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RETURNS TO PUBLIC R&D

Report for the Department for Science, Innovation and Technology (DSIT)

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Executive Summary

Context

It is important for the UK government to have robust evidence on the rate of return to public research and development (R&D) spending. The government invests significant sums of public money in R&D. The 2021 Spending Review confirmed plans to increase public R&D investment from £14.8 billion in 2021-22 to £20 billion per year by 2024-25.[1] Appraisal of future public R&D investment requires high quality evidence on the returns that this may generate.

Existing evidence on the rate of return to public R&D merited updating. Previous empirical evidence for the UK produced in 2014 using data from 1992 to 2007 suggested a rate of return to public R&D, in terms of increased annual private sector productivity, of around 20%.[2] Since that time the quality of data available with which to estimate returns have improved. Furthermore, the period since 2008 has seen productivity growth slow while levels of R&D have remained high, prompting questions as to whether the rate of return to public R&D might have changed. DSIT therefore commissioned Frontier Economics to provide updated evidence on the rate of return to public R&D investment.

This study encompasses both new empirical estimates of the rate of return to public R&D – defined as R&D that is both funded by and conducted in the public sector – and qualitative case studies to explore wider mechanisms through which public R&D investment can generate returns.

Estimated returns to public R&D

The new empirical results indicate that public R&D generates economically significant positive returns in terms of increasing private sector productivity growth.

Rates of return are inherently challenging to estimate, and the quantified rates of return should be interpreted cautiously. The range of results across different specifications in this report underline the uncertainty that is present in any single estimate. In addition, the estimates produced in this work may be biased upwards if:

- they capture the impact of measurement errors (there is known mis-measurement of private R&D, for example);[3]
- there are other omitted factors that correlate positively with both productivity and public R&D investment or the extent to which different sectors engage with public R&D.

[1] HM Treasury (2021), Autumn Budget and Spending Review 2021.

[2] Haskel et al. (2014); and Goodridge et al. (2015).

[3] Office for National Statistics (2024) Business Enterprise Research and Development, UK: 2022.

With such caveats in mind, the current estimates suggest an average rate of return to public R&D of up to 40% could be enjoyed 6 years after the investment is made.[4] In other words, £100m of public R&D investment could be expected on average to yield, in 6 years' time, an increase in annual private sector productivity worth £40m; annual gross value added (GVA) in the private sector is £40m higher as a result of the £100m public R&D investment. The £40m increase in annual GVA persists over time, and if anything the estimates suggest that an even greater return could be experienced over a longer time period.

The present results are higher than previous estimates for the UK which used a similar methodology. Replicating the previous estimates' methodology as closely as possible using revised data yields results that are different to those published previously. The differences between the current and previous results are believed to be largely due to revisions to macroeconomic data. In particular, revisions to GVA at the industry level have led to a very different pattern of TFP growth across industries and over time compared to the pattern that was documented a decade ago.

The methodology used to quantify the rate of return uses industry level data to examine the relationship between TFP growth in private sector industries and public R&D investment. This is the same approach as that used to produce previous estimates of the rate of return in the UK that were first published in Haskel et al. (2014) and subsequently in Goodridge et al. (2015). The present work updates and extends this approach, in particular **using data for a more granular breakdown of industries than was previously possible** (40 industries compared to 6) and available for a longer time period (1998-2019 compared to 1992-2007).

Differences in returns to public R&D over time are explored. The estimated results broadly suggest that the returns to public R&D have increased since the financial crisis. However, it is unclear what the drivers of this are, and therefore this is worthy of further exploration in future before concrete conclusions are drawn. Differences in returns to public R&D according to who conducts the R&D are also explored, but the results are not conclusive.

The estimated returns should be interpreted cautiously for the following reasons:

- **This study provides an estimate for the average rate for return, and not the return that would be expected from any individual R&D investment.** Some R&D investments will turn out to have little to no benefit, while some will turn out to be groundbreaking and generate significant productivity improvements relative to the initial investment.
- **The estimated rate of return understates the true return to public R&D because public R&D also stimulates private sector R&D which generates positive returns.** There is existing literature that provides evidence that public R&D spurs private R&D,[5] and that private R&D on average has positive returns.[6] This is not included in the estimated return to public R&D here, because the methodology used considers the impact

[4] The estimates vary across specifications. The exact estimates produced by this study should be interpreted with caution.

