Science and the economy

POLICY BRIEFING

PART OF SCIENCE 2040

Policy briefing

Politics and science frequently move on vastly different timescales. A policymaker seeking evidence on a new policy will often need the answer in weeks or months, while it takes years to design and undertake the research to rigorously address a new policy question. The value of an extended investigation into a topic cannot be understated, but when this is not possible good evidence is better than none.

The Royal Society's series of policy briefings is a new mechanism aiming to bridge that divide. Drawing on the expertise of Fellows of the Royal Society and the wider scientific community, these policy briefings provide rapid and authoritative syntheses of current evidence. These briefings lay out the current state of knowledge and the questions that remain to be answered around a policy question often defined alongside a partner.

This policy briefing was created as part of the Science 2040 programme, looking at what the UK science system could and should be in the future. The programme seeks to articulate the value of science to society and advocates for a long term vision for UK science.

For more information visit:
royalsociety.org/science2040

Science and the economy
Issued: June 2024
ISBN: 978-1-78252-719-0

This report can be viewed online at:
royalsociety.org/science-and-the-economy

Cover image © iStock.com / SweetBunFactory.

Contents

Executive summary

Science underpins the modern economy

Scientific research, and the innovations that build on it, have transformed the world. Some of the outcomes are highly visible – for example new treatments for disease or new consumer electronic devices. Others are less visible but provide the infrastructure for the modern economy, such as the network of fibre optic cables and associated optoelectronics on which the entire internet runs.

Science underpins innovation and technological advancement. This drives productivity which in turn boosts wages. Science-led innovation also benefits the economy indirectly, by contributing to national security, environmental protection and public health.

New metrics are needed to fully capture the economic impact of science

While the economy is founded on the products of scientific research, the direct economic impact is underestimated. Quantitative studies often focus on private rates of return on investment in research, with different authors producing estimates of anywhere up to 231%[1].

These studies do not however capture the whole value created by the science system because of the amount of time it can take before a piece of research can be economically exploited; the 'non-rival' and 'non-excludable' nature of scientific knowledge, meaning many people can benefit and build on any single scientific advancement; and the inherent uncertainty and variability on the journey from cutting-edge research to economic impact.

Rates of return studies therefore capture a portion of the value generated, but only a small slice. The total contribution of science to the economy is much larger and can be understood through four interconnected paths to impact:

1. **New knowledge and ideas**
   Scientific research produces specific bodies of knowledge and process that can be applied for economic benefit

2. **Innovation and productivity**
   The application of bodies of knowledge and process spills over into innovation and productivity gains

3. **Skilled people and jobs**
   Scientific research and development (R&D) has a significant impact on human capital, through education and training and the generation of new types of jobs

4. **Wider economic impacts which are not directly monetised**
   Science generates important benefits that enable other economic activity, from improved public health to environmental protection and national security

To illustrate the paths to impact and the ways they interact, this report contains case studies telling the story of optical fibres, high temperature alloys and synthetic insulin. Together with a detailed exploration of the evidence on the paths to impact these feed into an analysis of the evidence gaps that need addressing to understand better the relationship between science and the economy.

Basic research is critical to applied development

Emphasised throughout the report is the critical importance of basic research for applied development. Without sufficient basic research capacity, an economy can neither produce the cutting edge knowledge and processes that underpin future economic benefits, nor capitalise on such discoveries made elsewhere. Yet there is a market failure when it comes to producing such research. Curiosity-driven science benefits the economy over long timescales and spread more widely than applied knowledge, transforming the economy in ways that are impossible to predict.

The development of computers and the internet, for example, which have become central to everything in the global economy, built on decades of foundational investigations in electromagnetism and theoretical mathematics. The rapid production of vaccines to combat COVID-19 was underpinned by years of accumulated research on mRNA and coronaviruses. The origins of polymerase chain reaction (PCR) testing – another significant intervention during the pandemic – can be traced back to the chance discovery of a micro-organism *Thermus aquaticus* in the 1960s. Much of the underpinning science in all of these cases was publicly funded.

Role of the report

A better understanding of how science and innovation lead to economic impact is needed to ensure a productive and flourishing future economy. This report builds the evidence base for policymakers and proposes a taxonomy of how this economic impact ought to be assessed. It also serves as an input to the Royal Society's Science 2040 programme which aims to articulate the value of science to society and the case for the UK implementing a long-term vision and investment framework.

Introduction

Look anywhere in the modern economy and you will see the fruits of scientific research. An everyday device such as the smart phone, used by billions globally, provides data at our fingertips and can locate itself to within a few metres wherever you are. It has computing power beyond what the space programme half a century ago could have dreamt of. These devices embody decades of research across the world on everything from designing and manufacturing integrated circuits on a scale close to the atomic, to accessing the constellation of satellites that comprises GPS, to the global system of optical fibres which carry the enormous information flows of the internet, to the creation of ultra-pure materials – such as semiconductors, liquid crystals or organic light emitting materials – of which smart phones and other such devices are made. The COVID-19 pandemic reminded us just how quickly scientific research can be translated into saving lives and benefiting the economy when the situation is urgent enough. The journey from characterising the pathogen to the development of effective vaccines took place over an incredible eight-month period in 2020.

The world we live in and the economy we take part in have been transformed by science. Yet the mechanisms by which science translates into economic growth, or by which a specific piece of scientific research leads to economic impact, remain obscure. Attempts to measure the rates of return on investment in public R&D estimate an annual return of approximately 20%, or 20p back every year to a private firm for every £1 invested in R&D. But this is an underestimate, failing to capture either the breadth of economic benefits beyond an individual firm, or the timeframes over which economic returns from science investment are realised. These timeframes are often longer than most statistics designed to measure rates of return on investment can accommodate.

Furthermore, the economic transformations brought about by science can be too pervasive and transformative to be easily captured. It is impossible to capture the full economic impact of advances as fundamental to the modern economy as the application of electricity, or the development of the internet precisely because they have been so globally significant.

That science makes a central contribution to the economy is undeniable. It has direct economic impact by creating the knowledge, informing the processes, and catalysing the skills necessary for innovation and technological advancement. That in turn improves economic performance through innovation and technology-driven growth in productivity, which can boost industrial competitiveness and lead to higher wages (see Box 1 on means of measuring impact).

Science and the science system also make important indirect contributions to the economy. Applying scientific knowledge to develop new medicines and treatments, or to tackle complex global challenges such as climate change and biodiversity loss, contributes to our overall health, wellbeing and security. The question is not whether science leads to economic impact but exactly how much value it generates.

This report seeks to build the evidence for importance and transformative positive impacts through alternative means to standard rates of return. It proposes a taxonomy of the different paths to economic impact from science, and includes a set of case studies to illustrate these. It also identifies gaps in the current evidence base that could be filled to better quantify economic contributions.

Science defined as (part of) R&D

For the purposes of this report, the term 'research' describes a spectrum of activities around the creation and use of knowledge from basic research and discovery to applied development in the form of new technologies and other applications. In popular discourse it often gets used interchangeably, or in close association, with R&D defined by the OECD's Frascati manual as "creative and systematic work undertaken in order to increase the stock of knowledge – including knowledge of humankind, culture and society – and to devise new applications of available knowledge"[2].

While R&D is often underpinned by science, there are other forms of R&D activity that sit outside the natural and physical sciences. The boundaries between science and non-science are often blurred in this context. Much R&D creates value from combining the work of different subject areas reflecting the interdisciplinary nature of modern scientific inquiry. This is becoming more prominent with increasing interdisciplinary work in the technology space. Box X provides some examples of contributions to R&D drawn from the arts, humanities and social sciences as parts of the scientific spectrum.

Science has economic value beyond R&D activity. We need to distinguish between science as a method, and the body of scientific knowledge, process and techniques it produces. R&D refers to activity designed to systematically extend the latter.

Beyond R&D, activities that exploit the stock of scientific knowledge without necessarily extending it have considerable economic value. Routine analysis, quality control and the maintenance of equipment all rely on scientific knowledge, not just in high tech industries, but in many more basic sectors. The wider science system therefore has an important role in curating this stock of knowledge and in training people in its use.

The Frascati definition stipulates five criteria as requirements of R&D: being novel, creative, uncertain, systematic, and transferable or reproducible. The definition is widely recognised and used by policymakers, statisticians and researchers. Unless otherwise stated, it is the definition of R&D adopted below with the terms 'science' and 'scientific' used as modifiers.

Science and the relationship between the 'R' and the 'D'

Basic research and discovery-led science (the 'R' in R&D) do not lead to applied development (the 'D') in a linear fashion, and there is often no neat distinction between the two. Basic research can underpin development, and vice versa, in unpredictable ways, often over long timescales. It spreads more widely than applied knowledge and it remains relevant for longer[3].

The rapid development and deployment of COVID-19 vaccines for example, which indirectly enabled a significant increase in global economic activity and return to GDP growth, was only made possible through years of investment in the underpinning research on mRNA and coronaviruses, vaccine technology and manufacturing processes. Similarly, the polymerase chain reaction (PCR) process used worldwide for detecting the COVID-19 virus through testing owed its development to a chance discovery of a micro-organism *Thermus aquaticus* – the source of heat-resistant enzyme DNA polymerase – in the 1960s.

There are many such cases where the economic benefits of basic research are only realised over a long timeframe. In the early twentieth century, the experimental research of Ernest Rutherford at Manchester and Cambridge into the internal structure of the atom proved foundational to the discipline of nuclear physics and led to wide-ranging applications from medical technology through to power production in the hundred years that followed. Likewise, foundational investigations in electromagnetism and theoretical mathematics, along with more applied research into communications technologies such as telegraphy in the nineteenth century, underpin the development of the computer technologies that drive the modern global economy in a way that would have been impossible to predict at the time of the initial research. See Figure 1 below for an illustration of the non-linear relationship between ‘upstream’ discovery science and ‘downstream’ application.

While these examples underscore the lasting impacts of basic research, innovation can manifest differently in firms not primarily engaged in R&D. Companies can drive innovation through adoption of technological and process innovations, rather than through R&D. For example, participants in the Shoestring initiative in Cambridge exploit digital technologies and make operational improvements to innovate within their industries. They often use existing technologies in new ways to boost efficiency and effectiveness, instead of developing new knowledge through traditional R&D pathways. This type of innovation is vital in disseminating new technologies and practices across sectors, showing that significant advancements can arise from smart application and adaptation of existing resources, not just through groundbreaking research.

The unique characteristics of scientific knowledge affect how it impacts the economy

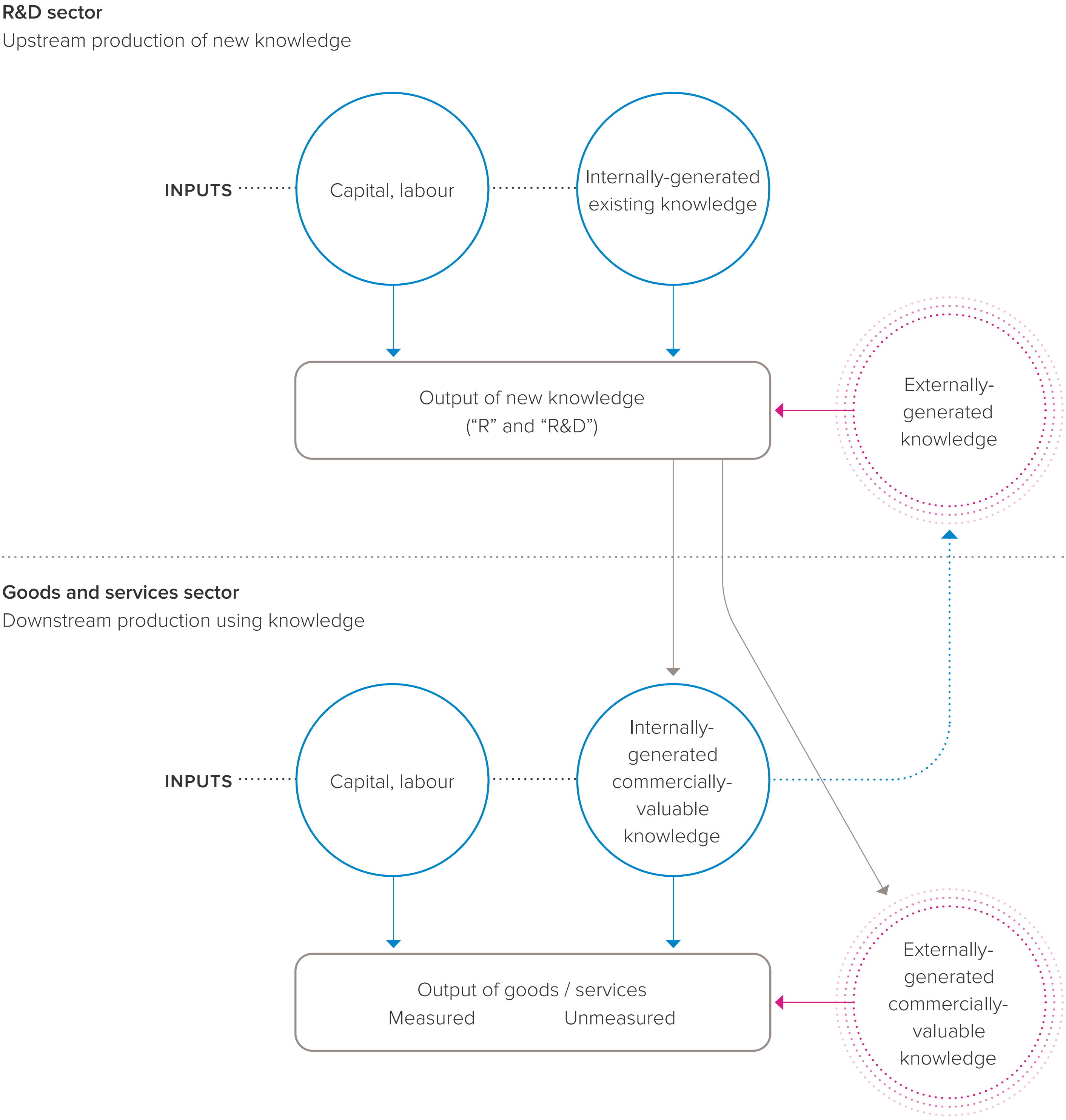
A crucial characteristic of scientific knowledge, which distinguishes it from other kinds of economic input into production and partially explains why its economic impact is so hard to capture, is that it can be used multiple times by different people or firms. It is ‘non-rival’ in character, in the terms used by economists. This greatly affects the economic incentives for increasing the stock of scientific knowledge by doing research and development. Another crucial characteristic is that the economic applications of discovery research are intrinsically uncertain. Future applications are often impossible to predict at the point at which discovery science takes place. No one can accurately predict what the future equivalent of electricity or the internet might be.

R&D investment affects not only the output of individual firms but the productivity of others through the broader dissemination and use of knowledge known as spillovers. These occur when other firms directly copy an innovation, benefit more indirectly from the R&D undertaken by applying the new knowledge in different contexts, or when they simply recognise that a certain technological achievement is possible and reproduce it.

Figure 1 is a stylised picture of some of the productive relationships in a knowledge economy. The arrows link the input/output relations in the economy: the economic incentives that might or might not support those relations are discussed below.

FIGURE 1

Rival and non-rival inputs and outputs in knowledge production and use[4].



Upstream
The upper block describes the R&D intangible asset/knowledge production sector. That sector uses capital and labour and a stock of knowledge to produce a flow of new knowledge. Crucially, and as in the downstream sector, that knowledge might be internally or externally generated. This is a key feature of knowledge: it is potentially non-rival in use and so while an R&D laboratory cannot use somebody else's capital, it can use somebody else's knowledge.

The output of that new knowledge is broad; for example, upstream knowledge might constitute general findings in biology versus a particular drug target. Roughly then we might think of both 'R' and 'R&D' with the latter perhaps more commercially orientated. Knowledge of both types then feeds back into the knowledge production process as shown by the upward arrow on the right.

Downstream
The lower block describes the production of goods and services. Like the production of knowledge, that production process requires capital and labour. It also requires knowledge which might be internally or externally generated. We refer to the knowledge used in this sector as 'commercially valuable' knowledge. That might be for example both 'product' and 'process' knowledge. Product knowledge could include the formula for a drug candidate and knowledge about its safety and efficacy, while process knowledge would be needed to manufacture it economically. The goods and services produced are then divided into measured and unmeasured output. This is designed to capture, for example, the measured output of computers and phones, but also unmeasured/non-monetised output such as improved security and well-being.

BOX 1

Challenges around measuring the impact of science on productivity

The economy grows when it produces a higher quantity and quality of goods and services year on year as measured by their monetary value. The fundamental driver of economic growth is increases in productivity. Labour productivity, defined as the average output produced per hour of labour, can be increased by incrementing the amount of human capital (skills) and capital – tangible and intangible, including plant and equipment and intellectual property (IP), respectively – deployed by workers[5]. An automatic car wash can clean many more cars per hour of labour than a team of people with sponges.

Productivity growth arises from the production of more goods and services from the same inputs. Thus productivity can increase in a number of ways. For example, scientific advances in the upstream sector, designing new materials for example in a jet engine, can then be used in the downstream sector, improving the output of goods and services, in this case of airline services. Likewise, those new materials can be reused in the upstream sector to discover further new materials.

What then is the difference between productivity and innovation? Economists like to differentiate between labour productivity and total factor productivity. Labour productivity is output per labour input. Even after taking account of increasing capital investment, there remains a substantial increase in productivity over time. This residual – the increase in economic growth after increases in labour hours and capital investment are taken account of – is known as Total Factor Productivity (TFP).

In the engine example, labour productivity in the downstream sector, in this case airlines, improves, because pilots and crew in the downstream airline sector are working with a better aeroplane. But the airline is more productive because the labour is equipped with better capital. Therefore total factor productivity in the downstream sector: the productivity of the pilots and crew and the capital with which they are working has not increased. Instead, the innovation has been in the upstream sector rather than in the downstream sector.

