

c) where the project summaries included explicit aims around addressing challenges of industrial partners or suggest that routes to commercialisation of products were actively explored as part of the project

These case studies, therefore, can be considered examples of the types of research projects that are more likely to have achieved environmental and economic impacts.

B.2.1 Return on Investment

Overview

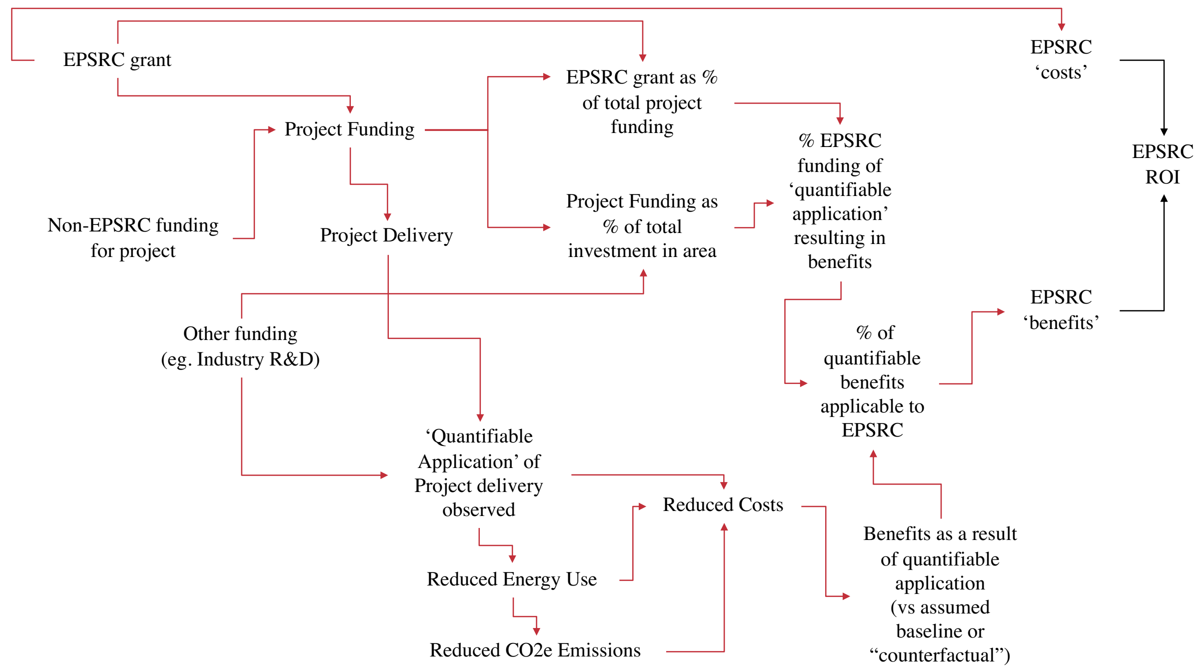
An estimated range of return on investment (ROI) has been provided for five of the seven case studies selected for in depth study.

The return on investment estimates are provided at both the individual case study level and for the 'Case Study Portfolio' of the five case studies in aggregate. The estimated return on investment figures should not be extrapolated to represent the total portfolio of EPSRC grants funding projects in the circular economy.

All ROI figures reported are for the EPSRC grant only, unless stated.

An illustrative approach to calculating the ROI is shown in the Figure 15 below:

Figure 15 Illustrative approach to calculating ROI



Source: Technopolis

The approach focuses on estimating the total funding associated with producing benefits associated with a 'quantifiable application' (e.g. reduced energy associated with production of a raw material) of the EPSRC funded project.

Benefits are then attributed to the EPSRC based on the estimated contribution of funding to the activity ('quantifiable application') that produced the benefits. Where possible, other funding (e.g. industry research and development not connected with the EPSRC project) was excluded from the analysis. However, in some cases, it was necessary to include the contribution of other parties as neglecting to do so would grossly over-state the benefits attributable to the EPSRC.

For example, the quantifiable application may be as a direct result of the EPSRC funded project. If the EPSRC provided 75% of the funding for the project (and a partner provided 25%), then 75% of the benefits associated with the 'quantifiable application' would be attributed to the EPSRC.