[5] Oxford Economics (2020).

[6] Frontier Economics (2023).

of private sector R&D and public R&D on productivity each in isolation. The impact of private R&D on TFP is estimated and controlled for, but the methodology does not attempt to attribute any of the private R&D (or the subsequent impact on TFP) back to public R&D when calculating the return to public R&D, even though in practice some private R&D may have only occurred as a result of public R&D undertaken.

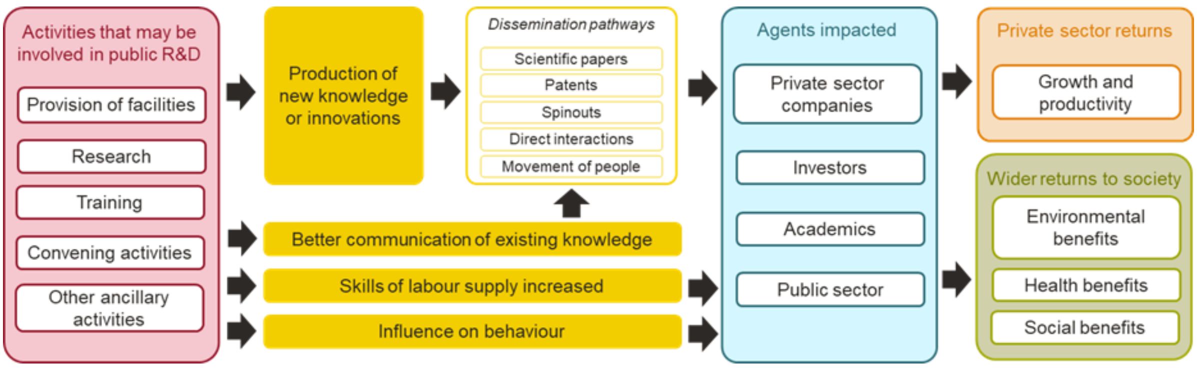
- **The estimated returns do not capture wider social benefits that are not reflected in private sector productivity, such as beneficial impacts on the environment or health.** The pathways through which some of these benefits are generated are explored in this study.

The estimates of the rate of return generated in this work should therefore be used in government appraisals as valuable context, alongside and not in place of individual project appraisal consistent with Green Book guidance.

Mechanisms through which returns are generated

There are many potential mechanisms through which public R&D generates returns – both returns to private sector productivity (as estimated in this work) and wider returns to society. An illustration of these potential mechanisms is set out in Figure 1.

Figure 1 Overview of mechanisms through which public R&D may generate returns



Source: Frontier Economics.

Evidence from two qualitative case studies provides real world examples which characterise mechanisms linking public R&D to private sector productivity and other returns to public R&D. These case studies are:

- "Beyond Blue": A £1 million grant from the Engineering and Physical Sciences Research Council (EPSRC) for semiconductor research conducted at the Centre for Gallium Nitride at the University of Cambridge between 2015 and 2020.
- "SPRINT": The Space Research and Innovation Network for Technology, a £7.5 million project funded primarily by Research England between 2018 and 2022, that sought to connect SMEs with space-related expertise in participating UK universities and provided

small grant funding to enable SMEs to purchase universities' input on collaborative R&D projects.

The case studies are provided respectively in annexes Annex E and Annex F .

Specific examples are able to be drawn from these case studies that evidence six distinct pathways through which positive returns are generated:

- The R&D produces new knowledge, or new applications of knowledge, that is transmitted to the private sector through the direct collaboration of a private partner in the R&D project.
- The R&D produces new knowledge that is transmitted to the private sector without the involvement of a private sector project partner.
- The R&D involves training and skills development which increases the productivity of workers in the public or private sectors.
- The R&D results in end products or services that have wider benefits to society, such as benefits to the environment or to health.
- The R&D has other influences on behaviour that result in wider benefits to society.
- The R&D has other influences on behaviour that increases the production of new knowledge or the faster adoption of knowledge, or may do so in future.