Some new technologies have a particularly powerful effect on economic growth, because they can be used in many different sectors – they are "general purpose technologies". A computer, for example, can be used in many different downstream and upstream sectors for the production of many different types of goods and services. General purpose technologies can also improve the innovation process in the upstream sector. For example, machine learning and artificial intelligence hold out the promise of accelerating the processes of drug and materials discovery – this might be regarded as an innovation in the process of innovation. Thus such general purpose technologies have the potential to raise productivity very significantly. This is not only because they are being used in lots of sectors, but they are improving the process of innovation in the upstream sector.

Measuring TFP to assess accurately the effects of science and technology on output is a complex process with new varieties and free goods. Furthermore, not only is it hard to measure TFP, but using it to assign subsequent growth to investment in R&D is even more complex. For example, technological progress, which encompasses more than just making existing products cheaper, involves the introduction of entirely new product types that can fundamentally change consumption patterns (eg generating a previously non-existent demand). This then likely leads to enhancements in consumer welfare in ways that are not easily quantified by traditional productivity metrics, including the widespread provision of 'free' digital services over the past couple of decades, such as Facebook (Meta) and WhatsApp.

How should the economy be organised to coordinate the links between upstream knowledge production and downstream knowledge use?

The market, in principle, provides a financial incentive for a new product or an improved process. The commercially useful knowledge that is needed to produce this may be produced internally, through its own R&D, which costs money. Aspects of this commercially useful knowledge can also leak back into the general knowledge stock; for example, products can be reverse engineered, to be copied by rivals. If firms can acquire the knowledge to make new products and improve their processes from external sources without cost, then that removes the incentive for them to generate that knowledge themselves, but it also removes the incentives for anyone else to generate that knowledge.

This constitutes a failure of the market mechanism. There are at least three ways of addressing this problem. The first is to assign property rights to the creation of knowledge: a patent for example. In this case the firm who does not wish to develop its knowledge internally pays for the knowledge from an outside source (a licence fee) and so the market system, with this addition, delivers. The drawback with this is if knowledge protection is not watertight and/or that if a firm needs to pay a fee for the use of many dimensions of knowledge (many patents are in the mobile phone for example) just one patent owner can 'hold up' the entire innovation.

The second is to create a larger organisation. The firm could merge with the other firms from which it is taking information so that the relevant knowledge is produced under the same roof. This restores the incentive to produce the knowledge in the first place. But it depends on the ability of firms to harness all the relevant knowledge inputs under one roof: patent pools where firms agree to share their patents with one another without charge are an often used effective private sector answer to this problem.

The third solution is to have the state subsidise knowledge production from general taxation, on the grounds that this coordination failure represents a market failure (see Box 2). This could be by:

a. direct state production of knowledge eg through R&D programmes in state-run laboratories, or through grants to public organisations such as research universities;

b. a prize for an invention, the knowledge for which might be freely shared;

c. direct grant funding for specific research and development projects to be carried out in the private sector, and;

d. a tax credit for private knowledge production. This runs into the problem of the state requiring the information, which it may not have, to produce the knowledge the downstream firms will use and/or subsidising effort that might have been expended anyway.

BOX 2

R&D market failures

A role for the state in supporting scientific research has been recognised since the nineteenth century. As Lord Derby told the Devonshire Commission of 1875,
"I am, as a general rule, very strongly in favour of private effort, and very decidedly against the application of State funds to any purpose that can be accomplished without them; but I think that if there is any exception to that which I venture to call a sound and wholesome rule, it is in the case of scientific research, because the results are not immediate, they are not popular in their character, and they bring absolutely no pecuniary advantage to the person engaged in working them out."

This is a succinct expression of what has become a mainstream economic view, that state intervention to support R&D is justified by market failures, which can take the following forms:

1. Non-rivalry and incomplete excludability: the primary characteristic of knowledge as a non-rival good (one person's consumption does not prevent another's) coupled with incomplete excludability (difficulty in preventing others from using the knowledge without paying for it) can lead to systematic R&D underinvestment by the private sector. Without adequate mechanisms to ensure that innovators can capture the full benefits of their investments, there is, therefore, little incentive to allocate sufficient resources towards R&D.

2. High fixed costs and small markets: in cases where the production of downstream goods (which utilise upstream knowledge) involves significant fixed costs, and the final market size is too small, the economic return may not justify the initial investment in R&D. This scenario is evident in industries like aerospace or pharmaceuticals, where initial costs are extraordinarily high with uncertain market demand. Consequently, without a guaranteed market, firms may hesitate to invest heavily in necessary upstream knowledge development.

3. Insufficient property rights enforcement: intellectual property rights, like patents, aim to make knowledge excludable by granting temporary monopolies to innovators. However, if these rights are not adequately enforced or are too weak, it can lead to a situation where downstream firms may not pay the full price for the use of upstream knowledge. They might bypass payments through copying or through complex negotiations around patent licensing, resulting in upstream firms receiving less compensation than the market value of their contributions. This can diminish the incentive for these firms to invest in R&D.

4. Property rights and monopoly implications: conversely, while making knowledge excludable addresses one aspect of market failure by providing incentives for R&D investment, it may also introduce another potential failure: monopoly power. The monopolistic nature of patents can inhibit competition in certain markets, keeping prices high and access limited. This could lead to a situation where the benefits of making knowledge excludable might be offset by reduced incentives for others to invest in R&D, especially in related fields.

Diffusion of economic benefits of science

While the economic benefits of science are significant, they are not evenly distributed. The ability to employ scientific and technological advances effectively to produce and capture value – and thereby achieve commercialisation – varies between places, between firms, and between individuals.

Globally, people's access to life-enhancing technologies is unevenly distributed due to differences in critical capabilities such as infrastructure and skills. Knowledge or products produced in one part of the world cannot be adopted in others without these. A frontier technology like AI, for example, will initially benefit some economies more than others, with strong differences between the economic and social benefits for the Global North as opposed to the Global South[6]. These regional variations are seen in the non-monetiseable benefits of science as well. For example, technological advancements sometimes exacerbate disparities in health outcomes depending on the capacity of different regions to make use of them[7].

Regions within the UK can also differ substantively in their ability to benefit from scientific advances for similar reasons. Across the UK for example, there is regional variation in the proportion of the population with basic digital skills, which affects the ability of such regions to absorb science and advanced technologies[8].

Similarly, not all firms possess the know-how to absorb scientific knowledge and apply it to innovation. The uptake of new technologies that could boost productivity varies by sector and firm size. While firms rely on the science system, over the past decade it has become increasingly clear that these benefits need to be increasingly applied in 'low-tech' or non-research-intensive industries, as well as those considered high-tech or research intensive.

At the level of individuals, not everyone has access to cutting edge medicine and other scientific applications or will benefit from the adoption and diffusion of new technologies[9]. Yet, the extent to which diffusion reaches markets and individuals varies considerably. This uneven distribution is illustrated by the contrasting examples of smart phones and electric vehicles (EVs). Smart phones have become rapidly ubiquitous globally since their inception in the 2000s, while the adoption of EVs has been much slower. This difference is largely explained by the requirements that must be met for them to penetrate the market, especially infrastructure. Unlike smart phones that leverage existing communications networks, EVs need new infrastructure, such as widespread and accessible charging stations.

These types of differences are especially important as the nature of work has been affected by rapidly emerging technologies. For example, rapid and widespread digitisation has led to what is termed the 'digital skills gap', whereby employers increasingly seek employees with digital skills[10].

Public policy has a pivotal role to play in addressing these diffusion issues in order to maximise the economic benefits that science can deliver while mitigating the societal risks that arise from scientific and technological advancement.

UK political context

While every G7 nation has experienced a slowdown in productivity growth since the financial crisis of 2008, this has been particularly marked in the UK (see Figure 2). It is against this backdrop that there has been a renewed political focus on investment in science and R&D more broadly as drivers of productivity, building upon longer standing political interest in incentivising private sector investment. The latter most notably came with the introduction of the R&D tax credit for SMEs in 2000, and for larger companies in 2002.

The domestic political debate on R&D has long centred on the narrative that the UK is good at basic research and discovery, but weaker when it comes to translating scientific knowledge for economic benefit. This relative weakness is reflected in the UK's poor productivity performance and is attributed to various factors including narrow specialisation across a few scientific fields involving few firms (which limits the scope for broad-based adoption and diffusion of technologies and other novel applications across the economy) and historic policy choices that have reduced emphasis on more applied R&D[11]. A notable feature of UK science policy from the 1980s onwards, for instance, was government withdrawing its support for near-to-market research being carried out by national laboratories while increasing funding for university research from which there is usually a greater distance to market[12].

The UK's position in innovation indices such as the Global Innovation Index (where the UK ranks fourth behind Switzerland, the US and Sweden) or the European Innovation Scorecard (where the UK's score places it twelfth but above the EU average) is consistent with this narrative in that it reflects strengths on basic research indicators such as academic publications, university rankings and doctoral graduates.

Conversely, on measures that relate to innovation and translation within firms, such as entrepreneurship policies and culture, business research talent, or process innovation, the UK achieves a lower score. While the outcome of these indices can be influenced by how innovation is defined and prioritised, there are well-established innovation indicators produced by statistical offices which include metrics based on innovation surveys following the OECD-Eurostat Oslo Manual[13].

The division between 'good at basic' and 'bad at applied' understates the complexity of R&D and its relationship with productivity. It also oversimplifies the distinction between discovery research and applied research, which in reality is often far more intertwined than such schemas recognise. A common theme from the case studies later in this report, for instance, is the constant iteration of research between academic and industrial sectors, and the importance of intersectoral partnerships. This notwithstanding, there is general consensus that more science-led innovation would contribute to solving the UK's productivity problem, and that with other countries increasing their expenditure on R&D, the UK must do more to compete for globally mobile talent and investment to maintain and enhance its share of the economic benefit.

To that end, the UK government increased public spending on R&D in the UK from just under £15 billion a year in 2022 to £20 billion by 2025 as a stimulus for crowding in private investment. The period since 2017 has seen the launch of UK Research and Innovation and the Advanced Research and Invention Agency with missions to "connect [scientific] discovery to prosperity and public good" and invest in high risk-high payoff projects "with potential to produce transformative technological change".

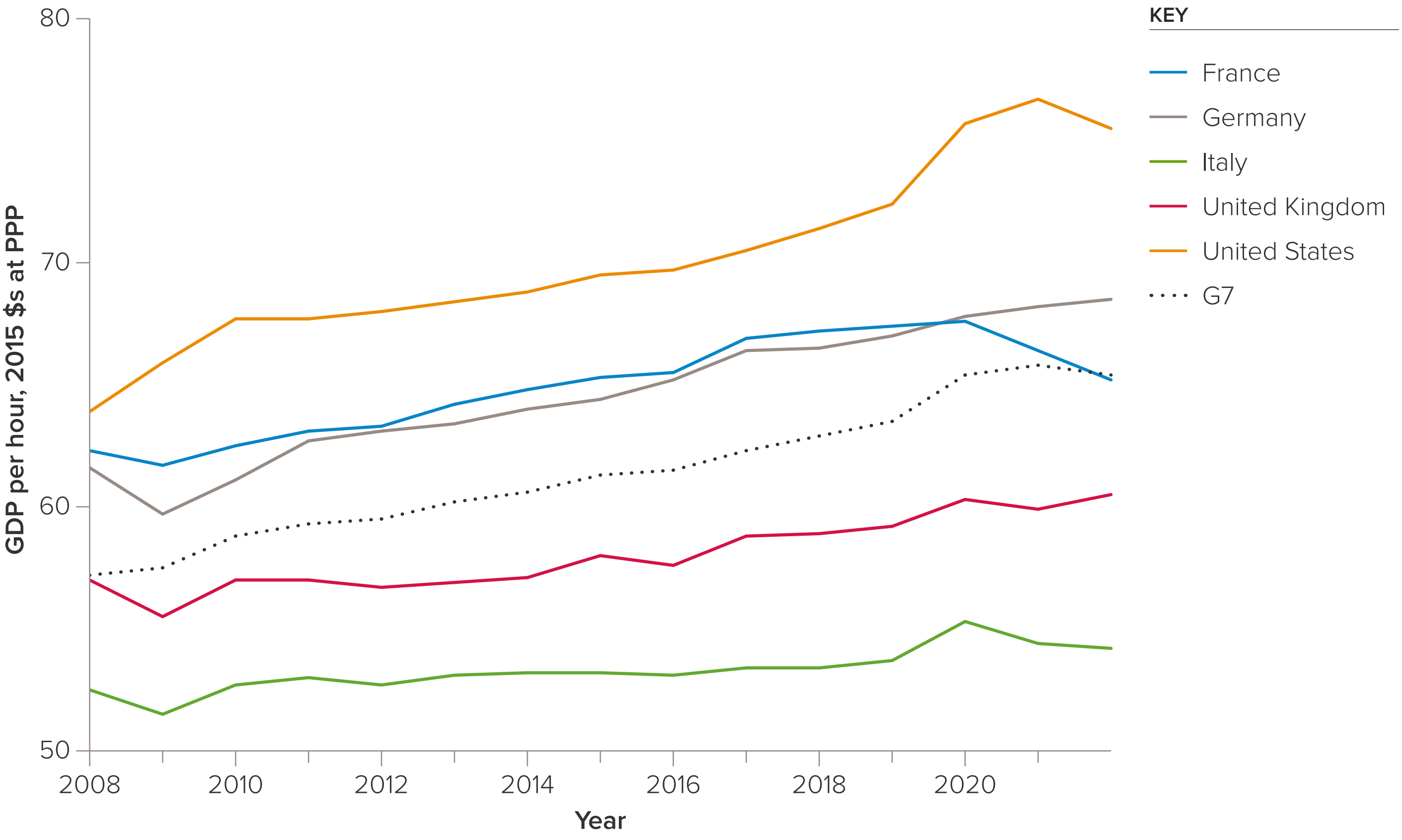
There has been growing recognition by UK policymakers of the role of science in addressing regional inequality and raising regional economic performance outside London and the South East. R&D has also become increasingly prominent in economic decision-making in Scotland, Wales and Northern Ireland.

While the international circulation of scientists and ideas is important, there remains a strong economic rationale for the UK to maintain its historic strength in discovery science rather than simply increasing its reliance ('free-riding') on basic research undertaken elsewhere.

As Case study 2 on the work of Rolls-Royce on high-temperature alloys demonstrates in the UK and Case study 3 on the development of synthetic insulin in California demonstrate, the ability to work with world-leading discovery scientists is one of the factors that leads R&D intensive companies to locate and remain in certain areas over others. Building capacity for this type of discovery research – including the people, institutions and facilities it requires – is key to allowing for rapid redeployment when needed, as demonstrated in the drive to develop a vaccine for COVID-19 at pace. Effectively accessing, interpreting and using cutting-edge science from elsewhere is also heavily dependent on having domestic capacity for discovery research.

FIGURE 2

Labour productivity in selected G7 countries. GDP per hour worked, in 2015 $s converted at purchasing power parity.



Data: OECD Productivity database

Purpose of report

This report aims to recognise the broad, long-term and transformative ways in which science and the science system benefits the economy. It goes beyond rates of return alone, which only capture a small slice of the value generated and sets out a framework for understanding four interconnected paths to economic impact, referencing existing literature, as well as case studies to move beyond the limits of quantifiable information. It seeks to build the evidence base for policymakers by exploring the various contributions of science to the economy, while identifying where gaps in that evidence currently exist.

The report also serves as an input to the Royal Society's Science 2040 programme which aims to articulate the value of science to society and the case for policymakers implementing a long-term vision and investment framework.

The next section sets out four interconnected paths by which scientific R&D leads to economic impact. Following that, there are three case studies on optical fibres, high temperature alloys and synthetic insulin. The report concludes with a summary of gaps in the evidence to inform further work.

BOX 3

The contribution of the social sciences, humanities and arts to R&D

Social Sciences, Arts and Humanities – sometimes collectively referred to as SHAPE[14] – also contribute significantly to R&D in ways that are currently not well measured in the UK.

UK policymakers have adopted the OECD Frascati definition of R&D, which has included SHAPE disciplines since 2015. However, application is patchy, with SHAPE included in the collection of official R&D statistics but excluded in business R&D tax relief[15]. This confusion about 'what counts' as R&D risks the creation of policies which cannot support the breadth of R&D activities, presenting a sizeable obstacle to government ambitions for the UK.

This presents the question: how well do we understand SHAPE in R&D in the UK? The British Academy has sought to answer this using a range of analysis, culminating in *Understanding SHAPE in R&D* (2023)[16]. From combining creative and technical skills to create Netflix content, to the use of geographers and economists to understand customer behaviour at Tesco, SHAPE alongside STEM is an important piece of the R&D puzzle.

Examples of the contribution of SHAPE R&D:

- The Economic and Social Research Council (ESRC) cohort studies have been instrumental in advancing genetics research in the UK. These longitudinal studies, such as the 1958 National Child Development Study, the 1970 British Cohort Study, and the Millennium Cohort Study, have linked social, environmental, and genetic data. This research has helped uncover genetic predispositions to health conditions, thereby contributing significantly to personalised medicine, public health policies, improving health outcomes and reducing healthcare costs.
- Research on synthetic phonics as means to teaching children to read had a significant influence on English schools, which significantly improved literacy rates – England moved up the international league table of reading ability from 10th to 8th between 2011 and 2016 as a result – and reduced class sizes by up to a third. Moreover, researchers identified that children taught synthetic phonics were ahead of those taught analytic phonics in word reading, spelling and reading comprehension.
- SHAPE research has helped deepen our understanding of the importance of lean production, its scarce presence amongst UK companies, and how to implement it effectively. For instance, studies on organisational culture and employee well-being offer insights into the psychological and social impacts of lean practices, guiding better implementation strategies. This research has significantly enhanced UK manufacturing by improving efficiency, financial performance, and reducing operational waste, thus driving economic growth.
- The Creative Fuse North East, a project integrating creativity, culture, and digital technology to boost economic and social development in North East England, has leveraged research in Social Sciences, Humanities, and the Arts. For example, the “MIMA Collections” project partnered Teesside University with local artists to create new products using MIMA's art collections. This initiative helped businesses align creative practices, draft business plans, and present pitches. Workshops an d pitch sessions using techniques like storyboarding and mind-mapping boosted participants' skills, confidence, and business growth.