If, conversely, the quantifiable application was likely to have resulted from the EPSRC funded project, but also relied on other sources of funding, such as industry research and development (i.e. not a project partner), then the magnitude of the relative funding streams would be estimated. If the EPSRC funded project provided 10% of the estimated funding to the 'quantifiable application', and the EPSRC provided 75% of the project funding, then 7.5% of the benefits associated with the 'quantifiable application' would be attributed to the EPSRC.

At the case study level, the benefits and costs of the grant provided to the project were defined as:

$$\text{Estimated 'EPSRC ROI'} = \frac{\sum \mathit{Benefits\ attributable\ to\ grant\ funding}}{\sum \mathit{Grant\ funds\ provided\ solely\ by\ EPSRC}}$$

The Estimated Total EPSRC circular economy 'Case Study Portfolio' Return on Investment, was the total of all costs and benefits identified in the case studies, defined as:

$$\text{Estimated 'Case Study Portfolio' ROI} = \frac{\sum \mathit{Benefits\ attributable\ to\ grant\ funding, for\ all\ case\ studies}}{\sum \mathit{Grant\ funds\ provided\ solely\ by\ EPSRC\ for\ all\ case\ studies}}$$

'Case Study Portfolio' here refers to the five in-depth Case Studies where ROI estimates were provided.

Benefit Attribution and Counterfactual Case Identification.

Benefits attributable to each case study can be categorised into one of the following types of benefit:

- Value of reduced energy usage associated with the reduction in production of "virgin" materials as a result of approaches to re-using existing materials.
- The value of the CO2e or GHG emissions associated with the reduction in energy use (see above).
- Cost reductions for project participants as a result of improved techniques to reduce capital or operating expenditure.
- The self-reported economic "value" to sector participants that a spin off company offers as part of its innovative product, given assumed market participation.

Table 21 Categorisation of attributable benefits

Case Study	Attributable Benefits
Case Study 1: Low Carbon Wastewater Treatment	Reduced energy associated with the replacement of WWT treatment plants (in line with normal asset replacement cycles). Reduced CO2e/ GHG emissions associated with a reduction in electricity use for WWT plants.
Case Study 2: Recycling Carbon Fibre using a Fluidised Bed Process	Reduced energy associated with the reduction in the production of virgin carbon fibre. Reduced CO2e/ GHG emissions associated with a reduction in energy use for production of virgin carbon fibre.
Case Study 3: Low Carbon Vehicle Structures (TARF-LCV)	Reduced energy associated with the reduction in production of virgin aluminium. Reduced CO2e/ GHG emissions associated with a reduction in energy use for production of virgin aluminium.
Case Study 4: Through-life Engineering Services (TES Centre)	Cost reduction to the project industry participants.
Case Study 5: Catalysts to reduce carbon dioxide in production of carbon-based fuels (Econic)	Self-reported estimated 'value' projected to be provided to producer of polyol. Reduced CO2e/ GHG emissions associated with increased market penetration of the product in producing catalysts.

Case Study	Attributable Benefits
Case Study 6: EPSRC Centre for Innovative Manufacturing in Continuous Manufacturing and Crystallisation (CMAC)	No specific and quantifiable benefits were attached to this case study.
Case study 7: EPSRC Centre for Innovative Manufacturing in Additive Manufacturing	No specific and quantifiable benefits were attached to this case study.

Source: Technopolis

Each Case Study assumed a baseline counterfactual scenario. Typically, the counterfactual scenario assumed that existing supply, demand, and price levels would remain constant through the study period. Specific details of counterfactual scenarios are detailed in the Case Study descriptions.

As stated above, the particular type of attributable benefit was, where possible, driven by the response to the case study interviews with the project participant. The calculation of per annum benefits was calculated using a techno-economic approach.

Data inputs to the techno-economic projection of benefits were taken from the following three sources:

- the respondents to the case studies provided estimates or data on expected benefits associated with the results of the grant-funded projects
- publicly available sector specific data (e.g. the projected price of virgin carbon fibre)
- generalised economic inputs, such as prices for energy, or CO_2e emissions.