1 Introduction

1.1 Context for this work

The UK government invests significant sums of public money in research and development (R&D). The 2021 Spending Review confirmed plans to increase public R&D investment from £14.8 billion in 2021-22 to £20 billion per year by 2024-25.[7]

In justifying investment in R&D, it is important for the Department for Science, Innovation and Technology (DSIT) to have robust evidence on the likely rate of return. The existing evidence base on the return to public R&D in the UK is relatively limited.[8] Previous research that sought to estimate the rate of return to public R&D investment in the UK has been interpreted as implying an average rate of return of around 20%.[9] However, that research was based on data up to 2007 and the estimates of the return to public R&D may no longer be up to date, not least given the slowdown in UK productivity seen since the financial crisis.

DSIT commissioned Frontier Economics to provide new and updated evidence on the rate of return to public investment in R&D. There were three purposes to the study:

- To produce an **updated estimate** of the rate of return to public investment in R&D;
- To examine **how the rate of return varies** according to different factors such as time and who conducts the R&D;
- To **explore the mechanisms** through which public R&D investment can generate returns.

1.2 Estimating rates of return

This report estimates the rate of return to public R&D – defined as R&D that is both funded by and conducted in the public sector using industry level data to quantify the relationship between public R&D and total factor productivity (TFP) growth in the private sector.[10]

Previous estimates of the rate of return to public R&D in the UK produced using this approach were published in Haskel et al. (2014) and Goodridge et al. (2015) (hereafter referred to as "HHBM/GHHW"). Their results, based on data from 1992 to 2007, have been widely interpreted as suggesting a statistically significant rate of return to public R&D of about 20%.

An updated estimate of the rate of return to public R&D is of particular value given changes both to public R&D and productivity since the financial crisis. Figure 2 illustrates how real public R&D and total factor productivity in the private sector have changed over the time

[7] HM Treasury (2021), Autumn Budget and Spending Review 2021.

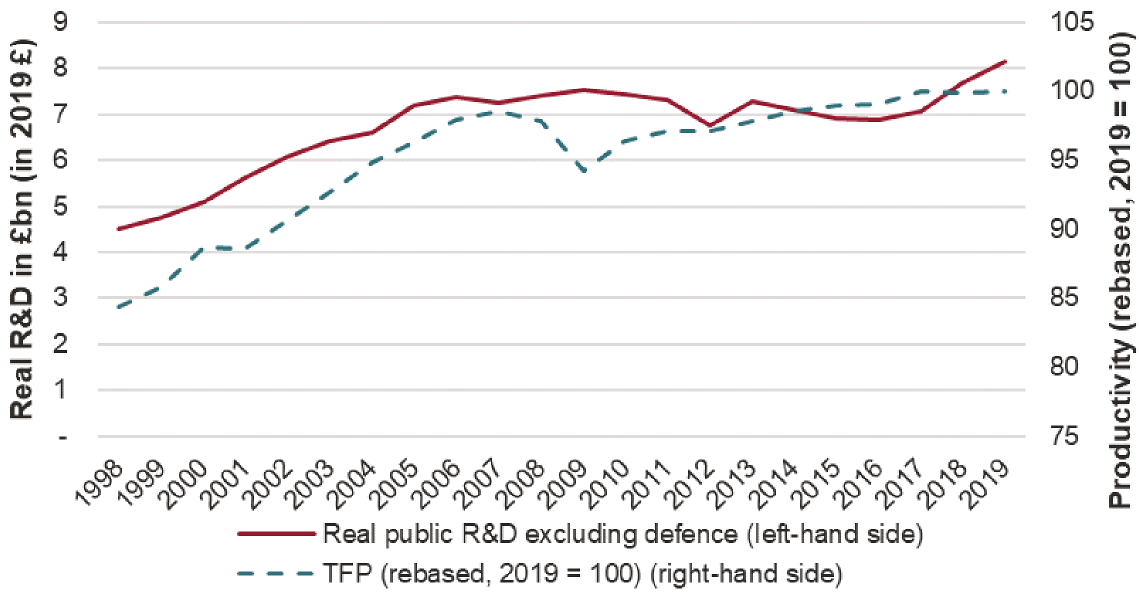
[8] Earlier work from Frontier Economics found limited high-quality quantitative evidence on the returns to R&D conducted by the public sector: Understanding the returns to R&D | Frontier Economics (frontier-economics.com).

[9] Haskel et al. (2014); and Goodridge et al. (2015).