Four paths to economic impact

Broadly speaking, there are four paths by which science and R&D lead to economic impact:

- New knowledge and ideas
- Innovation and productivity
- Skilled people and jobs
- Wider economic impacts which are not directly monetised

These four paths provide a framework for understanding the contribution of science to the economy, but in reality they build upon one another and are deeply interconnected. Section 4 provides three case studies that help illustrate these interrelationships.

Path to impact 1: New knowledge and ideas

Science creates economic impact through the production of new knowledge and ideas, some of which will later be applied for significant economic gain. However, the economic applications are unpredictable, the knowledge products of science are usually 'non-excludable' in nature (anyone can use them) and the timescales over which this knowledge will be economically exploited varies heavily. These factors combine to lead to systematic underinvestment in R&D by the private sector. Without adequate mechanisms to ensure that innovators can capture the full benefits of their investments there is little incentive to allocate sufficient resources towards R&D.

The non-exclusionary nature of scientific knowledge leads to underinvestment

As discussed earlier, a primary characteristic of knowledge, compared to other inputs such as capital or labour, is its non-rival nature. It does not deplete after usage in that one person's consumption does not prevent another's. Knowledge outputs are commonly intangible and always present in economies, contributing to new products, services and processes.

Occasionally, valuable knowledge outputs are produced that are capable of bringing about dramatic economic and societal changes.

Some of these are general purpose technologies (GPTs) which have had a widespread and transformative impact on society and the economy. GPTs have several fundamental features, including that they can (i) spread across sectors, (ii) get better over time, and (iii) make it easier to invent and produce new products or processes. Because of these properties, GPTs can drive whole eras of technological innovation and growth[17]. Electricity and information technology, along with telecommunications are important examples[18].

In Case study 1 (page 33), we look at how one new idea – the transmission of information through optical fibres – has transformed society. Optical fibres form the physical basis for the internet, enabling massive transcontinental flows of data. Here R&D in a UK based corporate laboratory, STL in Harlow, led to a Nobel Prize for Charles Kao, for the original discovery. This discovery was then realised and refined through subsequent work in materials and other science and the development of new lasers.

Case study 1 illustrates some of the difficulties in ascribing economic value to a scientific discovery. On the one hand, total worldwide trade in optical fibres, at approximately $11 billion, represents less than 0.05% of total global trade[19], so the direct impact of this discovery might seem to be almost negligible. Yet without optical fibres, many aspects of life in the modern world, from the widespread availability of on-demand entertainment, to the dispersion of manufacturing supply chains that underly the global economy, would simply not be possible.

Intangible knowledge outputs
Intangible assets are the abstract, non-physical assets such as knowledge, branding, designs and organisational processes that are becoming an increasingly important part of the economy[20].

Knowledge and other intangible assets enable firms to compete and derive economic benefit from applied R&D. Although this knowledge (when unpatented and otherwise unprotected) may in theory be freely available, this is not the case in practice. The knowledge to understand and implement research findings and analysis often requires advanced research capabilities and hiring in-house specialists[21].

BOX 4

Intellectual property

A long-standing approach to resolving the issue that the non-appropriability of knowledge suppresses any incentive for people or firms to invest resources in R&D, is the creation of a new class of property rights, intellectual property (IP). However, this does not fully resolve the problem, as there can still be spillovers from innovation even if IP protections are in place.

IP, such as patents, gives innovative creators and entities exclusive rights to their inventions. It offers a legal, time-limited monopoly on the sale of certain products and services. However, not only does the patent system protect and reward inventions, it also aims at diffusing them when patents are published, which implies they become generally available knowledge. IP primarily encompasses intangible assets, including inventions, literary and artistic works, and designs used in commerce, yet it also manifests tangibly within the economy. By incentivising the creation of new products, services and processes, it can be a critical driver of innovation.

IP protection through patenting ensures the exclusivity of innovative ideas. This means inventors and companies can achieve a return on their R&D investment, thereby promoting a culture of continuous innovation and development shielded from immediate imitation.

Furthermore, patents allow start-up businesses and innovators to attract investment by showcasing the unique value and protectability of their innovations. Certain practices however can create barriers around innovation. The emergence of ‘patent thickets’ and overly broad patents, for example, can complicate the development and commercialisation of new inventions. This has the potential to deter subsequent R&D[22,23].

IP can also be protected through trade secrets, where an individual or firm seeks to safeguard know-how and business practices that are difficult to patent or not suitable for public disclosure. Additionally, trademarks and copyright also play crucial roles in balancing the protection of both tangible and intangible forms of IP. Trademarks protect brand identity and logos that distinguish goods and services, while copyrights protect original works of authorship such as writings, music and artworks.

The optimal level of IP protection should sit at a point where a balance is struck between protecting the incentives of innovators to develop non-rival, non-excludable new ideas and ensuring that others have the opportunity to combine these ideas to develop new products and services.

Moreover, beyond just knowledge, firms frequently depend on specific intangible assets, such as software, databases and other advanced tools, to stay ahead. For instance, resources such as whole genome pathogen sequencing data or biomedical data have proved invaluable to drug discovery and pandemic preparedness[24]. Using these assets requires advanced analytical capabilities and a strong understanding of genomics, which are beyond the reach of many individuals and firms, but the results of which may be more broadly used in the future. Despite their significant value, quantifying the worth of these databases in monetary terms is impossible, as their downstream benefits will only be fully realised in the future, contingent upon future events. Hence, their contributions are not always fully reflected in national economic accounts[25].

Tangible knowledge outputs

As well as intangible outputs, R&D activities also contribute to developing tangible assets. New scientific instruments and tools, such as microscopes, are not just essential inputs to scientific research but can also be economically important capital goods[26].

The computer is an obvious example of this, starting off as a way of automating burdensome mathematical calculations before eventually becoming the cornerstone of economic activity. Rather than being conceived as an accessible global network, ARPANET – the progenitor of the internet – was developed in a defence and security context as a means by which a small number of engineers could share software and data between different locations[27].

The evolution of computer technology has necessitated the development of a range of specialised components. The extreme UV lithography tools produced by the Dutch firm ASML are some of the most advanced and valuable machines ever made and pivotal for manufacturing leading-edge integrated circuits. These tools further illustrate how new knowledge and ideas borne from science can lead to the creation of capital goods with significant economic impact.

The extent of the uptake of the computer and internet are extraordinary but indicative of a wider trend, where innovations initially developed for specific scientific purposes find widespread application across different sectors. For instance, nuclear magnetic resonance (NMR) spectroscopy was initially devised by physicists to measure magnetic fields around atomic nuclei but is now widely used as a medical diagnostics tool[28]. These examples highlight not only the important role of R&D's tangible effects in driving specific technologies forward, but also the critical role of such innovations in enabling widespread technological permeation across different fields within modern economies. Upstream outputs might often be intended for a particular downstream application but turn out to have broader uses than originally envisaged.

Path to impact 2: Innovation and productivity

A second path by which science leads to economic impact is through its positive impacts on productivity as the knowledge products and processes in Path 1 are applied in the 'downstream' economy.

Non-linear development

R&D provides an important underpinning for innovation, leading to the creation of new products and services, as well as enhancing the way existing ones are made[29]. This, in turn, can lead to higher productivity. In many cases, this arises not by any single transformative invention, but by a relentless process of incremental improvement, underpinned by targeted R&D directed to solve new questions that the improvement process throws up (some of these may well send researchers back to quite basic research questions).

Case study 2 on high-temperature alloys (page 39) illustrates the way continuous improvements in the efficiency of aircraft gas turbine engines have been driven by developments in materials science and manufacturing technology. It has been known ever since the invention of the gas turbine, more than a century ago, that the path to higher efficiency runs through higher operating temperatures. But converting this insight into practice has required the development, over decades, of new alloys, new designs and new manufacturing processes, often involving partnership between private sector firms and universities carrying out more basic research, inspired by the needs of this industry.

Over the last fifty years, the thermodynamic efficiency of commercial aircraft gas turbines has increased from 30% to 50%, a major contributor to the fall in the cost of aviation, as a result of a long series of innovations in high temperature materials and coatings[30]. The need for further innovations remains, both to increase fuel efficiency yet further, and to open the way to the economical use of alternative fuels such as biofuels and e-fuels.

Spillover effects

Innovation has a substantial impact on short and long-run economic growth, and vice versa, highlighting the dynamic interaction between advancing new ideas and economic prosperity[31]. A key mechanism for this impact is through R&D, which affects not only the output of individual firms but the productivity of others through the broader dissemination and use of knowledge known as spillovers. These occur when other firms directly copy an innovation, benefit more indirectly from the R&D undertaken by leveraging the new knowledge in different contexts, or when they simply recognise that a certain technological achievement is possible and reproduce it.

Although the exact extent of spillovers is context dependent, most literature has found them to be substantially greater than the original R&D investment[32]. A recent meta-analysis of econometric literature estimates that the social returns of R&D – the social, economic and environmental value created not reflected in a company's financial statements – from spillover effects are around twice those of the private returns[33]. More econometric evidence on the nature and size of R&D spillover effects is given in Box 5.

Spillovers are achieved through both private and public investment. Public R&D spending in the UK via the research councils, for example, is found to be significantly correlated with total factor productivity growth – ie a measure of productive efficiency in how much can be produced given a number of resources[34]. There are however multiple factors which make it difficult to estimate the return on investment for R&D, which often lead to underestimation. The path from R&D input to economic benefit is complex, non-linear, can span over a long time period (potentially several decades) and is often measured via imperfect proxy measures for R&D output such as publication metrics and patents (see Boxes 5 and 6 below).

Not all innovation is driven by R&D. For R&D to be useful, investments in product design, employee training and marketing are also necessary[35], and can represent a higher proportion of the total cost of an innovation[36]. The success of the iPhone, for example, was not only dependent on advances in technology, but the product's design features, accompanying services such as the App store, and intelligent marketing[37]. Some innovative firms do little or no R&D at all. A 2007 survey found that just over half of innovative European firms innovated without performing R&D or contracting out R&D[38]. In other words, growth was innovation-led for these firms but not driven by R&D.

Clusters

Productivity gains from innovation often benefit from physical proximity to other innovators. Geographic concentrations or 'clusters' of industries related by knowledge, skills, inputs, demand and/or other linkages, illustrate how proximity can increase innovation beyond the confines of individual firms. Notable examples are Silicon Valley for technology, Boston for life sciences, and Hsinchu for electronics. These and other clusters have been found not only to attract talent and facilitate the exchange of knowledge and ideas but also contribute to technological advancement and economic output both at a local and global level[39].

The decision to locate Diamond Light Source synchrotron at the Harwell campus in Oxfordshire – the most significant UK investment in large scale research infrastructure in recent history – had a particularly pronounced impact on the surrounding region[40], inducing clustering and increased research output within a 25-kilometre radius. This would have been driven by both direct effects, as more scientists moved to the proximity of the facilities, and indirect effects, via local externalities[41]. A similar picture can be seen in the US where studies have identified significant indirect effects on productivity related to geographical agglomeration in the high-tech sector, with larger cluster sizes associated with greater productivity gains[42].

BOX 5

Summary of rates of return R&D literature review

Private rate of return

Private rates of return seek to estimate the return on investment over time. For example, a recent meta-analysis found that a firm investing in R&D could expect a private rate of return of 20%, meaning that for every £1 a firm invests in R&D, a typical return of 20 pence per year would be expected from the knowledge generated[43].

However, the literature also makes clear in reality there is no single figure for private rates of return from investing in R&D that works across sectors. This is due to the wide array of differences in the multiple contexts that R&D investments take place. It is often not possible to 'average' the return in different contexts, as it is dependent upon several factors which often differ amongst countries. Many studies have attempted to control for such variance across relevant factors when assessing it quantitatively[44].

Some of the factors that affect rates of return in accordance with the literature include:

Country-specific context

Rates of return are likely to vary substantially across countries due to different institutional contexts, R&D spending, outputs, productivity and complementarity between public and private R&D investments.

Firm characteristics and industry

At the national level, some evidence suggests small firms may have greater returns than larger firms, all other factors being equal; yet, this variation has not been reliably and extensively quantified[45]. However, certain strands of the literature emphasise the importance of environments where public and private R&D efforts are synergistically aligned for companies to achieve higher returns. For instance, Soete *et al*. find that multinational corporations attain higher rates of return when a positive complementarity exists between public and private R&D investments[46]. Additionally, evolving industry dynamics such as the changes that may take place in a networked model involving both large and small firms, coupled with increased international competition, are crucial factors that influence the effectiveness and returns of R&D investments.

Externalities

Positive externalities, such as enhanced TFP and innovation through knowledge diffusion, contrast with potential negatives, like the duplication of efforts and the potential crowding out of private R&D causing it to decrease in an area. The balance between these impacts is significantly influenced by the degree of complementarity between public and private R&D, underscoring the complex interplay of factors that determine the overall economic effect of R&D investments[47].

Time-lag

The time R&D takes to effect influences on, for example, productivity, varies by type. Basic research, focusing on fundamental concepts, typically requires more time to contribute to the economy (eg increased productivity, net-zero solutions) but eventually leads to significant advancements. In contrast, applied and experimental research aims to solve specific problems or test theories, resulting in quicker but often less substantial impacts on productivity[48].

Declining returns

Although there is no conclusive evidence that private returns have decreased over the last 40 years, some studies acknowledge that sustaining innovation and economic growth have come to require further efforts, highlighting that both countries and firms must increase their efforts significantly to keep the innovation engine running[49]. Such escalating efforts required for research and development may have led to a decline in private returns on investment in innovation, indicating a shift in the dynamics of productivity gains from new technologies and ideas[50].

Social rate of return and spillovers

The non-rivalrous nature of knowledge implies that its benefits extend beyond the initial creator, leading to significant spillovers in the economy. The literature suggests that while private returns from R&D are substantial, social returns are even higher due to these spillovers. This disparity underlines the transformative impact of R&D on broader economic and societal levels, supporting the case for public investment in areas with high spillover potentials but lower direct private returns.

Publicly funded R&D performed in the private sector

The private rate of return for publicly funded R&D performed in the private sector is likely to be substantially lower than for privately funded R&D. This may be because publicly funded research is deliberately aimed towards areas with lower private returns but greater social returns, which are inherently less attractive for private investment. For instance, a recent study found that public R&D investment affects private R&D investment positively via human capital – improving the value of the skills and experience of the workforce – without crowding out private R&D investment. Yet, whilst they identify public R&D investment to encourage additional private patents in the life sciences sector, they don't in other sectors[51].

This would support the case for publicly funded R&D as an effective policy choice to plug a market failure where there is sub-optimal investment from the private sector. The literature notes that this likely lower rate of return is for the private rate of return, so does not account for the potentially larger social return of publicly funded R&D and crowding in of private investment.

Please refer to the separate annex for the full literature review and methodology, which can be found alongside this report at **royalsociety.org/science-and-the-economy**

Path to impact 3: Skilled people and jobs

Scientific R&D has a significant impact on human capital, through education and training and the generation of new types of job. Many accounts of the Industrial Revolution stress the importance of the development of institutions that propagated scientific and technological knowledge[52]. For economic take-off to take place, it was not enough that scientific discoveries were made and new technologies were invented. Skilled artisans, technicians, engineers and applied scientists were needed to implement the new discoveries across the economy. Throughout the nineteenth century, in the UK and elsewhere, a whole series of institutions came into being to meet this need – mechanics' institutes, technical schools and new or re-founded universities with a much stronger base in scientific research than their classically constituted forbears. In modern parlance, this was a systematic attempt to raise the human capital of the workforce, and this aspect of science remains crucial to continuing technological development and economic growth today.

The term human capital refers to the value associated with the skills and experience of a workforce and encompasses both the knowledge that the workforce has which enables workers to increase their own productivity, as well as its capacity to absorb knowledge and apply it to innovation – generating externalities for other workers. For example, research has shown that firms facing a more abundant supply of skilled workers are more likely to adopt productivity enhancing technologies and organisational practices[53,54]. Skilled people and jobs are therefore both an input into R&D and innovation activity in firms, and an output, with the potential to generate substantial economic impact[55].

R&D roles tend to be diverse and require a range of skills and competencies[56]. Across the workforce both research and technical roles play an important role, and the job requirements can be highly varied with some requiring a PhD, and others requiring vocational qualifications or specialist experience. Effective management skills are also an important success factor for these roles[57].

As is the case for general human capital, an important channel through which scientific skills and those associated with R&D enable innovation is by increasing organisations' absorptive capacity, which can be thought of as their ability to understand and apply new ideas and approaches. Increased absorptive capacity may lead to an organisation having a greater chance of developing a new technology or product, or adopting a new process to improve efficiency. Certain sectors and occupations are more strongly associated with absorptive capacity, and analysis has shown that variation across these sectors can occur, leading to differences in absorptive capacity across regions and variation in economic prosperity[58].

Scientific R&D also has a significant impact on human capital through education and training, not only for those going into STEM careers, but also for those working in other sectors. Many STEM graduates go into careers outside the R&D sector and possess skills that contribute positively to the wider economy. The advantages associated with employing STEM graduates can create spill-over effects. One study found that an increase in the STEM share of a city's total employment was also associated with wage growth of local non-college educated groups[59]. Additionally, the import of global scientific talent into the UK significantly enhances innovation capacity and economic growth by introducing diverse expertise and perspectives into the R&D sector.

While scientific and technological advancement may change the nature of certain jobs, and even displace certain roles, it can also generate significant new employment, particularly as R&D intensive sectors require a lot of human capital as resource. This can lead to the creation of better, higher-quality jobs for those with the requisite skills and competencies[60]. Between 2010 and 2020, the largest growth in jobs in the UK took place in the professional, scientific and technical activities sectors – sectors where there are above-average gross earnings[61].

Path to impact 4: Wider economic impacts which are not directly monetised

In addition to its direct economic contributions, science generates important societal benefits, ranging from national security and environmental protection to public health. These benefits may not be fully monetisable, but they still can have enormous indirect economic benefits. To give a recent example, the firm Moderna made about $20.5 billion profit from its COVID-19 vaccine[62]. However, the direct contribution to global GDP from the development and sales of vaccines was eclipsed by the indirect effect of allowing an earlier opening of the world economy, even before the huge effect in terms of saved lives and reduced suffering is taken into account.