The following generic assumptions have been made regarding the estimated benefits associated with all Case Studies, where applicable.

Table 22 Generalised assumptions across case studies

Assumption	Unit	Value	Source
Base Year		2009	Technopolis
Discount rate	%	3.5	Treasury Green Book
Industrial Electrical Tariff	£/kWh	0.08	BEIS DUKES
Carbon Intensity of Grid	gCO_2 / kWh	225	BEIS DUKES
Carbon Emissions Cost (EUA)	EUR/ tCO_2e	20	EEX.com EUA price (Feb 2019)

Source: Technopolis, and others

Benefits were limited to a maximum of ten years after they were anticipated to begin. Benefit streams associated with the case studies varied in terms of start date, with these dates based on responses from participants and the timing of the EPSRC grant itself

Sensitivity Analysis

Sensitivity Analysis was included as part of the ROI estimate process in order to account for high level of uncertainty that surrounds the derivation of estimated future benefits resulting from the EPSRC grants. The relative scarcity of information relating to the benefits necessarily means that analysis has focused on the responses from the interviews conducted as part of this analysis. In addition, sensitivity analysis is required as there is an acknowledged difficulty in accurately ascertaining the appropriate level of attribution to both the EPSRC-funded project and the associated EPSRC grant funding itself.

Using sensitivity analysis also allows for testing of the robustness of the ROI estimates. Central, high and low cases were identified for various key inputs for each case study. The table below highlighted the sensitivity cases used in each of the five case studies.

Table 23 Case Study attributable benefits

Case Study	Attributable Benefits
Case Study 1: Low Carbon Wastewater Treatment	No. of replacement WWT plants, per year Energy Consumption, per standard WWT plant
Case Study 2: Recycling Carbon Fibre using a Fluidised Bed Process	Value of rCF produced per annum Energy savings by using rCf vs vCF Avoided GHG emissions
Case Study 3: Low Carbon Vehicle Structures (TARF-LCV)	Electricity requirements for virgin aluminium Reduction in Energy used to manufacture rAl vs Val % of REALCAR gains attributable to TARF-LCV
Case Study 4: Through-life Engineering Services (TES Centre)	Reduction in Cost through adoption of TES
Case Study 5: Catalysts to reduce carbon dioxide in production of carbon-based fuels (Econic)	Market Penetration % of Econic benefits attributable to Nano-crystal project

Source: Technopolis

Specific values for the sensitivity assumptions are highlighted in the Case Study descriptions. The range of ROIs associated with the use of the inputs attached to each sensitivity case are reported for each Case Study.

B.3 Bibliometric methodology

B.3.1 Overview

Bibliometrics is the analysis of data derived from publications and their citations. Publication of research outcomes is an integral part of the research process and is a universal activity. Consequently, bibliometric data have a currency across subjects, time and location that is found in few other sources of research-relevant data. Citation levels measure of the volume and frequency in which a report is being referenced by other authors (including authors form separate fields of study), which gives an indication of advances in scientific knowledge, as explained further below.

The main data source used for bibliometric analysis was the Clarivate Analytics' Web of Science, which is widely acknowledged to be the world's leading source of citation and bibliometric data. The Web of Science 'Core Collection' focuses on research published in journals and conferences in science, medicine, arts, humanities and social sciences. The authoritative, multidisciplinary content covers over 27,000 of the highest impact journals worldwide, including Open Access journals and over 161,000 conference proceedings. Coverage is both current and retrospective in the sciences, social sciences, arts and humanities.

B.3.2 Summary of Methods

Research publications accumulate citation counts when they are referred to by more recent publications. Citations to prior work are a normal part of publication, and reflect the value placed on a work by later researchers. Some papers get cited frequently and many remain uncited. Highly cited work is recognised as having a greater impact and Thomson Reuters has shown that high citation rates are correlated with other qualitative evaluations of research performance, such as peer review. This relationship holds across most science and technology areas and, to a limited extent, in social sciences and even in some humanities subjects.

Indicators derived from publication and citation data should always be used with caution. Some fields publish at faster rates than others and citation rates also vary. Citation counts must be carefully normalised to account for such variations by field. Because citation counts naturally grow over time it is essential to account for growth by year. Normalisation is usually done by reference to the relevant global average for the field and for the year of publication.