[10] Total Factor Productivity (TFP) is a measure of productivity. It is used to understand how efficiently one (e.g. an industry or a national economy) can generate outputs with a given level of input factors such as labour and capital.

horizon of this study. Since 2007, **productivity growth has slowed**, while the level of real **public R&D has remained high** (and towards the end of the period began to grow again). This has raised questions about the continued validity of older estimates of the rate of return to public R&D.

Figure 2 Trends in UK total factor productivity and real-terms public R&D, 1998 to 2019



Source: Frontier Economics calculations based on ONS. Public R&D data available from GERD. Productivity data available from the ONS.

Note: Public R&D defined as R&D that is both funded and performed by the public sector excluding defence-related R&D (see section 2.2.3 for further details). Nominal R&D deflated using GDP deflator. Productivity data is for "Multi-factor productivity: annual indices and growth rates (industries P and Q suppressed)". TFP = Total Factor Productivity. Time period restricted to 1998-2019 due to data availability.

New evidence is also important given the revisions to UK macroeconomic data over the past decade. Methodological improvements have impacted the pattern of industry gross value added (GVA) growth, which in turn markedly changed the picture of TFP growth across industries.[11]

This present study sought to update estimates to a more recent time period using revised macroeconomic data, estimating the rate of return to R&D over a period that extends beyond the financial crisis (2008 onwards).

Furthermore, the present study sought to improve on previous estimates through the use of more granular industry data (up to 40 sectors, compared to the 6 broad sectors used in

[11] For example, Blue Book 2021 introduced double deflation of GVA and the use of an annual Supply Use Table (SUT) framework for inflation-adjusted (real) GDP estimates. These changes resulted in significant revisions to industry-level GVA estimates. More information available via the ONS (available at: Indicative impact of a new framework including double deflation on industry volume estimates of GDP – Office for National Statistics (ons.gov.uk)) and the Bank of England (available at: Bank of England Monetary Policy Report November 2021).

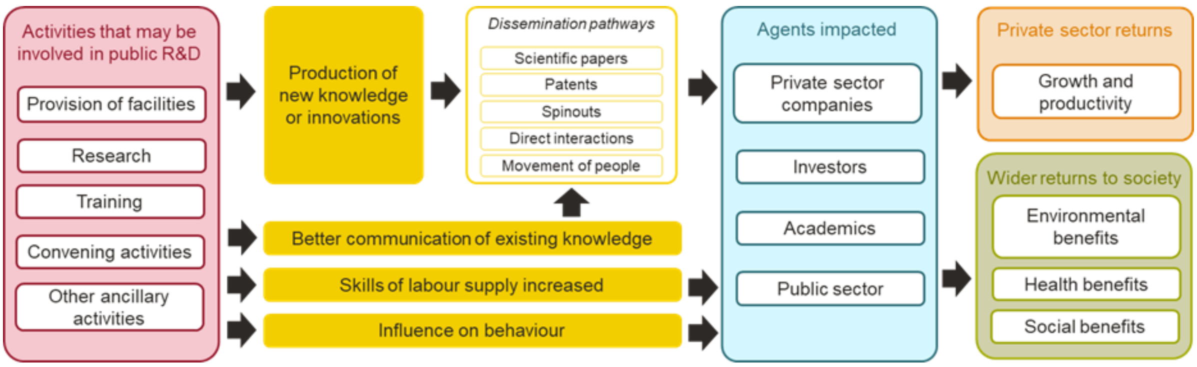
HHBM/GHHW).[12] The additional time and sectoral variation available should increase the precision and robustness with which returns can be estimated, as well as opening up the possibility of exploring variation in the rate of return by key characteristics of interest.

The quantitative econometric approach is presented in **section 2**, which also includes a brief summary of alternative approaches used in the literature. **Section 3** discusses the results of the quantitative rate of return estimation.

1.3 Exploring mechanisms through which public R&D generates returns

The econometric approach taken in this study produces an estimate of the return to public R&D in terms of the impact on private sector productivity, but it does not shed light on the mechanisms through which that return is generated. Figure 3 illustrates various mechanisms through which public R&D may have an impact on private sector productivity. It also shows how public R&D may have wider social benefits that are not reflected in private sector productivity, such as beneficial impacts on the environment or health.