Poor health can impact workforce productivity both through individuals not being able to work themselves, and through the increased demand for caring responsibilities whereby individuals have to care for others. As a result, medical treatments emerging from scientific research can boost the labour supply by improving the health of economically-inactive individuals resulting in their return to employment[i]. Some studies have attempted to quantify this, monetising the net health gains from biomedical R&D, as well as its more direct economic impact and spillovers[63]. Through improvements to people's health, healthcare positively impacts the economy.

There are also other areas in which science adds significant value through indirect economic benefits. For example, science plays a critical role in ensuring that the UK is resilient to security threats, thereby supporting the UK economy. The UK government's Integrated Review of Security, Defence, Development and Foreign Policy recognised the importance of R&D for addressing national security challenges, and the need to prioritise strength in science and technology[64]. Another area where it can be harder to monetise is the benefits from scientific contributions to achieving environmental sustainability. Climate change and biodiversity loss both have profound implications for future prosperity. While some of these impacts can be directly quantified, they only form a part of the overall picture. Many of the standard approaches to the economic assessment of climate change impacts that have been used, such as the integrated Assessment Models, are now widely considered to have omitted important characteristics to reflect accurately the severity of the consequences[65].

The Stern Review on 'The economics of climate change' concluded that early public expenditure to stimulate innovation in low-carbon technologies and processes was one of the key factors that will determine the cost of stabilising greenhouse gas levels in the atmosphere, and the economic impacts of climate change[66].

---

[i] Mental and physical ill-health has been shown to have deleterious impacts on firm productivity.

Recent studies continue to reinforce both the importance of innovation in clean technologies in limiting the economic disruption of climate change, and the need for a more conducive policy environment for these[67,68,69]. The Dasgupta review on 'The economics of biodiversity' highlights the importance of technological innovation in food production industries in reducing harm to the biosphere and making most efficient use of the natural services that underpin the ecosystem[70].

Market-led and mission-led innovation

The timeframes for realising the benefits of these four paths to economic impact vary, and to be fully realised require both government and private sector action. Government actions aimed at boosting the supply of scientific research and researchers, or the demand for innovations, enhancing conditions for adopting innovations, and/or refining the articulation of demand can encourage innovations and facilitate their spread. For instance, demand-side innovation policies can be applied in scenarios where markets for innovative products are underdeveloped (such as some renewable energy technologies), yet there exists a technology or product with significant potential advantages, and public demand presents opportunities to encourage innovation to address societal requirements. Demand-side policy tools are commonly employed by governments to incentivise innovation and can "include innovation-friendly public procurement, regulations and standards as well as consumer-oriented schemes"[71].

While demand-side policies play a significant role in innovation-fostering, supply-led interventions have a critical role too. Supply-side policies to incentivise innovation are primarily focused on enhancing firms' capacity to engage in innovative activities by reducing associated costs and barriers. These policies include various forms of government support such as tax incentives, direct subsidies, grants and direct equity participation aimed at increasing firms' incentives to invest in innovation as well as strengthening human capital and increasing public investment in R&D. Publicly funded R&D can crowd in or leverage investment from private firms that would not have otherwise occurred.

This leads to the generation of new knowledge outputs and ideas, innovation and productivity growth, and creation of new jobs. This leveraging of public R&D investment may be directly from private firms which themselves receive public financial support, or indirect. One econometric study found that in the long-run, public R&D investment continues to leverage private R&D spending in future years, resulting in a long-term impact more than three times the short-term impact[72]. The leverage rate was estimated to be greater at between 1.01% and 1.32%. In monetary terms this means that in the UK for every £1 of public R&D invested, between £1.96 and £2.34 of private R&D investment is stimulated in the long-run[73].

In conclusion, the paths through which science and R&D generate economic impact highlight the intricate web of innovation ecosystems, emphasising not just the value of direct contributions but also the significance of broader, systemic effects. This analysis reveals the nuanced interplay between market-led innovations, which emerge from the dynamics of supply and demand, and policy-driven initiatives, which aim to address market and system failures. Market failures refer to instances where markets alone do not accomplish appropriate levels of resources into R&D activities, which often justify policy interventions to stimulate R&D activities. System failures, on the other hand, occur when the innovation ecosystem itself is inefficient due to factors like inadequate knowledge diffusion, coordination problems among stakeholders, insufficient absorptive capacity. Such distinctions underscore the need for well-orchestrated innovation systems, often facilitated more effectively by organisations rather than left to market forces alone. Successful innovation systems integrate policy interventions and market signals to foster environments where new knowledge and ideas, innovation and productivity, skilled people, and broader economic impacts can thrive.

Case studies

The previous section demonstrates the complexity of measuring the economic impact of science and the limits of quantifiable information. To present a more nuanced picture, the case studies below illustrate three high impact outputs derived from science and their relationship to the economy.

Case study 1 examines optical fibres, which have transformed telecommunications and enabled the high-speed internet connectivity we rely on today. Despite underpinning much modern economic activity, the costs of optical fibres have reduced dramatically over time. This case study illustrates the ways in which scientific research and technological application can underpin productivity and economic activity, without that value being captured by rates of return on that investment.

This is followed by case study 2, which focuses on the development and application of high-temperature alloys, essential materials that have revolutionised industries requiring performance under extreme conditions, such as aircraft engines. This case study illustrates the importance of a strong research base to attracting and retaining private innovation activity in the UK, and the symbiotic relationship between commercial and academic science.

Case study 3 takes a deep dive into synthetic insulin which transformed the treatment of diabetes and acted as a catalyst for the development of the wider biotechnology sector within the United States. This case study highlights the non-monetiseable benefits arising from developments in medical research, and also the way in which one success story can catalyse a wider industry, in this case the US' now dominant biotech sector, if appropriate policy support is developed.

These examples of international and domestic success stories demonstrate the ways in which discovery research, development and commercialisation have been fundamentally intertwined.

CASE STUDY 1

Optical fibres

Summary

Optical fibres enable the low cost and rapid transmission of data across long distances. They present an interesting case study as although the market value of optical fibres today is fairly low, their value to society remains significant. The ability to communicate globally was made possible through optical fibres and as a result they have shaped the global economy that we live in today. When the first fibre optic cables were laid across the Atlantic the increase in transmission capacity was stark – the first fibre optics could support 40,000 simultaneous calls – a ten-fold increase from even the most advanced copper cables at the time[74].

Optical fibres have shaped the modern world in which we live. They provide the backbone of the internet and have underpinned its rapid growth. The ubiquitousness and relatively low cost of optical fibres makes calculating their true economic impact challenging. At a high-level the photonics industry in the UK is estimated to contribute £15.2 billion to the economy, although the true impact of optical fibres is impossible to measure.

Beyond rates of return, in this case study we have highlighted economic impact in the form of:

- New knowledge and ideas. Following the breakthroughs in the 1960s, which enabled rapid improvements in long-distance signal transmission, there have continued to be significant advances in the field. One example is the generation of hollow-core fibres which have enabled signal transmission at faster speeds with lower rates of loss.
- Innovation and productivity gains. Through their role in long-distance telecommunications, and the critical role they played in the growth of the internet, optical fibres have had a transformative impact on global innovation and productivity. In the UK, the photonics industry is one of the most productive sectors in terms of manufacturing, and advances across the field have led to increased application and utility of optical fibres including Internet of Things systems, autonomous vehicles, military and aerospace applications, lasers, surgical sensors and smart grid applications.

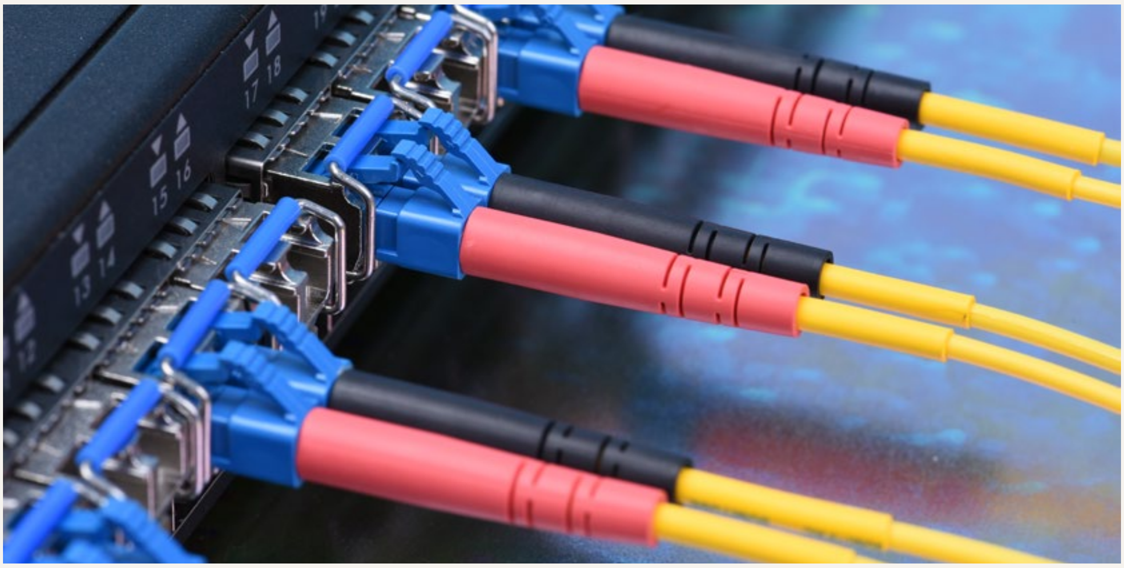


Image:
Switch with fiber optic cables.
© iStock.com / FactoryTh.

Several factors have supported the creation of value and impact generation from optical fibre research and development. Collaboration across academia and industry, institutional support and funding have all contributed to the research breakthroughs, and continued development of optical fibres today.

Introduction

Optical fibres and the field of photonics

Optics and photonics technologies are 'central to modern life'[75]. The technologies are ubiquitous, responsible for applications from providing internet infrastructure and connectivity to biomedicine, autonomous vehicles as well as military and aerospace applications. Whilst the field of photonics broadly refers to all science and technology related to the 'generation, transmission, detection and manipulation of light'[76] optical fibres refer specifically to using long thin strands of glass or plastic as a transmission source for light to send data at high speed, and across long distances. Optical fibres have made the sheer volume of global communication possible. The first transatlantic copper cable (TAT-1) laid in 1956 was able to transmit 36 telephone calls simultaneously[77]. Fast-forward to 1988 – when the first transatlantic fibre optic cable was laid (TAT-8) and the number of simultaneous calls now reached 40,000[78].

World-class research and a strong knowledge base

The use of optical fibres for data transmission began to gain interest in the early 1960s, however it wasn't until the paper by Kao and Hockham, published in 1966, that the idea gained real traction[79,80,81]. In the UK, several research groups across different institutions were working on optical fibres. This included large-scale private laboratories such as the Standard Telecommunications Laboratories (STL); military research establishments such as the Royal Signals Research and Development Establishment (RSRE); public sector institutions such as the British Post Office, as well as university-based research labs such as the University of Southampton and Imperial College London.

Focus of the case study

This case study focuses on the research, development and commercialisation of optical fibre-related technologies and their application across a range of different areas. Whilst there has been and continues to be a strong global research base for this technology, this case study highlights the role that the UK research base has played, and specifically how breakthroughs at the University of Southampton contributed to the continued innovation of this technology.

Work on optical fibres to enable long-distance communication at the University of Southampton began in 1966, pioneered by Professor Gambling who founded the Optical Fiber Group[82,83]. Since the 1960s, optical fibre research has continued and there are now several groups based at the University of Southampton working on different aspects of their development. Alongside the traditional use of the fibres within telecommunications, there are now several other areas of research including for sensors and devices, high power lasers, industrial materials processing, aerospace and biological applications[84].

The economic impact of optical fibres

By enabling low cost and fast communication, optical fibres have become central to modern life and how we live today. Here we describe how optical fibres have contributed to economic impact across the following pathways: (i) new knowledge and ideas and (ii) innovation and productivity.

Pathway to economic impact – new knowledge and ideas

Scientific research and development can generate new knowledge and ideas which can in turn contribute to economic benefits. Whilst research organisations and labs across the world were involved in developing optical fibres viable for data transmission, the UK played a pivotal role in their development. One key player in this field was Charles Kao, a researcher based at the Standard Telecommunications Laboratories (STL) in Harlow, UK. Kao pioneered the use of a glass optical fibre for long distance communication, calculating how to transmit light across long distances via the optical glass fibres, improving the distance range through increasing the purity of the glass[85]. In 1966 Kao and a colleague at STL, George Hockham, published a paper demonstrating their findings, and enabling the idea of using optical fibres to gain real traction. In recognition of this research, Charles Kao was awarded the Nobel Prize in 2009 for ‘groundbreaking achievements concerning the transmission of light in fibres for optical communication’[86].

Advances in the field at the University of Southampton – the development and commercialisation of hollow-core fibres

Since these initial breakthroughs, there have been several advances in the field, both within the UK and globally. One area of increasing focus has been the development of hollow-core fibres, a refinement to the original optical fibre technology which enables faster speeds. Hollow core fibres are fibres where the conventional glass core has been replaced with a gas or vacuum. Compared with the more traditional glass-based structures, hollow core fibres can support faster light speeds as well as increased data transmission[87]. Researchers at the University of Southampton were able to make hollow core fibres with high data transmission capacity, very low rates of loss and smaller delays, compared to conventional fibres[88,89]. The underpinning research performed at the University of Southampton led to the generation of IP and a growing realisation of the utility of hollow core fibres[90,91]. Recognising their potential commercial impact, Professors Richardson, Poletti, Petrovich, and Dr Parker founded the spin-out company Lumenisity Ltd in 2017 in order to provide high-performance hollow core fibre solutions[92]. Lumenisity has since raised additional funding through external investment: in 2020 the company received a £7.5 million investment[93], alongside additional investment from overseas[94]. Through the development and commercialisation of hollow core fibres, the company became the first fibre supplier capable of producing hollow core fibres with low enough loss over >10km distance scales, and the company’s telecommunications customers benefited from reduced latency within their networks[95]. In 2021, one of the UK’s largest telecommunications and network provider BT trialled the use of Lumenisity hollow core fibre technology for a variety of use cases including 5G networks and ultra-secure communications[96]. Lumenisity was acquired by Microsoft in December 2022 and valued at £20 million.

Pathway to economic impact – innovation and productivity

Scientific research and development can lead to advances in innovation and productivity gains through the development or advances of goods and services. Because of the underpinning role that optical fibres play in the architecture for data transmission and communication, the impact they have had on innovation and productivity continues to be significant.

The UK photonics industry contributes £15.2 billion to the economy per year and with a productivity estimate of £89,400 per employee, the photonics industry as a whole is considered to be one of the UK's most productive manufacturing sectors[97]. In addition, the industry is continuing to experience growth. A report published by The Photonics Leadership Group in 2023 found that the UK photonics industry had grown at an average growth rate of 4% over the past decade[98].

Optical fibres have become an 'indispensable backbone' of the network infrastructure required for the internet and telecommunication[99]. The continued rise in internet use[100], as well as increasing demand for connectivity and 'Internet of Things' applications[101], places increasing demand on their use. Unsurprisingly, the global market for optical fibres is forecasted to grow significantly[102]. The UK plays a small but not insignificant role in global trade, with UK exports of optical fibres and cables valued at approximately £120 million and imports valued at approximately £275 million[103]. The rapid transmission of text, music and images across the globe is a result of optical fibres[104]. Whilst the market value of optical fibres today is fairly low, their value to society remains significant.

Manufacturing optical fibres for a range of applications and environments

Building on the strong research base and utility of optical fibres, researchers have continued to develop optical fibres for a wide range of practical applications. An example of this was the successful spin-out company Fibercore which was established in 1982 to offer the fibres developed at the University of Southampton commercially. Alongside the traditional use of fibres in telecommunications, Fibercore fibres have been developed for use across a range of applications including those relating to Internet of Things systems, autonomous vehicles, military and aerospace applications, lasers, surgical sensors, and smart grid applications. Because typical fibres can degrade at extreme temperatures or harsh environments, Fibercore have developed innovative, coated fibres which can be used across a range of harsh and varied environments. Fibercore products are currently used by over 1000 customers across 50 countries[105].

Factors which support the value creation of optical fibres

From the initial research through to development and then commercialisation, many factors have supported the creation of value and commercial success of the optical fibre research in the UK including the strong knowledge base and world-class research, investment and links between academia and industry.

Collaboration across academic institutions and industry

The successful photonics industry in and around Southampton as well as the history of spin-out companies and commercialisation provided a favourable environment to support the researchers in their venture including enabling them to collaborate with those experienced in commercialisation[106]. Collaboration was also highlighted as a positive. For example, the collaborative relationship between Lumenisity and the University of Southampton supported synergy between the two with joint R&D contracts. In addition, whilst Lumenisity invested in improving and upgrading the University infrastructure and equipment, the Optoelectronics Research Centre (ORC) provided Lumenisity with a pipeline of skilled individuals who joined the enterprise on finishing their PhDs[107].

Institutional support

The ORC is an Interdisciplinary Research Centre and leading institute for photonics research[108]. The research centre is based at the University of Southampton and has enabled a community of researchers in photonics research to come together, contributing towards the growth of the photonics industry. Institutional support was highlighted as being a strong positive with both support from the ORC, and the University of Southampton Research and Innovation Services team. The team are the central point for the university's enterprise and research activities, and support with knowledge transfer and commercialisation of IP. One of the Lumenisity co-founders Professor Marco Petrovich highlighted that 'They were our first port of call for many of the initial steps, such as enabling the company to exploit the intellectual property, and the transition of staff from the University to the company'[109].

Private and public investment

The optical fibre research which contributed to the breakthroughs we see today was supported by significant funding from UK and non-UK research programmes. For example, the hollow core fibre research was funded from sources including the Engineering and Physical Sciences Research Council (EPSRC) and European Commission programmes in excess of £25 million[110,111]. Today, over half of UK photonics companies invest more than 10% of their turnover in R&D, and industrial funding remains a significant source of income for research groups[112].

Conclusions

This case study highlights the value of optical fibres which have had a transformative impact on modern life. The world-leading discovery research coupled to a strong history of spin-out success and supportive institutional environment enabled the initial research, resulting breakthroughs, and eventual commercialisation of this technology. The inclusion of ‘Future telecommunications’ as one of the five critical technologies within the UK government’s Science and Technology Framework may well have further implications for optical fibre research and development[113].