The following terms and bibliometric indicators have been used for this evaluation:

- **Papers/publications**: Clarivate Analytics abstracts publications including research journal articles, editorials, meeting abstracts and book reviews. The terms 'paper' and 'publication' are often used interchangeably to refer to printed and electronic outputs of many types. In our analyses, the term 'paper' is used exclusively to refer to substantive journal articles, reviews and some proceedings papers and excludes editorials, meeting abstracts or other types of publication. Papers are the subset of publications for which citation data are most informative and which are used in calculations of citation impact.
- **Research field**: Standard bibliometric methodology uses Web of Science journal subject category or Clarivate Analytics InCites: Essential Science Indicators fields as a proxy for research fields. Essential Science Indicators aggregate data at a higher level than the journal categories – there are only 22 Essential Science Indicators research fields compared to 252 journal categories. Journals are assigned to one or more categories, and every article within that journal is subsequently assigned to that category. Papers from prestigious, 'multidisciplinary' and general medical journals such as Nature, Science, The Lancet, The BMJ, The New England Journal of Medicine and the Proceedings of the National Academy of Sciences (PNAS) are assigned to specific categories based on the journal categories of the references cited in the article. The selection procedures for the journals included in the citation databases are documented at the Clarivate Analytics master journal list website.
- **Citations**: The citation count is the number of times that a citation has been recorded for a given publication since it was published. Not all citations are necessarily recorded since not all publications are indexed. However, the material indexed by Clarivate Analytics is estimated to attract about 95% of global citations.
- **Field-normalised citation impact**: Citation rates vary between research fields and with time. Consequently, the analyses takes into account both field and year into account. In addition, the type of publication will influence the citation count. For this reason, only citation counts of papers (as defined above) are used in calculations of citation impact. The standard normalisation factor is the world average citations per paper for the year and journal category in which the paper was published.
- **Highly cited papers**: Highly cited work is recognised as having a greater impact and Thomson Reuters has shown that high citation rates are correlated with other qualitative evaluations of research performance, such as peer review. In this analysis, publications that are in the top 10% in terms of citation frequency are considered to be highly cited, taking into account year of publication and field. This threshold was selected after the review of a number of previous analysis showed this to be a useful value for general management purposes. The term very highly cited papers is used in this report to refer to papers in the world's top 1% of most highly cited papers.
- **Co-authorship of publications**: The metadata associated with every research publication include the addresses of the authors. This has been used to develop an analysis of the organisations that co-author publications by extracting and examining these data.

The EPSRC provided Technopolis and Clarivate Analytics with lists of the publications associated with its Circular Economy grants, as reported by project leads in the Researchfish® system. Clarivate Analytics matched all of the publication records provided by EPSRC (the worksheet named "Publications" in the Excel spreadsheet file named "UniqueOutcomes 2018 data collection.xlsx") to the publication records in the Clarivate Analytics Web of Science. This allowed to link these documents to the citations they have received and to calculate bibliometric indicators.

Appendix C Research Excellence Framework Case Studies

The Research Excellence Framework (REF) assesses the quality of research in UK higher education institutions and was last conducted in 2014. The REF, which replaced the Research Assessment Exercise (RAE), incorporated elements of "impact" into the research assessment in the UK. Consequently, the REF2014 showcased the impact of research beyond academia by developing impact case studies. The REF 2014 case studies outline how research has transformed and advanced the UK science base, economy, society, environment and quality of life, as well as known impacts internationally.

The Technopolis team ran a database matching analysis to identify if any of the 223 EPSRC grants in the Researchfish® database provided were linked to the REF2014 case studies. The analysis matched a total of 12 relationships between eight EPSRC grants which were cited in ten REF2014 case studies. Table 24 shows the relation between the EPSRC grants and the REF2014 case studies. Table 26 provides a summary of the impacts that have been described in the case studies. Note that these descriptions of impact are based on the case study author's own claims.