Figure 3 Overview of mechanisms through which public R&D may generate returns



Source: Frontier Economics.

To provide evidence on these aspects, the present study also includes two case studies of public R&D projects, which were explored through desk research and interviews with key stakeholders.

Section 4 discusses the mechanisms through which public R&D may be expected to generate returns, and summarises the evidence of these mechanisms provided by the case studies. A detailed write up of each case study is provided in Annex E and Annex F .

[12] While the HHBM/GHHW studies consider seven sectors, their estimates are derived using only six.

2 Quantifying the rate of return: methodology

Summary

The rate of return to public R&D is quantified by **estimating the relationship between public R&D and total factor productivity growth in the private sector**. This is estimated using **industry level data covering 40 industries over the time period 1998 to 2019**. Proxies for the relative size of spillovers from public R&D to the private sector are used to capture the extent to which the rate of return to public R&D varies across sectors. The time spent between public R&D investment and its impact on private sector productivity is modelled using 3-year, 6-year and 10-year lags.

The methodology used here is largely analogous to that used previously to estimate the rate of return to public R&D in the UK. The main differences are the data sources (which are more recent), the granularity of the industry data used (40 industries rather than 6), and the time period examined (1998-2019 rather than 1992-2007).

Public R&D is defined as R&D that is both funded by and conducted in the public sector (excluding defence), and therefore the rate of return estimated in this study relates to this subset of public funded R&D only.

The return estimated is the **impact on private sector productivity only. It excludes any impact on public sector productivity or any impact on wider social outcomes**. It also excludes any impact on private sector productivity that arises as a result of the public R&D stimulating additional private R&D (that itself has impacts on productivity).

2.1 Estimation methodology

This research estimates the rate of return to public R&D by using industry level data to examine the relationship between TFP in market sector industries and public R&D spending. This is the same approach as that used previously by HHBM/GHHW to produce estimates of the rate of return to public R&D in the UK. This section provides an overview of the approach used, and briefly mentions some other approaches used in the academic literature. Further technical details are also provided in Annex A .

2.1.1 Overview of approach used

The approach starts from a model of how industry productivity evolves over time. This is set out in equation (1):

$$\Delta lnTFP_{it} = A_{it} + \gamma_1 \Delta lnR_{it}^{PRI} + \gamma_2 M \Delta lnR_{-it}^{PRI} + \gamma_{3it} \Delta lnR_{t-3}^{PUB} + \epsilon_{it} \quad (1)$$

Productivity growth in an industry *i* ($\Delta lnTFP_{it}$) is modelled as depending on growth in the knowledge stock of that industry (ΔlnR_{it}^{PRI}), growth in the relevant stock of knowledge from other industries ($M\Delta lnR_{-it}^{PRI}$), and growth in the stock of knowledge from the public sector (ΔlnR_{t-3}^{PUB}).

The relevant stock of knowledge from other industries is calculated as the weighted sum of knowledge from other industries, where the weights (M) are designed to reflect the likelihood of knowledge spillovers from each industry to industry *i*.

It is reasonable to assume that it takes some time for public sector knowledge to impact on private sector productivity. It takes time for private firms to learn about any new discoveries and then to build on this and produce new innovations in their processes or products. The baseline model assumes a 3-year lag between an increase in the public sector knowledge stock and any impact on private industry TFP. The effect of the assumed lag length on the estimated rate of return is explored by also modelling a 6-year and 10-year lag.

Assuming that the knowledge generated from public R&D does not depreciate,[13] and defining ρ_{it} as the rate of return to industry *i* from public knowledge ($\rho_{it} = \frac{\delta V_{it}}{\delta R_{t-3}^{PUB}}$), equation (2) can be derived (see Annex A) from equation (1):

$$\Delta lnTFP_{it} = A_{it} + \gamma_1 \Delta lnR_{it}^{PRI} + \gamma_2 M\Delta lnR_{-it}^{PRI} + \rho_{it}\frac{N_{t-3}^{PUB}}{V_{it-3}} + \epsilon_{it} \qquad (2)$$

where, $\frac{N_{t-3}^{PUB}}{V_{it-3}}$ is public R&D investment in year t-3 (N_{t-3}^{PUB}) as a proportion of gross value added (output less intermediate consumption) V_{it-3}

The rate of return to total public R&D would be expected to vary across industries depending on, for example, the relevance of the knowledge generated to firms in a given industry and the ability of firms in that industry to understand and work with the knowledge arising from public R&D (their 'absorptive capacity' for public knowledge). With only industry-level data it is not possible to estimate robustly the rate of return for each individual industry (ρ_{it}).[14] However, by modelling the *relative size* of spillovers expected from the public sector to each industry it is possible to estimate an **average rate of return**.