The Framework, published in March 2023, sets out the government’s goals and vision for science and technology. On the back of this it was announced that the UK has joined a global coalition to enhance the resilience of communication networks. The UK government has allocated £70 million to advance next generation telecom technology through the UKRI Technology Missions Fund[114]. In addition, the European Commission actions aimed to ensure Gigabit connectivity for all citizens and businesses across the EU by 2030, including the proposal for a ‘Gigabit Infrastructure Act’, are likely to further advance incentives for the continued research and development of optical fibres[115]. These advances coupled to the European Union regulation 2022/72 which imposes anti-dumping duties on imports of optical fibre cables from China, are likely to continue to create a conducive environment for UK researchers within this field[116].

CASE STUDY 2

High-temperature alloys

Summary

The development of high-temperature alloys in the UK demonstrates the iterative nature of innovation, with significant economic value in the improvement of materials used in aircraft engines arising from steady progress over time and a continual cycle of innovation in which basic research and commercial application are closely interlinked. The story of high-temperature alloys highlights the crucial role of (and support for) long-term partnerships between academia and industry in the UK, leading to a world-leading industry.

High-temperature alloy technologies, pioneered by the effective collaboration between UK academia and Rolls-Royce, have underpinned the development of materials resistant to extreme conditions and more efficient aircraft engines. This has significantly reduced aviation fuel emissions, thereby reducing the industry's environmental footprint, having indirect economic benefit. Novel alloy compositions and manufacturing techniques have become essential components of modern aerospace systems.

High-temperature alloys: a catalyst for economic growth and innovation in aerospace

Background

For over a century, the aviation and aerospace industries have been putting significant efforts towards achieving more efficient gas turbine engines. This has accelerated with the push for emissions reduction in the last couple of decades. One of the most pressing challenges is to arrive at greater efficiency and power within engine architectures, for which raising turbine temperature is essential. Achieving higher temperatures within engine architectures presents, in turn, a series of difficulties for the underlying components and materials in use, which face a tougher environment that demands relatively greater resistance. Currently employed materials are constrained by their low melting points and so unlikely to satisfy the necessary requirements for the desired increase in within-engine temperatures and efficiency. High-temperature alloys, as an advanced material, are proven to provide much more stable characteristics at high temperatures.

Image:
Aircraft mechanics.
© iStock.com / EXTREME-PHOTOGRAPHER

The search for materials that can withstand extreme temperatures started in the 1930s in the United States, driven by the aerospace industry's need for materials that could endure the harsh conditions of aircraft engine turbosuperchargers. Such demand grew further with the advent of gas turbine engine technology in the 1940s and space-based nuclear reactor programs in the early 1950s[117]. The development and application of nickel-based superalloys has been key. These alloys are characterised by their exceptional combination of mechanical and physical properties at temperatures up to 1,150°C, making them the structural material of choice for high-temperature applications in aerospace and beyond.

However, the operational limits of nickel-based superalloys, dictated by their melting temperatures, prompted the exploration of new material solutions to reach even higher temperature and efficiency levels. The discovery and subsequent research into high-temperature alloys, including high entropy alloys (HEAs) and refractory high entropy alloys (RHEAs), have broadened the field of materials science, offering alloy compositions with unprecedented mechanical properties. These include yield strengths greater than 1,000 megapascals (MPa) at temperatures below 600°C and notable strength and toughness even at cryogenic temperatures. RHEAs, in particular, have shown promise for retaining significant strength up to 1,600°C, addressing the critical high-temperature limitations of nickel-based superalloys.

Despite their potential, high-temperature alloys also have limitations. This includes poor high-temperature oxidation resistance and sensitivity to oxygen, which have hindered their widespread adoption and diffusion. Efforts to address these obstacles have involved doping high-temperature alloys, such as RHEAs, with elements like aluminium, chromium, titanium and silicon to enhance their oxidation resistance. This balance between maintaining superior mechanical properties while enhancing resistance to environmental degradation is the focus of current research.

Rolls-Royce and UK academia have taken a comprehensive approach towards innovating aerospace engine technology by focusing on the critical need for engines to produce fewer emissions and be more fuel-efficient and resistant to the extreme conditions of high-temperature operations. The focus on high-temperature alloys, particularly in the context of aviation, underlines an effort to push the boundaries of material science to enhance the performance, reliability and environmental sustainability of aircraft engines.

High-temperature alloys: advancing engine performance and environmental sustainability

High-temperature alloys, such as nickel-based superalloys and potentially RHEAs are crucial for components such as turbine blades and discs, which are subjected to the harshest operating conditions within the engine. By improving the materials' resistance to issues such as creep, oxidation and thermal fatigue, researchers have been able to develop engines that surpass current operational efficiency and environmental standards.

The practical application of this research extends beyond merely improving engine design. It also enhances the overall sustainability of aviation by reducing fuel consumption and carbon emissions, thereby contributing to the industry's efforts to combat climate change and make air transport more cost-effective. Furthermore, advances in high-temperature materials are likely to have ripple effects across various sectors, including power generation, automotive and even space exploration, where materials capable of enduring extreme conditions are essential[118].

The science behind superalloys focuses on the means of withstanding extreme conditions within jet engines, where turbine blades are exposed to temperatures exceeding 1,500˚C. Research explores the metallurgy of these materials, which includes optimising their properties for safety and efficiency. Additionally, it involves developing new alloys capable of operating at even higher temperatures, thereby further reducing fuel consumption and emissions[119].

Global competitive landscape

The high-temperature alloys sector is at the centre of technological innovation and strategic market positioning globally. Beyond market leaders in Europe and the US, the Asia Pacific region, across China and increasingly India, Japan and South Korea, has come to hold a substantial share of the high-temperature alloy market. China has seen its share grow substantially, having developed its own high-temperature materials sector in pursuit of self-sufficiency. This has been pivotal to its progress in the automobile and aerospace industries[120]. As a result, the high-temperature alloys market is increasingly competitive, with companies such as Rolls-Royce, ATI, and Nippon Yakin Kogyo dominating globally, but with other businesses in pursuit.

Advancing high-temperature alloys: the Rolls-Royce and UK academia collaboration

The development of high-temperature alloys by Rolls-Royce, significantly shaped through close collaboration with universities and support from the government, has a long history. One of its most significant partnerships with academia began with the establishment of the Rolls-Royce University Technology Centre (UTC) at the University of Cambridge in 1994. This supported the development of the next generation of nickel-based alloys and high-temperature alloys, intermetallics and titanium alloys, and was crucial for components such as turbine blades that must endure temperatures up to 1,200°C[121]. Rolls-Royce's initial funding of £1.25 million over five years, coupled with additional funding from the EPSRC, the Department of Trade and Industry (now DSIT) and European Commission (EC) sources, underscored a collaborative effort aimed at pioneering advancements in aerospace materials[122].

Another notable collaboration was Rolls-Royce's work with the University of Birmingham in establishing the High Temperature Research Centre (HTRC). This centre was funded through a £40 million investment from Rolls-Royce, matched by a £20 million government grant through the Higher Education Funding Council for England's UK Research Partnership Investment Fund (UKRPIF). Since 1989, the HTRC has focused on production-scale research and experimentation to foster rapid product and process innovation in the field of aerospace engine technologies. It has concentrated on developing advanced metallic alloys for turbine blades and discs, aiming to enhance engine efficiency, reduce emissions and address environmental concerns.

Such collaborative efforts have led to cutting-edge advancements in aero-engine technologies, particularly in the development of advanced metallic alloys for turbine blades and discs, which have improved engine efficiencies and contributed to the aerospace industry's goals of reducing emissions and enhancing sustainability. Furthermore, the partnership has notably developed high-strength, powder-based nickel alloys, enabling lighter, more efficient turbine components through advanced manufacturing techniques such as inertia welding. In 2022, the University of Birmingham and Rolls-Royce were awarded the Bhattacharyya Award by the Royal Academy of Engineering for their partnership at the Materials UTC and the HTRC, focusing on advanced alloys for aero-engines. This collaboration's significant environmental and economic benefits were recognised for innovations like high-strength, powder-based nickel alloys for turbine discs, improving engine efficiency and reducing weight. Their efforts exemplify the award's goal of fostering industry-academia collaboration to enhance the UK's aerospace sector and develop future talent[123,124,125].

Nevertheless, Rolls-Royce has not only promoted R&D&I activities through such kinds of partnerships but also beyond UK shores, including a significant UK-Japan collaboration. This collaboration focuses on the development of high-temperature superalloys for gas turbine engines, which continues the strong track record of UK-Japanese collaboration in aerospace. Amongst the outcomes of such collaboration, its contribution towards the Rolls-Royce Trent, the engine that powers and allows the Boeing 787 Dreamliner to be about 20% relatively more fuel-efficient, stands out as one of the most significant Rolls-Royce collaborative programmes.

Such tripartite collaboration has allowed the UK to further strengthen its position as a leader in aerospace technology, promoting economic growth and high-tech employment opportunities. Worldwide, this partnership has contributed to significant advancements in fuel efficiency and reductions in carbon emissions, aligning with environmental sustainability goals.

Economic impacts

Skilled workforce development

Demand for high-temperature alloys has led Roll-Royce's partnerships to play a pivotal role in skill development and job creation within the UK. By establishing such academia-industry relationships and engaging in collaborative research projects, Rolls-Royce and its academic partners have provided valuable training and employment opportunities. This initiative has contributed to building a highly skilled workforce capable of addressing the complex challenges of aerospace engineering and materials science.

Examples of such skill development include the collaboration of Rolls-Royce with the Universities of Cambridge and Birmingham. The former, realised via the University of Cambridge and Rolls-Royce's two University Technology Centres (UTCs): the University Gas Turbine Partnership at the Whittle and Hopkinson Laboratories and the Materials UTC at the Department of Materials Science and Metallurgy, have been instrumental in advancing expertise in gas turbine technology and materials science, ensuring the provision of highly specialised skills. Overall, this partnership supports over 50 Cambridge PhD students, providing them with invaluable industry experience and contributing to the development of a highly skilled workforce capable of tackling future challenges in aerospace engineering.

The latter refers to the University of Birmingham's partnership with Rolls-Royce on Advanced Metallic Alloys, involving the University of Birmingham's Materials UTC and the HTRC, which have significantly contributed to developing the necessary talent to develop and employ new technologies, including high-temperature alloys, in the aviation sector. At the time of writing, this 34-year partnership "spans 70 Academic Staff, 30 Postgraduate Students, and 120 Rolls-Royce employees working to enhance the scientific understanding of the metallic alloys used for safety-critical components in aero-engines". Since its inception in 1989, it has led over 100 doctoral students to be trained in Birmingham and join Rolls-Royce as materials and manufacturing specialists.

Overall, the strategic partnerships have significantly bolstered the UK's knowledge stock, human capital and absorptive capacity significantly in the field of advanced materials. Concretely, it has contributed to equipping the UK with a workforce that not only possesses the necessary theoretical knowledge, but also the practical skills to apply this new knowledge effectively. As a result, the UK's competitive edge in the global aviation sector has been markedly strengthened, ensuring its leadership through a virtuous cycle of knowledge creation and application, which drives forward technological progress and industry advancements.

Advancing aerospace, fuelling efficiency and achieving net-zero ambitions

The development of high-temperature alloys as a result of the collaborative efforts of the UK Government, Rolls-Royce and academia has had direct implications for the aerospace industry at home and worldwide, enabling the production of more efficient and environmentally friendly aircraft engines. These materials have led to engines that consume less fuel and produce fewer emissions, aligning with global efforts to mitigate climate change and advance sustainable aviation. Over its lifetime, the Airbus Dreamliner has been made 20% more fuel-efficient[126]. The partnership between Rolls-Royce and the University of Birmingham, particularly through the Materials UTC and the HTRC, has been central to advancing materials science for aerospace applications. This collaboration has been instrumental in developing advanced metallic alloys for turbine blades and discs, crucial components at the heart of aero-engines.

Economic and productivity stimulus

The collaboration between Rolls-Royce and UK academia to further advancements in high-temperature alloy research has stimulated economic growth in different ways. Not only has it led the UK to pioneer advancing aerospace technologies, but also to produce beneficial economic and productivity outcomes. Such partnerships have been recognised for their transformative advances in aerospace energy efficiency, notably through the development of high temperature and advanced metallic alloys for turbine blades and discs.

Rolls-Royce's work with academia has led to a range of economic impacts. This includes increasing the knowledge stock of the UK and worldwide in this particular area – for instance, the partnership between the University of Birmingham and Rolls-Royce "has produced over 100 patents, delivering a significant competitive advantage to Rolls-Royce" and the UK[127].

Additionally, these innovations have contributed significantly to the extension of capital equipment lifespans and reduction in maintenance costs, which are crucial for the sustainability and financial viability of aerospace operations[128,129]. The adoption of high-temperature alloys has led to more durable components that can withstand higher stresses and temperatures, translating into fewer maintenance needs and extended service intervals. This has ensured capital assets remain operational for longer periods, optimising capital expenditure and enhancing overall fleet productivity[130].

Furthermore, the collaboration between Rolls-Royce and UK academia in researching and innovating in the high-temperature alloy field has significantly contributed to the UK's gaining and maintaining a worldwide leading position as an aerospace export nation, after the US. As a whole, the UK civil aerospace industry saw a staggering turnover of approximately $34.5 billion in 2022 and 70% of its production, highly sought after in global markets, exported.

The UK defence and space industries' turnover totalled approximately $29 billion and $22 billion in 2022 and 2021; of which $15 billion and $9.5 billion was exported, respectively. These efforts underscore the strategic importance of such collaborations in enhancing the UK's technological capabilities, driving economic growth, and reinforcing its status as a global leader in aerospace innovation[131].

Factors which supported 'value creation'

The collaborations between Rolls-Royce, academia, and the UK Government have been pivotal in advancing high-temperature alloy technologies, with several factors supporting value creation in these projects.

Integral to this collaborative ecosystem has been the interplay between Government funding and Rolls-Royce's private investment. Government grants, like those provided through initiatives such as the UK Research Partnership Investment Fund, have acted as catalysts, encouraging Rolls-Royce to commit substantial private funds to research projects. This collaboration has ensured continuous support for innovative research, which often faces challenges in attracting private funding. By alleviating the financial burden on Rolls-Royce, this partnership has facilitated Rolls-Royce's investments, and long-term pioneering research efforts that have significantly enhanced innovation and value creation in the aerospace industry.

Likewise, collaboration between Rolls-Royce and academic partners has been a key driver of value creation, as it has maximised the strengths of both sectors. Academic institutions' cutting-edge research facilities and capabilities and new knowledge, along with Rolls-Royce's industry expertise and real-world application knowledge, have led to breakthroughs in materials science and aerospace technology that might not have been achievable independently.

Indeed, such collaborative efforts have not only considerably reduced barriers to innovation, delivering tangible results as previously discussed, but have also exemplified the critical role of absorptive capacity in fostering innovation and competitiveness. Access to state-of-the-art facilities and equipment, facilitated by research centres like the HTRC, have democratised access to critical resources, levelling the playing field for both industry and academia. This has fostered an environment where creativity and experimentation flourish, unencumbered by resource limitations. Consequently, Rolls-Royce and its academic partners have been able to explore uncharted territories, accelerating the development of high-temperature alloys and related technologies, which translates into tangible value through improved product offerings and market competitiveness.

Furthermore, the importance of knowledge transfer as a pivotal element in value creation by Rolls-Royce and its academic collaborators cannot be overstated. The dynamic exchange of expertise and insights between the industrial and academic spheres has not only propelled technological progress but has also fostered a reservoir of highly skilled professionals. This vital interchange ensures the UK's aerospace sector's vitality and competitive edge, continually attracting and refining top-tier talent. Knowledge exchange has acted as a catalyst, multiplying the impact of innovations as newly equipped professionals drive further advancements. This iterative cycle of knowledge sharing and application spearheads the development of innovative solutions and promotes the growth of a robust aerospace research ecosystem, ultimately generating substantial value and reinforcing the industry's capacity for continuous evolution and excellence.

Conclusions

The partnership between Rolls-Royce and UK academia in advancing high-temperature alloy technologies stands as a testament to the great value that science contributes to economic growth, technological innovation, and environmental sustainability. By synergising the expertise of industry, academia and Government, this collaboration has propelled the UK aerospace sector to new heights, bolstering its competitive edge on the international stage and creating high-value jobs. Moreover, the relentless pursuit of scientific knowledge has not only led to breakthroughs in aerospace engineering but has also played a pivotal role in steering the global journey towards more efficient and environmentally friendly aviation solutions. This partnership highlights the transformative impact of scientific research and underscores the importance of continued investment in science and innovation for the betterment of society and the advancement of human endeavours.

CASE STUDY 3

Synthetic insulin

Summary

Rates of return only capture a small slice of the economic value created by R&D-intensive firms. The commercialisation of synthetic insulin in 1970s California was an essential catalyst in the development of the world-leading US biotech sector. Beyond private returns, it had economic impact by:

- Creating tangible knowledge products that were then distributed via academia that became cornerstones of the sector,
- Acting as a leading example of the commercial possibilities of high-risk investments in biotechnology,
- Pushing the US government to develop a policy environment that lowered barriers, unlocked private funding and was more conducive to the sector as a whole.

The history of synthetic insulin demonstrates the essentially iterative nature of technological development. Commercial development depends on continued discovery research with access to long-term funding without the expectation of short-term commercial return.

Introduction

The isolation, development and mass production of insulin illustrates the way in which the economic impacts of R&D can be far larger and broader than the value caught in rates of return literature. It demonstrates some of the key innovation policy considerations and trade-offs inherent in this type of economic activity, and the essential relationship between commercially ended applied research and basic research and discovery.

This study starts by looking at the mass production of synthetic insulin in the 1970s, and its role in catalysing the US biotechnology sector as a whole. It then considers the foundation of insulin research that this built upon.

This case study demonstrates the significant non-monetised economic impacts of R&D activity, Path 4 of the taxonomy above. In this case, the treatment of diabetes has been completely transformed by the development of synthetic insulin. Further, in acting as a catalyst for the development of the wider biotechnology

Image:
Vial of Insulin injection with a syringe. © iStock.com / Bernard Chantal.

sector on the West Coast of the US, this case study illustrates the spillover effects possible from successful R&D, as well as the virtuous circle possible from creating the conditions in which skilled people can collaborate effectively across institution types in a given region.