Table 24 EPSRC associated to the REF2014 case studies

Grant Reference Number	Grant Title	Lead theme	REF 2014	ID case study
EP/F029624/1	SUPERGEN Photovoltaic Materials for the 21st Century	Energy	1 case study	28167
EP/F029748/1	SUPERGEN 2 - Conventional Power Plant Lifetime Extension Consortium - CORE	Energy	2 case studies	18356, 31024
EP/G031681/1	SUPERGEN HDPS - CORE	Energy	2 case studies	16774, 42169
EP/G066477/1	Control for Energy and Sustainability	Energy	1 case study	9043
EP/H020047/1	Light alloys towards environmentally sustainable transport: 2nd Generation Solutions for advanced metallic systems (LATEST2),	Manufacturing the future	1 case study, 2 DOIs	28167
EP/H021779/1	Evolution and Resilience of Industrial Ecosystems (ERIE)	Mathematical Sciences	1 case study, 2 DOIs	40330
EP/I012206/1	Processes, mechanics and management of wastes	Engineering	1 case study	44180
TS/H000623/1	SHIELD - Sustainable High Energy Absorbing Lightweight Material Development	Manufacturing the future	1 case study	31035

Although eight EPSRC grants were mentioned on the REF2014 case studies, not all the case studies described impacts that were relevant to the theme of the circular economy. Therefore, following the initial identification, the team selected five case studies, where associated impacts were most relevant to the Circular Economy. However, it is important to highlight that in some cases the impacts described are the result of several years of research and cycles of funding from different organisations and industrial partners. Therefore, while the EPSRC grants' outcomes may have contributed to achieving these impacts, they are not entirely attributable to EPSRC funding.

The following case studies were noted as being informed by the EPSRC grants but their descriptions of impact are less relevant.

Table 25 Case studies informed by the EPSRC grants but less relevant impact

Grant Reference Number	Grant Title	Case Study ID	Case study Title	Associated impacts
EP/G066477/1	Control For Energy and Sustainability	9043	The Inerter	The case study primarily focuses on explaining the impacts of the Inertter, a new mechanical device and suspension component, which became endemic in F1 and IndyCar racing manufacturing
EP/F029748/1	SUPERGEN 2 - Conventional Power Plant Lifetime Extension Consortium - CORE	31024	Use of novel small specimen testing methods for improvements in power plant maintenance operations	This case study refers to the same EPSRC grant than the 16774 case. Both focus on the environmental induced degradation of materials. However, the second one (included in table B) explains a more significant impact associated with the circular economy, which is extending the life of manufacturing components.
EP/G031681/1	SUPERGEN HDPS - CORE	42169	Case 5 - Design and optimisation methods for power networks impacting industrial strategies and government policies	Impacts focus on improvements for electricity networks. Thus, even though this research can facilitate the connection of higher amounts of wind and foster smart grid technologies, the impact to the CE is secondary.
TS/H000623/1	SHIELD - Sustainable High Energy Absorbing Lightweight Material Development	31035	Passively safe street furniture	Major impacts are related to safety, as a result of better street posts

Source: Technopolis, using Researchfish®

Table 26 Summary of REF2014 case studies related to CE impacts

REF 2014 Case Study Title and ID	**Grant Title, Ref number and Institution**	**Aims of underpinning research**	**Summary of Circular Economy related impacts**
35123 Guiding the implementation of photovoltaic systems in the UK and Europe	SUPERGEN Photovoltaic Materials for the 21st Century (EP/F029624/1), University of Northumbria	Underpinning research focused on understanding solar PV system design and performance. The overall aim was to uncover the potential of solar resources to increase the generation of solar energy, by accelerating the deployment of PV technologies. Research focused on the following areas: PV potential assessment; performance monitoring and PV Materials; and Device Research. Major related grants: • EPSRC EP/F029624/1, SUPERGEN Photovoltaic Materials for the 21st Century. The project intended to build the research capacity in PV solar energy materials and devices research in the UK throughout a consortium. • ENER/FP7EN/249782/PEPPER, Demonstration of high-performance processes and equipment for thin film silicon photovoltaic modules produced with lower environmental impact and reduced cost and material use	This research led to solar energy technology and policy developments in the UK, that have contributed to increasing renewables energy resource flows, which is crucial for the CE approach. The research has underpinned the accelerate deployment of Solar PV technology in the UK and thus, helped to avoid CO2 emissions and reduce the use of fossil fuels. Research also led to an increase in materials utilisation efficiency, which implies that less energy and raw materials are needed now in the manufacturing process of Solar PV technologies. <u>Technological impact</u> The PV Materials and Device Research led to an improvement of photovoltaic (PV) system performance. The PV system materials impacts were supported by the development of new and sustainable materials for PV devices, (**EPSRC EP/F029624/1**, ENER/FP7EN/249782/PEPPER). For instance, the kesterite compound CZTS (Cu2ZnSnSe4) material that achieved a world record in device efficiency in 2009. <u>Policy impact</u> Research provided informed guidance and performance benchmarks used in: • the Standard Assessment Procedure used by the Department for Energy and Climate Change for energy assessment in buildings; • the UK Government's Microgeneration Feed-In Tariff scheme to support the development of the UK solar energy market;