Synthetic insulin and its impacts

Entering the 1980s, the international competitiveness of the biotechnology sector in the US was in doubt[132]. By 2022, it led on almost all relevant metrics. In terms of current market share, North American biotech accounts for 37.76% of global revenue or $462.35 billion[133].

Synthetic insulin was an important catalyst in the development of the sector. It created specific tangible knowledge and technological breakthroughs that became cornerstones of many early biotech companies. It pushed the US government to develop an industrial policy by stealth geared towards commercialisation of biomedical research[134]. It also provided a successful model of commercial research operating in collaboration with universities that came to be widely replicated in the US, especially in San Francisco and Boston[135].

This was all built on the foundations laid by discovery-orientated research conducted at Stanford University and University of California at San Francisco (UCSF) in the 1970s. Funded by public money, in the form of grants from the National Institutes of Health and the National Science Foundation, teams of scientists developed techniques to divide and recombine strands of DNA from multiple sources, allowing for genetic engineering of novel sequences[136]. This research built on a wide range of discovery science being pursued in the preceding decades across a range of universities internationally, especially the initial isolation and identification of DNA plasmids that could replicate outside of chromosomes, and into the restriction enzymes that enabled the recombination of DNA strands done at University of Geneva.

Synthetic insulin was first produced in the late 1970s by Genentech, a San Franciso start-up founded by one of the lead biochemists of this work at UCSF, Herbert Boyer, and venture capitalist Robert Swanson. Through application of recombinant DNA (rDNA) Genentech could produce synthetic human insulin, replacing the need to use animal-derived insulin in the treatment of diabetics. In the 1980s, Genentech partnered with long-standing pharmaceutical company Eli Lilly, a leading player in the existing North American insulin market, making hundreds of millions of dollars a year from animal insulin, but concerned about the continued ability of this source to meet growing demand. This enabled the ability to produce and commercialise synthetic insulin, marketed as Humulin, at scale[137].

Humulin was extremely profitable for the partnership. Unusually for the time, it was taken public in October 1980, raising $35 million at its initial public offering. In the words of one of its backers it “established the idea you could start a new biotechnology company, raise obscene amounts of money, hire good employees, [and] sell stock to the public. Our competitors started doing that”[138].

Genentech was foundational in the development of the modern insulin market. Humulin accounted for 60% of sales of the domestic US insulin market in 1995. The global insulin market was valued at $18.73 billion in 2022[139]. However, even this alone underplays the economic impact that synthetic insulin has had, both in catalysing a much broader biotechnology in the US, and in its benefits to population health.

The specific advancements required to produce synthetic insulin also enabled other advances. The rDNA cloning technology initially developed to synthesise human insulin came to have significantly more use cases and was pivotal as the "technical foundation of the biotechnology industry"[140]. Genentech itself went to further apply these techniques to develop medicines treating a wide range of conditions, including strokes, growth hormone deficiency and cystic fibrosis.

Effective cross-sector collaboration enabled the success of Genentech

Crucial to the success of Genentech was the interplay between different research institution types, and especially continued effective collaboration between industry and academia. Stern argues that "firms and university labs represent fundamentally different organisational structures", drawing a sharp distinction between narrowly focused, profit driven firms such as Genentech and universities, more interested in scientific rather than commercial considerations[141]. Owen & Hopkins identify the specific abilities that Swanson brought to the firm from the commercial world in setting clear priorities based on business opportunity in driving progress[142]. At the same time, both institution types are "members of a single technological community"[143]. Herbert Boyer remained in employment at UCSF, and funnelled additional financial support back into the academics in this lab. Genentech actively endeavoured to create "an atmosphere which would take the best from industry and the best from the academic community and put them together"[144]. Genentech scientists openly shared reagents and samples with the wider scientific community, as was common academic practice, and Boyer "insisted [Genentech] scientists publish their research in journals"[ii].

The policy environment supported the nascent industry

In 1984, shortly after the Genentech partnership with Eli Lilly, the Office of Technology Assessment (OTA) published an assessment of the sector titled "Commercial Biotechnology: An International Analysis". This identified the potential for US leadership in the global economy but warned that it "could have difficulty maintaining its competitive position in the future" without state support and regulatory change[145].

Federal policy approaches were beginning to be taken that enabled Genentech's commercial research. The 1980 Bayh-Dole Act enabled universities and individual scientists to patent and license discoveries emerging from federally funded research. This "changed the longstanding presumption that publicly funded work could not be privately owned and [commercially] exploited"[146]. This was followed by the Stevenson-Wydler Technology Innovation Act of 1980, which obligated federally funded laboratories to establish and budget for technology transfer offices. Ultimately, UCSF and Stanford would earn over $100 million in royalties from the patent on rDNA[147].

[ii] Open sharing clearly had its limits: notably, Genentech were obliged to pay USCF $350,000 in compensation for "unlawfully acquired reagents".

Especially influential for Genentech was the ruling of the Supreme Court in the Chakrabarty case of 1980. This allowed engineered microbes, including rDNA technologies to be patented for the first time[148]. When the Court ruled in favor of patenting biological matter, this enabled the US Patent Office to process a backlog of applications. One of the first cases to be approved was Genentech scientists' rDNA cloning techniques, critical to the synthesis of insulin and to the wider industry of biotechnology[149]. Broader economic considerations were critical to the Court's decision. Several briefs were written to the Supreme Court, including by Genentech, stressing the importance of intellectual property protections for the biotechnology industry and "revitalising the health of the domestic economy"[150].

Policy changes also unlocked more sources of private investment. In 1979, reforms to the regulation of pension funds allowed the annual investment from these sources into venture capital funds to increase six-fold, to approximately $3 billion, enabling a wave of investment into R&D intensive industries, of which Genentech was one beneficiary.

Background: Genentech's success was built on half a century of iterative discovery and commercial research

Discovery and isolation of insulin

Without first understanding the composition of insulin as a protein, it would have been impossible to decipher the genetic code and clone recombinant human insulin. In the early twentieth century, a number of academic research teams were simultaneously seeking to identify and isolate what we now call insulin. University of Toronto researchers Frederick Banting and George Macleod eventually won the Nobel Prize for their work, but were part of an international network of researchers in this area that included Georg Zuelzer in Berlin; Nicolae Constantin Paulescu in Bucharest; Israel Kleiner at the Rockefeller Institute; and John Murlin at the University of Rochester[151]. All had, with varying levels of success and persuasiveness, "prepared pancreatic extracts with a proven anti-diabetic effect"[152]. This kind of simultaneous discovery is the norm in scientific research. As one author puts it, "the whole history of inventions is one endless chain of parallel instances"[153].

The Toronto team's early association with a major pharmaceutical firm, Eli Lilly, was fundamental to the development of insulin as a clinical treatment, which played a determining role in the team awarded the Nobel Prize. Eli Lilly had the requisite manufacturing capabilities and expertise to scale up insulin to commercial levels and meet market demand for insulin. This was critical as the team at Toronto had been unable to purify and isolate insulin reliably even for individual patients. They had employed an expensive, cumbersome and dangerous process of isolation[154]. Aside from having vastly greater facilities and capital at their disposal to scale up insulin, Eli Lilly was also able to improve the production process.

Their chief chemist, George Walden, devised a means of precipitating insulin out of solution and vastly improving its purification[155]. This innovation cheapened the whole process of purification and enabled Eli Lilly to mass-produce insulin from February 1923 onwards. Given the difficulties in scale up encountered by the Toronto team, this would likely have been impossible to do within the university. The support and backing of a big pharmaceutical firm represented an essential step in the mass production of insulin.

The contrast between Toronto researchers and the work of Georg Zuelzer, a German physiologist working in early twentieth century Berlin, is illustrating. Zuelzer isolated insulin early. Like the Toronto team, he sought to work with and receive funding from pharmaceutical companies. However, he had notably less success. Despite initially secure investment from Schering, formerly Chemische Fabrik Auf Actien, this support was quickly withdrawn as they deemed the costs of producing Zuelzer's pancreatic extract, now recognised as insulin, to be too high. Zuelzer subsequently gained funding from another pharmaceutical firm, Hoffman La Roche, but again their support was not steadfast. Roche were not convinced that injected insulin would be commercially viable and dropped the project.

Researchers at the University of Toronto benefitted from more secure public funding for similar research, decreasing the need for short-term commercial returns. Also, while Zuelzer had only contacts at various Berlin clinics, Toronto researchers benefitted from institutional links to Toronto General Hospital, and being the "first to establish a model of a research clinic"[156]. The route to a commercially viable, clinically useful product was better supported and clearer in the Toronto case, which was crucial to the viability of the partnership with Eli Lilly.

Development

Following the initial isolation and production of insulin, subsequent innovations and improvements in its use as a medicine were developed through an iterative process between both industry and academia. Rather than there being a distinction between a clear period of research followed by a period of application, the incremental innovation in the development of synthetic insulin was a messy, non-linear process and not all of these individual steps were necessarily constructive[157].

An example of cross-sector development of this kind was the addition of protamine in the 1950s, a basic protein, and zinc to insulin which reduced its solubility and prolonged its action[158]. This enabled diabetics to take their daily dosage of insulin in one single injection, rather than multiple injections during the day and often at night. For this, protamine zinc insulin (PZI) was hailed by Banting as "'the greatest advance in the treatment of diabetes since the discovery of insulin"[159]. While enthusiastically received at the time, PZI and other "lente" insulins were associated with an increased incidence of allergic actions and hypoglycaemic attacks. The historian and diabetes physician Tattersall claims that such daily "lente" insulins led to "three decades during which poor control of blood glucose was the rule rather than the exception"[160].

Subsequent innovation and scientific research were key to resolving some of these issues, especially around the clarification of the chemical structure of insulin. When insulin was first discovered and isolated, its chemical structure was completely unknown, and it was described by one physician as "thick brown muck"[161]. Through advents in chromatography and X-ray crystallography, this changed as its exact amino acid sequence and then DNA composition was revealed.

A variety of scientists, such as Frederick Sanger and Dorothy Hodgkin were particularly important, both winning Nobel Prizes for work related to insulin. Not only did such work raise the former prospect of improving "efficiency in the management of diabetes" but also "raised the exciting possibility that new, improved forms of insulin might now be deliberately engineered"[162]. These incremental innovations paved the way for the academic development of rDNA in Stanford University and UCSF in the 1970s discussed above, and the synthetic synthesis of human insulin achieved by Genentech that followed.

Health impacts of the insulin industry

In terms of its impact on health, the mass production of insulin is widely regarded as a "medical miracle"[163]. It has enabled diabetics to manage their condition and live normal, healthy lives. While non-synthetic sources of insulin remain important – Novo Nordisk's market value exceeded the rest of Denmark's GDP at some points in 2023 – synthetic insulin has allowed a much greater scale of insulin treatment to be used globally[164]. Furthermore, as with the economic impacts, the knowledge and techniques that underpinned the development of synthetic insulin by Genentech would go on to be used and improved throughout the biotechnology industry, including in the development of drugs involved in the treatment of a wide range of conditions, including strokes, growth hormone deficiency, and cystic fibrosis.

Quantifying the health impact of synthetic insulin is extremely difficult. The current health economics of diabetes offers some perspective. In the UK, with insulin widely available via the NHS, the long-term complications of diabetes make up 10% of its annual budget, or £10 billion each year[165]. This is projected to grow to £16.9 billion a year by 2035 – 2036[166]. The indirect costs of illness, work loss and the need for informal care associated with diabetes are even greater still, estimated by York Health Economic Consortium (YHEC) to be £13.9 billion each year[167]. While challenging to imagine a counterfactual scenario where insulin had not been developed as a clinical treatment, with almost a quarter of Type 2 diabetes patients in the UK regularly injecting insulin it is reasonable to suggest that these costs to the NHS would be considerably greater without insulin.

There is a tension and trade-off between the commercial value of insulin and its positive impacts on health economics. Cost limits access. While insulin is free for diabetics in the NHS, this is not the case in private healthcare systems, such as the US. There, the real terms cost of insulin has increased over time. One recent study estimated that 14% of diabetics spend more than 40% of their post-sustenance income on insulin and other treatments[168]. Unsurprisingly, many US diabetics either go without insulin or carefully ration it, leading to greater incidence of complications. In the developing world, issues of access are even more restricted; in certain African countries, the mortality rate for children born with Type 1 diabetes is estimated to still be equivalent to that of children born in the West before the discovery of insulin[169].

Such issues of access have limited population health and societal impact. This is particularly true of Humulin. In this case, during the initial stock value flotation of Genentech, the cost per dose of human insulin was projected to be twice as expensive as the cheapest bovine insulin[170]. A Cochrane systematic review of the literature states this clearly: "Human insulin was introduced into the market without scientific proof of advantage over existing purified animal insulins, especially porcine insulin"[171]. The need for synthetic insulin in the 1970s is disputed. While some, including Eli Lilly who were the leading North American producer of animal-derived insulins, expressed concern for producing enough to meet growing demand, some later historians suggest these projections were "remote and disputed"[172].

The same is true of subsequent innovations in analogue insulins, where the DNA sequence of insulin was altered to develop longer acting recombinant insulin. These are more expensive than standard human recombinant insulin, but evidence around their improved efficacy remains lacking. A meta-analysis has found that there is "no evidence for a beneficial effect of long-acting analogues on patient-oriented outcomes like mortality, morbidity, quality of life or costs"[173]. Innovations in insulin can be scientifically important and commercially valuable without necessarily having significant impacts on public health.

Evidence gaps

Although there is plenty of existing literature on science and its relationship to the economy, there remain critical areas in the UK context where evidence is either missing, scarce or underutilised. This section identifies gaps in the available data as the basis for further exploration. It is not a comprehensive analysis.

Firstly, there is significant variation in the evidence on the generation of new knowledge, its transfer and deployment into generating innovative products, services or processes, and the implications this has for productivity. While data on the UK's university sector is relatively comprehensive[174], the contributions of other research-performing organisations in the public and private sector are less well-documented. Furthermore, the interconnectedness among these actors in the R&D system is incompletely measured, which limits analysis of their joint contributions to generating new knowledge flows and innovation. Understanding this interconnectedness better would help to create a more holistic view of how science impacts the economy.

Secondly, while there is a reasonable depth of information on the supply of skills by universities and the employment creation among graduates, measuring the broader upskilling effects of science across the economy and through all career stages presents significant challenges. While resources such as the Longitudinal Education Outcomes (LEO) provide some indication of the earnings of graduates and postgraduates, this does not capture the full value of the skills added to the economy. The dynamic nature of the science and technology sectors, coupled with the evolving demands of the labour market and the diversity of pathways for technical skills qualifications require more nuanced metrics than currently available to capture the true extent of upskilling achieved by scientific and technological advancement.

Employment generation through science and R&D activities is another critical area where detailed insights are lacking. The direct and indirect job creation resulting from scientific research, particularly in emerging fields and high-tech industries, is not adequately captured. This limits understanding of the role of science in fostering economic growth and job opportunities across different regions and sectors of the UK economy.

Finally, the non-monetised benefits of science – such as advancements in public health, environmental sustainability and societal wellbeing – while widely recognised, lack systematic quantification and analysis. These benefits often go unmeasured in conventional economic assessments, again highlighting a further area for research.

Image:
Offshore wind farm.
© iStock.com / LanceB.

BOX 6

Limitations of current R&D data collection in UK higher education, industry and the public non-profit sector

Higher education

Despite the higher education sector having relatively advanced data collection infrastructure, there are significant limitations when it comes to comprehending the nuances of the system. For example, while data on universities' licensing, patenting, disclosures, spin-offs and similar activities is available via the Higher Education Business Community Interactions Survey, these lack the granularity and context necessary to offer a comprehensive understanding of the sector's contributions to innovation and knowledge commercialisation. This includes understanding the specific areas of innovation, the disciplines that are most actively contributing to new discoveries, and the ways in which these innovations are being commercialised, whether through start-ups, licensing agreements, or partnerships with existing companies.

Likewise, although it is possible to quantify the number and value of interactions such as consultancy, contract research and the use of university facilities and equipment by industry as proxies for knowledge generation and exchange, this approach does not provide a complete picture of the knowledge flows taking place and their wider impacts.

Industry

UK industry plays a pivotal role in the R&D ecosystem, not just through direct research and innovation it performs, but also through increasing R&D demand from other sectors. This multifaceted relationship encompasses a range of activities from collaborative research projects to funding and licensing the outputs of academia and public and non-profit research organisations.

When assessing the quantifiable scientific contribution made by industry through science, there had been an increasingly significant discrepancy between reported R&D expenditures by the Office for National Statistics (ONS) and His Majesty's Revenue & Customs (HMRC). Currently, ongoing methodological changes by the ONS have led to a significant revision of the UK's business expenditure on R&D (BERD), especially highlighting the contributions from small and medium-sized enterprises (SMEs). Historically, R&D data collection efforts had been skewed towards larger corporations, whose activities were easier to track through business surveys and tax credit claims, with smaller businesses' R&D efforts largely underrepresented. Such methodological adjustments resulted in the upward revision of the 2020 R&D expenditure estimate from £26.9 billion to £43 billion.

Whilst such adjustment suggests that a considerable portion of R&D conducted by SMEs had been overlooked, concerns have arisen regarding a potential increase in the number of businesses that effectively broaden the definition of R&D, thereby exploiting tax credit incentives for activities that may not traditionally fall under R&D. The extent to which the discrepancy between tax credit claims and survey-detected R&D spending is attributable to both overlooked SME R&D activities and the broadening of R&D definitions for tax incentives will become clearer once the ONS produces a complete dataset based on its new sampling methodology[175].

In addition, the level of detail provided by BERD in relation to industry expenditure on R&D activities in the UK faces further shortcomings. BERD provides R&D expenditure based on the standard industrial classification (SIC) system, which has been criticised for lacking adaptability, and being unrepresentative of services and emerging industries. The static nature of the SIC system makes it challenging to accommodate changes in industries and technological advancements, leading to misclassification and inaccurate representation of economic activities that make it challenging to produce accurate sectoral breakdowns of where R&D is happening within the economy. Additionally, the over-generalisation inherent in SIC obscures important distinctions within industries, hindering policymakers' ability to develop targeted interventions.