REF 2014 Case Study Title and ID	Grant Title, Ref number and Institution	Aims of underpinning research	Summary of Circular Economy related impacts
			• the development of the Microgeneration Certification Scheme for UK PV installers; • the development of new European PV system monitoring guidelines and the updating of IEC monitoring standards.
28167 High-Performance Magnesium Alloys	Light alloys towards environmentally sustainable transport: 2nd Generation Solutions for advanced metallic systems (LATEST2), (EP/H020047/1), University of Manchester	Magnesium is an attractive material for manufacturing components, in a sector where weight reductions are essential to improve fuel efficiency and reduce CO_2 emissions, because it is the lightest structural metal; 35% lighter than aluminium, and 80% lighter than steel. The underpinning research aimed to overcome three challenges of traditional magnesium alloys: poor strength, poor corrosion resistance, and limited elevated temperature capability. The overall objective was to develop new lightweight magnesium alloys to be used in a full range of new applications for magnesium. Research led to: • Designing the strongest alloy composition, and alloy microstructures stable at elevated temperatures, • Understanding magnesium alloys textures and strengthening mechanisms, • Developing corrosion protection systems, including the first environmentally-friendly corrosion system.	<u>Technological and socio-environmental impacts</u> Research at Manchester has led to the development of a new class of high-performance magnesium alloys that have allowed a reduction in energy consumption, fuel consumption and CO_2 emissions: • In helicopter and fixed-wing military aircraft, new alloys produce weight savings of 35% by improving performance and reducing fuel consumption. Therefore, there is also a decrease in CO_2 emissions and energy consumption. • Aerospace industry calculations have demonstrated that a 10% reduction in fuel consumption and emissions will be obtained through increased used of high-performance magnesium alloys in a typical large passenger aircraft[77] • In the motorsport industry, an improvement in strength/weight materials ratio of between 20-25% is possible by using these new magnesium alloy. The improvement reduces vehicle mass by around 10 kg.

[77] Aeromag: Aeronautical Application of Wrought Magnesium, EU FP6 consortium report http://www.transport-research.info/web/projects/project_details.cfm?id=11198

REF 2014 Case Study Title and ID	Grant Title, Ref number and Institution	Aims of underpinning research	Summary of Circular Economy related impacts
		The EPSRC grant contributed, particularly, to encourage industry partners to use more lightweight materials in transport applications to increase fuel efficiency.	Results contribute to the CE by controlling the use of natural resources and increase resource efficient utilisation. <u>Other economic impacts</u> Commercialisation of these alloys by Magnesium Elektron (ME), the international leader in magnesium alloy development – ME has designed over 80% of the new magnesium alloys developed in the last 30 years – contributes over $20m per annum to company revenue. This is the result of a 20-year collaboration between the University and ME.
18356 Extended life of industrial gas turbine blades using novel coatings	SUPERGEN 2 - Conventional Power Plant Lifetime Extension Consortium – CORE, (EP/F029748/1), Loughborough University	The research aim has been to investigate environmentally induced degradation (forms of hot corrosion and oxidation) for various materials systems (base alloys and metallic coatings) used in components (e.g., blades, vanes, discs and seals) of industrial gas turbines and jet engines. Underpinning research comprises work done in the following areas: • Improving the understanding of hot corrosion (high and low temperature) and oxidation in these systems • Optimising a methodology for assessing hot corrosion damage of materials • Exploring the ability of alternative metallic coating compositions to resist particular degradation modes	<u>Technological impact</u> Research has improved resource yields by prolonging the life of different manufacturing components. For instance, Siemens, Rolls Royce and others have improved the potential life of components in jet engines and gas turbines, e.g. blades, vanes, discs, and seals. <u>Policy Impacts</u> • Test standardisation Research outputs have been incorporated or used as a reference in: The EU code of practice of deposit recoat BS ISO 26146:2012 and BS ISO 14802:2012 Approaches to assessing the performance of metallic gas turbine materials for these forms of damage used by Rolls Royce and Siemens

REF 2014 Case Study Title and ID	Grant Title, Ref number and Institution	Aims of underpinning research	Summary of Circular Economy related impacts
		• Research on the performance of existing and developmental metallic coatings/alloys in industrial gas turbines, in future power generation systems The EPSRC EP/F029748/1 research grant contributed to improving the understanding of hot corrosion and oxidation in these systems, contributing to optimise the methodology for assessing hot corrosion damage of materials and investigating the performance of existing and developmental metallic coatings/alloys in industrial gas turbines.	
16774 Shaping energy Efficiency Policy , "The Green Deal" and Energy Saving Feed-in Tariffs."	SUPERGEN HDPS – CORE, EP/G031681/1, University of Oxford	The underpinning research aimed at studying and understanding problems in the UK´s Grean Deal policy. And providing a potential policy solution for such problems in line with UK´s energy market reforms.	Policy Impacts • The research was fundamental to set up energy policy in the UK. It concluded that ESFITs, a similar Feed-in Tariffs (FiTs) mechanism, offered a promising way of improving energy efficiency and reducing energy demand, thereby decreasing carbon emissions. The research influenced the interactions with policymakers at DECC and resulted in a formal government consultation including the idea of a "premium payment" by DECC. Impacts on Research and capacity development • At the time when the research was conducted, the Green Deal was the most substantial financing mechanism in the world. The policy was carefully observed outside the UK. In 2013, the research was featured in a plenary

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			session presentation at the leading European energy efficiency conference • The concept of ESFITs was influential worldwide and was cited in the final draft of the forthcoming IPCC Working Group III Report.
40330 Modelling the evolution of a bio-based economy in the Humber region	Evolution and Resilience of Industrial Ecosystems (ERIE), (EP/H021779/1), University of Surrey	The underpinning research is attributable to the EPSRC grant: In 2010, an interdisciplinary research team at Surrey was formed as part of the EPSRC-funded "Evolution and Resilience of Industrial Ecosystems" (ERIE) project, to study the application of complexity science to social and economic systems. The aim was to provide models of multi-level socio-economic systems that were useful for decision-makers to steer policies goals towards a bio-based economy. The Centre for Environmental Strategy (CES) developed a case study of the Humber region, which is one of the UK's major energy generators and CO_2 emitters, and they introduced ERIE to Humber. Researchers, in collaboration with critical industrialists from the Humber region, have produced a mathematical model of the main factors influencing the transition to, and establishment of, a bio-based economy. This	<u>Impacts on Research and capacity development</u> The EPSRC grant led to improvements in the position of UK's national/regional research capacity in the area of bio-based economy research. <u>Socio-environmental and economic impacts</u> Regarding CE, the concept of bio-based economies involves "the production of renewable biological resources and the conversion of these resources, residues, by-products and side streams into value-added products, such as food, feed, bio-based products, services and bioenergy"[78] (EU, 2018). Therefore, it contributed to advance the circular economy in the Humber region, as well as to improve environmental and economic regeneration

[78] For more information about this concept: http://www.biobasedeconomy.eu/

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		model has been used by the Humber Environmental Managers (HEM) group, and the Humber local authorities to help guide strategic planning for the region. Throughout the research, participants and policymakers were introduced to the key factors influencing the start-up of a bio-based economy, how these factors interact with each other, and how to turn the information into a mathematical model.	

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