Public and non-profit research organisations

The UK's R&D data collection infrastructure lacks a mechanism for systematically capturing and measuring the R&D activities performed by public and non-profit research organisations. This means that the knowledge generated, transferred and utilised for innovation-related purposes by these entities remains largely unquantified. Although there have been efforts to understand the role of these organisations within the R&D system[176], detailed insights into their specific contributions to regional and sectoral knowledge stocks, innovation, and productivity levels are hard to measure quantitatively and is likely to encompass both technical and conceptual difficulties.

These organisations operate across a wide array of fields, from social sciences to biomedical research, contributing not only through direct R&D activities but also through knowledge dissemination, policy influence and community engagement. Their contributions are diverse, extending beyond traditional R&D metrics to include social innovation, public engagement and the development of skilled research personnel.

Annex

Working Group members

The members of the Working Group involved in this report are listed below. Members acted in an individual and not a representative capacity, and declared any potential conflicts of interest. Members contributed to the project on the basis of their own expertise and good judgement.

Chair	
Professor Richard Jones FRS	Professor of Materials Physics and Innovation Policy, University of Manchester

Members	
Professor Diane Coyle CBE	Bennett Professor of Public Policy, University of Cambridge
Dr Jonathan Grant	Director, Different Angles Ltd
Dr Susan Guthrie	Director of Science and Emerging Tech, RAND Europe
Andy Haldane FRS	Chief Executive, Royal Society of Arts
Professor Jonathan Haskel CBE	Professor of Economics at Imperial College Business School, Imperial College London
Professor Paul Nightingale	Professor of Strategy at the Science Policy Research Unit, University of Sussex Business School, University of Sussex
Dr Dirk Pilat	Research Fellow, The Productivity Institute
Dr Anna Valero	Director of Growth at the Centre for Economic Performance, LSE

Royal Society staff	
Ellie Bloom	Data Analyst (until December 2023)
Hamish Evans	Research Analyst (until September 2023)
Thomas Frostick	Head of Policy
Timothy Rees Jones	Senior Policy Adviser and Science 2040 Programme Lead
Marcos Rodriguez	Senior Research Analyst (from December 2023)
Cagla Stevenson	Senior Policy Adviser (from January 2024)

Acknowledgements

The Royal Society would like to thank all those who contributed to the development of this project, including Sir Jon Kingman KCB FRS for his advice, Dr Sarah Cowan and Dr Eleanor Hopkins from the British Academy for supplying some of the text for Box 3, and Sarah Eibenschutz for her editorial support.

References

1. Leicester, A. and Crawford, R. Understanding the Returns to R&D, Frontier Economics. (2023).
2. OECD, *Frascati Manual 2015: Guidelines for Collecting and Reporting Data in Research and Experimental Development (OECD Publishing, Paris, 2015). Available from:* https://www.oecd.org/innovation/frascati-manual-2015-9789264239012-en.htm (accessed 30 April 2024).
3. Barrett, P. Hansen, N.J. Natal, J.M. and Noureldin, D. '*Why Basic Science Matters for Economic Growth: Public Investment in Basic Research Will Pay For Itself', IMF Blog, 6 October 2021,* https://www.imf.org/en/Blogs/Articles/2021/10/06/blog-ch3-weo-why-basic-science-matters-for-economic-growth (accessed 30 April 2021).
4. Corrado, C. Haskel, J. Jona-Lasinio, C. Iommi, M. 'Intangible Capital and Modern Economies', *Journal of Economic Perspectives,* **36**, 3-28 (2022)
5. Van Reenen, J. and Yang, X. (2024) *Cracking the Productivity Code: An International Comparison of UK Productivity, POID Special Report*, Centre for Economic Performance. Available from: https://poid.lse.ac.uk/PUBLICATIONS/abstract.asp?index=10566 (accessed 30 April 2024).
6. Yu, D. Rosenfeld, H. Gupta, A. (2023) The 'AI divide' between the Global North and the Global South, World Economic Forum Annual Meeting. Available at: https://www.weforum.org/agenda/2023/01/davos23-ai-divide-global-north-global-south/ (accessed 30 April 2024).
7. Saeed, S.A. and Masters, R.M. 'Disparities in Health Care and the Digital Divide', *Curr. Psychiatry Rep.* **23**, 61 (2021) (https://doi.org/10.1007%2Fs11920-021-01274-4)
8. ONS (2019), Exploring the UK's Digital Divide. Available from: https://www.ons.gov.uk/peoplepopulationandcommunity/householdcharacteristics/homeinternetandsocialmediausage/articles/exploringtheuksdigitaldivide/2019-03-04 (accessed 30 April 2024).
9. UNESCAP (2018) Inequality in Asia and the Pacific in the Era of the 2030 Agenda for Sustainable Development, Available from: https://www.unescap.org/publications/inequality-asia-and-pacific-era-2030-agenda-sustainable-development (accessed 30 April 2024).
10. Feijao, C. Flanagan, I. Van Stolk, C. and Gunashekar, S. (2021) The Global Digital Skills Gap: Current Trends and Future Directions, RAND Corporation. Available from: https://www.rand.org/pubs/research_reports/RRA1533-1.html (accessed 30 April 2024).
11. Jones, R.A.L. (2022) Science and Innovation Policy for Hard Times: An Overview of the UK's Research and Development Landscape, Productivity Insights Paper, The Productivity Institute. Available from: https://www.productivity.ac.uk/research/science-and-innovation-policy-for-hard-times-an-overview-of-the-uks-research-and-development-landscape/ (accessed 30 April 2024).
12. Agar, J. Science Policy under Thatcher. (UCL Press, 2019)
13. OECD/Eurostat, *Oslo Manual 2018: Guidelines for Collecting, Reporting and Using Data on Innovation, 4th Edition (OECD Publishing, Paris,2018). Available from:* https://www.oecd.org/science/oslo-manual-2018-9789264304604-en.htm (accessed 30 April 2024).
14. The British Academy, 'This is Shape', https://www.thebritishacademy.ac.uk/this-is-shape/ (accessed 26 June 2024).
15. OECD *op. cit.* (note 1).
16. The British Academy (2023) *Understanding SHAPE in R&D*. Available from https://www.thebritishacademy.ac.uk/documents/4812/Understanding_SHAPE_in_RD_-_bridging_the_evidence_gap.pdf (accessed 26 June 2024).
17. Bresnahan, T.F. and Trajtenberg, M. 'General Purpose Technologies 'Engines of growth'?', *Journal of Econometrics,* **65**, 83–108 (1995) (https://doi.org/10.1016/0304-4076(94)01598-T)
18. Jovanic, B. Rousseau, P.L. Handbook of Economic Growth, (Elsevier, 2005), vol.1, Chapter 18, p. 1181. Available from: https://doi.org/10.1016/S1574-0684(05)01018-X (accessed 30 April 2024).
19. OEC, *Optical Fibres and Cables. Available from:* https://oec.world/en/profile/hs/optical-fibres-and-cables (accessed 30 April 2024).
20. Haskel, J. and Westlake, S. *Capitalism without Capital: The Rise of the Intangible Economy. (Princeton University Press, 2018).*
21. Rosenberg, N. 'Why Do Firms Do Basic Research (with Their Own Money)?', *Research Policy,* **19**, 165–174 (1990) (https://doi.org/10.1016/0048-7333(90)90046-9)
22. Pisuke, H. and Kelli, A. 'Intellectual Property in an Innovation-based Economy' *Review of Central and East European Law*, **33**, 223–238 (2008) (https://doi.org/10.1163/092598808X262614)
23. Saravanan K.A. Panigrahi, M. Kumar, H. Rajawat, D. Nayak, S.S. Bhushan, B. Dutt, T. 'Role of Genomics in Combating COVID-19 Pandemic', *Gene*, **823**, 146387 (2022) (https://doi.org/10.1016/j.gene.2022.146387)

24. Saravanan K.A. Panigrahi, M. Kumar, H. Rajawat, D. Nayak, S.S. Bhushan, B. Dutt, T. *op.cit. (note 20)*
25. Corrado, C. Criscuolo, C. Kaskei, J. Himbert, A. Jona-Lasinio, C. (2021) New Evidence on Intangibles, Diffusion and Productivity, OECD Science, Technology and Industry Working Papers. Available from: https://doi.org/10.1787/de0378f3-en. (accessed 30 April 2024).
26. Rosenberg, N. Exploring the Black Box: Technology, Economics, and History (Cambridge University Press, 1994)
27. Lukasik, S. 'Why the ARPANET Was Built', *IEEE Annals of the History of Computing,* **33**, 4–21 (2010) (https://doi.org/10.1109/MAHC.2010.11)
28. Rosenberg, N. *op. cit.* (note 18)
29. Aitken, A. Rincon-Aznar, A. Marioni, L. (2021) From Ideas to Growth: Understanding the Drivers of Innovation and Productivity across Firms, Regions and Industries in the UK, National Institute for Economic and Social Research. Available from: https://assets.publishing.service.gov.uk/media/615d9a36e90e07198108144f/niesr-report.pdf (accessed 30 April 2024).
30. National Academies of Sciences, Engineering, and Medicine, *Commercial Aircraft Propulsion and Energy Systems Research: Reducing Global Carbon Emissions (The National Academies Press, Washington, DC, 2016). Available from:* https://doi.org/10.17226/23490 (accessed 30 April 2024).
31. Bloom, N. Van Reenen, J. and Williams, H. 'A Toolkit of Policies to Promote Innovation.' *Journal of Economic Perspectives,* **33**,163–84 (2019) (DOI: 10.1257/jep.33.3.163)
32. Teichgraeber, A. and Van Reenen, J. (2022) A Policy Toolkit to Increase Research and Innovation in the European Union, Centre for Economic Performance. Available from: https://cep.lse.ac.uk/_new/publications/abstract.asp?index=9125. (accessed 30 April 2024)
33. Leicester, A. and Crawford, R. (2023) Understanding the Returns to R&D, Frontier Economics. Available at: https://www.frontier-economics.com/uk/en/news-and-articles/news/news-article-i10181-understanding-the-returns-to-rd/ (accessed 30 April 2024).
34. Haskel, J. and Wallis, G. (2010) Public Support for Innovation, Intangible Investment and Productivity Growth in the UK Market Sector, Institute of Labor Economics. Available from: https://www.iza.org/publications/dp/4772/public-support-for-innovation-intangible-investment-and-productivity-growth-in-the-uk-market-sector (accessed 30 April 2024).
35. Bravo-Biosca, A. Westlake, S. Mulgan, G. Marston, L. (2013) Plan I for Europe, Nesta. Available at: https://www.nesta.org.uk/report/plan-i-for-europe/ (accessed 30 April 2024).
36. Bravo-Biosca, A. Westlake, S. Mulgan, G. Marston, L. *op. cit.* (note 31)
37. Bravo-Biosca, A. Westlake, S. Mulgan, G. Marston, L. *op. cit.* (note 31)
38. Arundel, A. Bordoy, C. and Kanerva, M. (2008) Neglected Innovators: How Do Innovative Firms That Do Not Perform R&D Innovate? Results of an Analysis of the Innobarometer 2007 Survey No. 215, INNO-Metrics.
39. The Royal Society (2020) Research and Innovation Clusters. Available from: https://royalsociety.org/topics-policy/publications/2020/research-and-innovation-clusters (accessed 30 April 2024).
40. Helmers, C. and Overman, H. (2013) My Precious! The Location and Diffusion of Scientific Research: Evidence from the Synchrotron Diamond Light Source, SERC, Centre for Economic Performance. Available from https://cep.lse.ac.uk/_new/publications/abstract.asp?index=4197 (accessed 30 April 2024)
41. Helmers, C. and Overman, H. *op. cit.* (note 36)
42. Moretti, E. 'The Effect of High-Tech Clusters on the Productivity of Top Inventors', *American Economic Review* **111**, 3328–75 (2021) (https://doi.org/10.1257/aer.20191277).
43. Frontier Economics (2023) Rate of Return to Investment in R&D. A Report for the Department of Science, Innovation and Technology. Available from: https://www.frontier-economics.com/media/015adtpq/rate-of-return.pdf (accessed 30 April 2024).
44. Soete, L. Verspagen, B. Ziesemer, T.H.W. 'Economic impact of public R&D: an international perspective', *Industrial and Corporate Change*, **31**, 1–18 (2022) (https://doi.org/10.1093/icc/dtab066)
45. Frontier Economics, *op. cit.* (note 39).
46. Soete, L. Verspagen, B. Ziesemer, T.H.W. *op. cit* (note 40).
47. Soete, L. Verspagen, B. Ziesemer, T.H.W. *op. cit* (note 40).
48. Frontier Economics, *op. cit.* (note 39).
49. Frontier Economics, *op. cit.* (note 39).
50. Bloom, N., Jones, C. I., Van Reenen, J., & Webb, M. 'Are Ideas Getting Harder to Find?', *American Economic Review*, **110**, 1104–1144 (2020) (https://doi.org/10.1257/aer.20180338)

51. Arora, A. Belenzon, S. Cioaca, L. C. Sheer, L. Zhang, H. (2023) The Effect of Public Science on Corporate R&D, National Bureau of Economic Research. Available from: https://www.nber.org/papers/w31899 (accessed 30 April 2024).
52. For example: Friedel R.D. A Culture of Improvement: Technology and the Western Millennium (MIT Press, 2007).
53. Beaudry, P. Doms, M. and Lewis, E. 'Should the Personal Computer be Considered a Technological Revolution? Evidence from U.S. Metropolitan Areas', *Journal of Political Economy,* **118 (2010) (**https://doi.org/10.1086/658371)
54. Feng, A. and Valero, A. 'Skills-Biased Management: Evidence from Manufacturing Firms', *The Economic Journal,* **130**, 1057–1080 (2020) (https://doi.org/10.1093/ej/ueaa005)
55. Valero A. (2021) Education and Economic Growth, Centre for Economic Performance. Available from: https://cep.lse.ac.uk/pubs/download/dp1764.pdf (accessed 30 April 2024).
56. Belt, V. Ri, A. Akinremi, T. (2021) The UK's Business R&D Workforce: Skills, Sector Trends and Future Challenges, Enterprise Research Centre. Available from: https://www.enterpriseresearch.ac.uk/wp-content/uploads/2021/09/ERC-Insight-The-UK%E2%80%99s-business-RD-workforce-Belt.Ri_.Akinremi.pdf (accessed 30 April 2024).
57. Lucking, B. Bloom, N. and Van Reenen, J. 'Have R&D Spillovers Declined in the 21st Century?', *Fiscal Studies,* **40**, 561–590 (2019) (https://doi.org/10.1111/1475-5890.12195)
58. The Royal Society (2022) Regional Absorptive Capacity: The Skills Dimension. Available from: https://royalsociety.org/topics-policy/publications/2022/absorptive-capacity/ (accessed 30 April 2024).
59. Peri, G. Shih, K. and Sparber, C. 'STEM Workers, H-1B Visas, and Productivity in US Cities', *Journal of Labor Economics,* **33**, (2015) (https://doi.org/10.1086/679061).
60. Directorate General for Research and Innovation (2017) The Economic Rationale for Public R&I Funding and its Impact*,* European Commission. Available from: https://data.europa.eu/doi/10.2777/047015. (accessed 30 April 2024).
61. The Royal Society, *op. cit.* (note 57)
62. Lex, 'Moderna: Searching For a Second Act After Covid', Financial Times, 13 September 2023, https://www.ft.com/content/46d61078-edbe-4e2a-922f-41bfdd132470 (accessed 30 April 2024).
63. Grant, J. and Buxton, M.J. 'Economic Returns to Medical Research Funding', *BMJ Open,* **8**, e022131 (2018) (https://doi.org/10.1136/bmjopen-2018-022131)
64. HM Government (2023) Integrated Review Refresh 2023: Responding to a More Contested and Volatile World. Available from: https://assets.publishing.service.gov.uk/media/641d72f45155a2000c6ad5d5/11857435_NS_IR_Refresh_2023_Supply_AllPages_Revision_7_WEB_PDF.pdf (accessed 30 April 2024).
65. The Royal Society (2023) New Horizons for Understanding Economic Consequences of Climate Change. Available from: https://royalsociety.org/-/media/policy/publications/2023/climate-change-economics-conference-report.pdf (accessed 30 April 2024).
66. Stern, N. *The Stern Review Report on the Economics of Climate Change* (Cambridge University Press, 2006).
67. For example: Cervantes, M. Criscuolo, C. Dechezlêpretre, A. Pilat, D. 'Driving low-carbon innovations for climate neutrality', *OECD Science, Technology and Industry Policy Papers,* **143 (2023) (**https://doi.org/10.1787/8e6ae16b-en)
68. Stern, N. and Valero, A. 'Innovation, Growth and the Transition to Net Zero Emissions', *Research Policy,* **50, 104293 (2021) (**https://doi.org/10.1016/j.respol.2021.104293)
69. Zenghelis, D. Serin, E. Stern, N. Valero, A. Van Reenen, J. Ward, B. (2024) Boosting growth and productivity in the United Kingdom through investment in the sustainable economy, Grantham Research Institute on Climate Change and the Environment. Available from: https://www.lse.ac.uk/granthaminstitute/publication/boosting-growth-and-productivity-in-the-united-kingdom-through-investments-in-the-sustainable-economy/ (accessed 1 May 2024).
70. Dasgupta, P. *The Economics of Biodiversity: The Dasgupta Review. (HM Treasury, 2021)*
71. OECD (2011) *Demand-side innovation policies*.
72. Frontier Economics, *op. cit.* (note 39).
73. Oxford Economics (2020) The Relationship between Public and Private R&D Funding, *BEIS*.
74. Science Museum Group, *Section of TAT-8 transatlantic optical fibre cable, 1989, Science Museum Group Collection Online. Available from:* https://collection.sciencemuseumgroup.org.uk/objects/co34077/section-of-tat-8-transatlantic-optical-fibre-cable-1989-optical-fibre (accessed 1 May 2024)
75. Lincoln, J. Lohmann, A. Mcleod, A. (2023), UK Photonics 2023: The Hidden Economic Engine, Photonics Leadership Group. Available from: https://photonicsuk.org/wp-content/uploads/2023/06/UK_Photonics_2023_Hidden_Economic_Engine.pdf (accessed 1 May 2024).
76. Lincoln, J. Lohmann, A. Mcleod, A. *op. cit.* (note 74)

77. Schwartz, M. and Hayes, J. 'A History of Transatlantic Cables', *IEEE Communications Magazine,* **46**, 42–48 (2008) (doi: 10.1109/MCOM.2008.4623705)
78. Farrell, H. and Newman, A. *Underground Empire* (Random House, 2023)
79. Optoelectronics Research Centre*, Who We Are? Available from:* https://www.orc.soton.ac.uk/the-early-years (accessed 1 May 2024).
80. For example: Gambling, W.A. 'Possibilities of optical communications', *British Association for the Advancement of Science,* **198**, 776 (1964)
81. Kao, K.C. and Hockham, G.A. 'Dielectric-fibre surface waveguides for optical frequencies', *Proc. I.E.E.,* **113**, 1151-1158 (1966) (https://doi.org/10.1049/piee.1966.0189)
82. Optoelectronics Research Centre*, History of the ORC?*, Available from: https://www.orc.soton.ac.uk/history-of-the-orc (accessed 1 May 2024).
83. Optoelectronics Research Centre, 'Obituary for Professor Alec Gambling – first Director of Southampton's Optoelectronics Centre', 27 January 2021, https://www.orc.soton.ac.uk/news/6902 (accessed 1 May 2024).
84. University of Southampton, *Research Group: Fibres and Communications*, available from: https://www.southampton.ac.uk/research/groups/fibres-communications (accessed 1 May 2024).
85. NobelPrize.org, Press Release, The Nobel Prize in Physics, 6 October 2009. Available from: https://www.nobelprize.org/prizes/physics/2009/press-release/ (accessed 1 May 2024).
86. NobelPrize.org, *op. cit.* (note 84)
87. REF 2021 (2021) Hollow Core Fibres: Delivering Economic Impact Via the Commercialisation of a Disruptive Optical Fibre Technology for Next-Generation Communications Systems, Impact Case Study Database. Available from: https://results2021.ref.ac.uk/impact/6168e649-490b-4e7b-8497-e532259b80ca?page=1 (accessed 1 May 2024).
88. https://www.southampton.ac.uk/research/institutes-centres/hollow-core-fibre
89. https://www.orc.soton.ac.uk/marco-petrovich-interview
90. REF 2021 (2021) *op.cit.* (note 85)
91. Optoelectronics Research Centre, Interview with Professor Marco Petrovich, Lumensity Ltd. Available from: https://www.orc.soton.ac.uk/marco-petrovich-interview (accessed 1 May 2024).
92. Optoelectronics Research Centre, *op. cit.* (note)
93. 'Microsoft Snaps Up Southampton Spin-Out Lumenisity', optics.org, 13 December 2022, https://optics.org/news/13/12/16 (accessed 1 May 2024).
94. REF 2021 (2021) *op.cit.* (note 87)
95. REF 2021 (2021) *op.cit.* (note 87)
96. 'BT Kicks Off Trials of Revolutionary New Optical Fibre', BT Group Newsroom, 1 June 2021, https://newsroom.bt.com/bt-kicks-off-trials-of-revolutionary-new-optical-fibre/ (accessed 1 May 2024).
97. Lincoln, J. Lohmann, A. Mcleod, A. *op. cit.* (note 74)
98. Lincoln, J. Lohmann, A. Mcleod, A. *op. cit.* (note 74)
99. Bouwfonds (2016) Fibre-Optics: 21st Century Communication Backbone. Available from: https://www.bouwfondsim.com/wp-content/uploads/2017/06/Fibre-optics-21st-century-communication-backbone.pdf (accessed 1 May 2024)
100. Statista 2024, *Number of Internet Users Worldwide from 2005 to 2023. Available from:* https://www.statista.com/statistics/273018/number-of-internet-users-worldwide/ (accessed 1 May 2024).
101. Sinha, S. (2023) State of IoT 2023: Number of Connected IoT devices growing 16% to 16.7 billion globally, IOT Analytics. Available from: https://iot-analytics.com/number-connected-iot-devices/ (accessed 1 May 2024).
102. Infiniti Research Limited (2024) Fiber Optics Market Global Outlook: 2023–2027. Available from: https://www.reportlinker.com/p04961848/Global-Fiber-Optics-Market.html (accessed 1 May 2024).
103. Data from 2021, *op.cit.* (note 14)
104. NobelPrize.org, *op. cit.* (note 85)
105. Fibercore, Humanetics Group, https://fibercore.humaneticsgroup.com/ (accessed 1 May 2024).
106. Optoelectronics Research Centre, *op.cit.* (note 91)
107. Optoelectronics Research Centre, *op.cit.* (note 91)
108. Optoelectronics Research Centre, https://www.orc.soton.ac.uk/ (accessed 1 May 2024)
109. Optoelectronics Research Centre, *op.cit.* (note 91)

110. Optoelectronics Research Centre, *op.cit.* (note 91)

111. REF 2021 (2021) *op.cit.* (note 87)

112. Lincoln, J. Lohmann, A. Mcleod, A. *op. cit.* (note 75)

113. DSIT (2024) The UK Science and Technology Framework. Available from: https://www.gov.uk/government/publications/uk-science-and-technology-framework/the-uk-science-and-technology-framework (accessed 1 May 2024).

114. DSIT and UKRI, Press Release, UK Joins Leading Nations to Form New Telecoms Coalition and Invests £70 Million in New Future Telecoms Technologies, 5 October 2023. Available from: https://www.gov.uk/government/news/uk-joins-leading-nations-to-form-new-telecoms-coalition-and-invests-70-million-in-new-future-telecoms-technologies (accessed 1 May 2024).

115. European Commission, Press Release, Commission Presents New Initiatives with Gigabit Infrastructure Act Proposal, 23 February 2023. Available from: https://digital-strategy.ec.europa.eu/en/news/commission-presents-new-initiatives-gigabit-infrastructure-act-proposal (accessed 1 May 2024).

116. 'Commission Implementing Reglation (EU) 2022/72 of 18 January 2022 imposing definitive countervailing duties on imports of optical fibre cables originating in the People's Republic of Chia and amending Implementing Regulation (EU) 2021/2011 imposing a definitive anti-dumping duty on imports of optical fibre cables originating in the People's Republic of China' (OJ L12 19.1.2022, p. 34). Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32022R0072 (accessed 1 May 2024).

117. Atli, K.C. and Karaman, I. 'A Short Review on the Ultra-High Temperature Mechanical Properties of Refractory High Entropy Alloys', *Frontiers in Metals and Alloys,* **2**, 1135826 (2023) (https://doi.org/10.3389/ftmal.2023.1135826)

118. NASA Technology Transfer Program, Materials and Coatings, High-Temperature Ni-Based Superalloy Composition. Available from: https://technology.nasa.gov/patent/LEW-TOPS-152#:~:text=Innovators%20at%20the%20NASA%20Glenn,temperatures%20above%20700%C2%B0C (accessed 1 May 2024).

119. University of Cambridge, 'Super' Superalloys: Hotter, Stronger, For Even Longer, 1 September 2008, https://www.cam.ac.uk/research/news/super-superalloys-hotter-stronger-for-even-longer (accessed 1 May 2024).

120. http://218.28.6.71:81/Qikan/Article/Detail?id=1001069234&from=Qikan_Search_Index

121. University of Cambridge Rolls-Royce UTC, *About*, https://www.rrutc.msm.cam.ac.uk/about-us (accessed 1 May 2024).

122. University of Cambridge Rolls-Royce UTC, *History,* https://www.rrutc.msm.cam.ac.uk/about-us/History (accessed 1 May 2024).

123. University of Birmingham, High Temperature Research Centre (HTRC), https://www.birmingham.ac.uk/research/activity/htrc (accessed 1 May 2024).

124. University of Birmingham, High Temperature Research Centre (HTRC), *About*, https://www.birmingham.ac.uk/research/activity/htrc/about.aspx (accessed 1 May 2024).

125. University of Birmingham, 'The University of Birmingham and Rolls-Royce partnership wins prestigious award', 29 September 2022, https://www.birmingham.ac.uk/news/2022/the-university-of-birmingham-and-rolls-royce-partnership-wins-prestigious-award (accessed 1 May 2024).

126. University of Birmingham, 'The University of Birmingham and Rolls-Royce partnership wins prestigious award', 29 September 2022, https://www.birmingham.ac.uk/news/2022/the-university-of-birmingham-and-rolls-royce-partnership-wins-prestigious-award (accessed 1 May 2024).

127. University of Birmingham, 'University of Birmingham and Rolls-Royce receive Queen's Anniversary Prize', 22 February 2022, https://www.birmingham.ac.uk/news/2024/university-of-birmingham-and-rolls-royce-receive-queens-anniversary-prize#:~:text=Professor%20Marika%20Taylor%20and%20Professor,longstanding%20partnership%20with%20Rolls%2DRoyce (accessed 1 May 2024).

128. University of Birmingham, *op.cit*. (note 125)

129. Royal Academy of Engineering, 'Sustainable Aviation Collaboration Wins Best UK Industry-Academia Partnership for 2022', 29 September 2022, https://raeng.org.uk/news/sustainable-aviation-collaboration-wins-best-uk-industry-academia-partnership-for-2022 (accessed 1 May 2024).

130. University of Birmingham, *op.cit*. (note 125)

131. International Trade Administration, *United Kingdom – Country Commercial Guide, Aerospace and Defence*, 3 November 2023. Available from: https://www.trade.gov/country-commercial-guides/united-kingdom-aerospace-and-defense (accessed 1 May 2024).

132. Vallas, S.P. Kleinman, D.L Biscotti, D. *Structures and the Making of US State of Innovation (Routledge, 2015)*

133. Precedence Research, *Biotechnology Market Size 2023 to 2033, February 2024*. Available from: https://www.precedenceresearch.com/biotechnology-market (accessed 2 May 2024).

134. Wade, R.H. (2014) Transforming Economies, 14: The Paradox of US Industrial Policy: The Developmental State in Disguise'. Available at: https://jacksondetoni.files.wordpress.com/2019/04/making-industrial-policy-work.pdf (accessed 2 May 2024)

135. Owen, G. and Hopkins, M.H. *Science, the State, and the City: Britain's Struggle to Succeed in Biotechnology* (Oxford University Press, Oxford, 2016). Available from: https://doi.org/10.1093/acprof:oso/9780198728009.001.0001 (accessed 2 May 2024).

136. Cohen, S.N. Chang, A.C.Y. Boyer, H.W. and Helling, R.B. *Construction of Biologically Functional Bacterial Plasmids In Vitro*, Proc. Nat. Acad. Sci. **70, 3240–3244 (1973) (**https://doi.org/10.1073%2Fpnas.70.11.3240)

137. Hall, K.T. Insulin, The Crooked Timber: A History from Thick Brown Muck to Wall Street Gold (Oxford University Press, Oxford, 2021)

138. Tom Perkins of Kleiner Perkins Venture Capital firm, as quoted in Owen, G. and Hopkins, M.H. *op.cit.* (note 119)

139. Fortune Business Insights (2024) Human Insulin Market Size. Available from: https://www.fortunebusinessinsights.com/industry-reports/human-insulin-market-100395 (accessed 2 May 2024).

140. Vallas, S.P. Kleinman, D.L Biscotti, D. *op.cit.* (note 116)

141. Institute of Medicine (US) Committee on Technological Innovation in Medicine, Incentives and Focus in University and Industrial Research: The Case of Synthetic Insulin, Sources of Medical Technology: Universities and Industry (National Academies Press, Washington DC, 1995). Available from: https://www.ncbi.nlm.nih.gov/books/NBK232052/ (accessed 2 May 2024)

142. Owen, G. and Hopkins, M.H. op.cit. (note 119)

143. Smith, J.O. and Powell, W. Knowledge Networks in the Boston Biotechnology Community, in Science as an Institution and the Institutions of Science, January 2002, University of Siena

144. Hall, K.T. *op.cit* (note 121)

145. US Congress, Office of Technology Assessment (1984) *Commercial Biotechnology: An International Analysis*. Available from: https://ota.fas.org/reports/8407.pdf (accessed 2 May 2024).

146. Jasanoff, S. Designs on Nature: Science and Democracy in Europe and the United States (Princeton University Press, Princeton, 2005)

147. National Research Council (US), Intellectual Property Rights and the Dissemination of Research Tools in Molecular Biology: Summary of a Workshop Held at the National Academy of Sciences, February 15–16, 1996. (National Academies Press, Washington DC, 1997) Available from: https://www.ncbi.nlm.nih.gov/books/NBK233539/ (accessed 2 May 2024).

148. Vallas, S.P. Kleinman, D.L Biscotti, D. *op.cit.* (note 116)

149. Rasmussen, N. *Gene Jockeys: Life Science and the Rise of Biotech Enterprise* (John Hopkins University Press, Baltimore, 2014)

150. Hall, K.T. *op.cit* (note 121)

151. Bliss, M. *The Discovery of Insulin (University of Chicago Press, Chicago, 2013).*

152. Hall, K.T. *op.cit* (note 121)

153. Kroeber, A.L. 'The Superorganic', *American Anthropologist,* **19**, 163–213 (1917)

154. Hall, K.T. *op.cit* (note 121)

155. Rosenfeld, L. 'Insulin: Discovery and Controversy', *Clinical Chemistry,* **48**, 2270–88 (2002) (https://doi.org/10.1093/clinchem/48.12.2270)

156. Hall, K.T. *op.cit* (note 121)

157. Rosenberg, N. *op.cit.* (note 20)

158. Vecchio, I. Tornali, C. Bragazzi, N.L. Martini, M. 'The Discovery of Insulin: An Important Milestone in the History of Medicine', *Frontiers in Endocrinology,* **9**, 613 (2018) (https://doi.org/10.3389/fendo.2018.00613)

159. Hall, K.T. *op.cit* (note 121)

160. Bradwel, S. Tattersall, R. 'The Pissing Evil: A Comprehensive History of Diabetes Mellitus', *Social History of Medicine,* **32**, 652–654 (2019) (https://doi.org/10.1093/shm/hkz036)

161. Hall, K.T. *op.cit* (note 121)

162. Hall, K.T. *op.cit* (note 121)

163. Barbetti, F. and Taylor, S.I. ‘Insulin: Still a Miracle after All These Years’, *The Journal of Clinical Investigation,* **129**, 3045–47, (2019) (https://doi.org/10.1172/JCI130310)

164. Eshe Nelson, ‘Novo Nordisk Tilts G.D.P. In Denmark’, The New York Times, 30 August 2023

165. Diabetes UK, *How Many People in the UK Have Diabetes? Available from:* https://www.diabetes.org.uk/professionals/position-statements-reports/statistics (accessed 2 May 2024).

166. Hex, N. Bartlett, C. Wright, D. Taylor, M. Varley, D. ‘Estimating the Current and Future Costs of Type 1 and Type 2 Diabetes in the UK, Including Direct Health Costs and Indirect Societal and Productivity Costs’, *Diabetes Medicine,* **29**, 855–862 (2012) (https://doi.org/10.1111/j.1464-5491.2012.03698.x)

167. University of York, *Diabetes and the NHS, National Spotlight for York Research into Cost Of Diabetes Treatment. Available from:* https://www.york.ac.uk/news-and-events/features/diabetes-nhs/ (accessed 2 May 2024).

168. Bakkila, B.F. Basu, S. and Lipska, K.J. ‘Catastrophic Spending On Insulin In The United States, 2017–18’, *Health Affairs,* **41**, 1053–60 (2022) (https://doi.org/10.1377/hlthaff.2021.01788)

169. Beran, D. and Yudkin, J.S. ‘Diabetes Care in Sub-Saharan Africa’, *The Lancet,* **368**, 1689–95 (2006) (https://doi.org/10.1016/S0140-6736(06)69704-3)

170. Hall, K.T. *op.cit* (note 121)

171. Richter, B. and Neises, G. ‘“Human” Insulin versus Animal Insulin in People with Diabetes Mellitus’, *Cochrane Database of Systematic Reviews,* **1** (2005) (https://doi.org/10.1002/14651858.CD003816.pub2)

172. Rasmussen, N. *op.cit.* (note 133)

173. Horvath, K. Jeitler, K. Berghold, A. Ebrahim, S.H. Gratzer, T.W. Plank, J. Kaiser, T. Pieber, T.R. Siebenhofer, A. ‘Long-Acting Insulin Analogues versus NPH Insulin (Human Isophane Insulin) for Type 2 Diabetes Mellitus’, *The Cochrane Database of Systematic Reviews,* **2** (2007) (https://doi.org/10.1002/14651858.CD005613.pub3)

174. UKRI (2024) Higher Education Statistics Agency’s Higher Education Business and Community Interaction Survey. Available from: https://www.ukri.org/councils/research-england/our-funds-for-research-and-knowledge-exchange/the-higher-education-business-and-community-interaction-survey/ (accessed 2 May 2024).

175. Jones, R.A.L. *op.cit.* (note 10)

176. The Royal Society (2020) The Role of Public and Non-Profit Research Organisations in the UK Research and Innovation Landscape. Available from: https://royalsociety.org/topics-policy/publications/2020/uk-research-organisations/ (accessed 2 May 2024).

The Royal Society is a self-governing Fellowship of many of the world's most distinguished scientists drawn from all areas of science, engineering, and medicine. The Society's fundamental purpose, as it has been since its foundation in 1660, is to recognise, promote, and support excellence in science and to encourage the development and use of science for the benefit of humanity.

The Society's strategic priorities emphasise its commitment to the highest quality science, to curiosity-driven research, and to the development and use of science for the benefit of society. These priorities are:

- The Fellowship, Foreign Membership and beyond
- Influencing
- Research system and culture
- Science and society
- Corporate and governance

For further information
The Royal Society
6 – 9 Carlton House Terrace
London SW1Y 5AG

T +44 20 7451 2500
E science.policy@royalsociety.org
W royalsociety.org

Registered Charity No 207043

ISBN: 978-1-78252-719-0
Issued: June 2024 DES8894