[13] This is a standard assumption used in the literature that seeks to estimate returns to public R&D using a production function approach (see Frontier Economics 2023), since public knowledge is often thought of being built on incrementally rather than being rendered obsolete by new innovations (as may happen in the case of firm-specific knowledge and R&D). A zero depreciation rate may be more appropriate for investments in basic research since the underlying scientific knowledge, once discovered, can reasonably be assumed to remain in place in perpetuity. Public investments in applied R&D may be subject to some deprecation, but arguably at a lower than for private investments if the public investment is not on a new product or process for a single firm but rather on developing innovations with broader applicability. A more detailed discussion of depreciation rates can be found in Hall, Mairesse, and Mohnen (2009).

[14] This would require firm-level data to examine the relationship between productivity and public R&D spending at the firm level and whether this varies systematically between firms in different industries.

Specifically, it is assumed that the industry-specific rate of return (ρ_{it}) can be modelled (in a way that varies over time) by:

$$\rho_{it} = \rho_1 \frac{X_{it}}{\sum_{i=1}^{N} X_{it}} \quad (3)$$

In other words, ρ_{it} is modelled as a return ρ_1 that is scaled across industries according to a variable X_{it}, which is a proxy for the extent of spillovers from public sector knowledge to industry *i*. This scaling factor is normalised (i.e. divided by the sum of X_{it} across all industries in that year) so that the estimated coefficient ρ_1 can be interpreted directly as the average rate of return to all industries (i.e. $\sum \rho_{it} = \sum \rho_1 \frac{X_{it}}{\sum_{i=1}^{N} X_{it}} = \rho_1$).

Annual sector-level data on TFP is noisy. Rather than estimating equation (2), the approach taken (following HHBM/GHHW) is to model a smoothed version of the relationship in (1) using average growth rates over 3 years.[15] This can be estimated as in equation (4):

$$\Delta_3 lnTFP_{it} = A_{it} + \gamma_1 \Delta_3 lnR_{it-3}^{PRI} + \gamma_2 M \Delta_3 lnR_{-it}^{PRI} + \rho_1 \frac{X_{it-3}}{\Sigma X_{it-3}} \frac{N_{t-3}^{PUB}}{V_{it-3}} + \epsilon_{it} \quad (4)$$

where the growth rates Δ_3 signify average annual growth over 3 years. Equation (4) is derived in an analogous way to equation (2), except that equation (4) only includes the 3-year lag of public R&D $\frac{N_{t-3}^{PUB}}{V_{it-3}}$ in the final term, rather than an average of the 3, 4 and 5-year lags, as including further lags would significantly reduce the number of data points available for estimation.[16] This approach, also taken by HHBM/GHHW, is justified on the basis that public R&D spending does not change sharply from one year to the next, which allows a robust approximation of the 3, 4 and 5-year lags by the 3-year lag only.

To provide interpretation of the estimated coefficients:

- ρ_1 is the average rate of return to all industries from public R&D conducted three years earlier – the key parameter that this work is seeking to estimate;
- γ_1 is the average elasticity of industry TFP with respect to own-industry R&D. TFP is a measure of output (in this study gross value added or GVA) relative to inputs (factors of production). The TFP measure used is calculated after taking into account not only labour and tangible (physical) assets but also intangible assets including privately conducted R&D. As a result, a 'normal return' to private R&D (i.e. the impact on GVA as a result of private R&D spending) is already taken into account when TFP is calculated. The impact of own-industry R&D on TFP that is estimated by γ_1 will therefore capture a return *over and above* what is already taken into account when calculating TFP; in other words, an 'excess return'.

[15] In other words, the approach is to model $\Delta_3 lnTFP_{it} = A_{it} + \gamma_1 \Delta_3 lnR_{it}^{PRI} + \gamma_2 M \Delta_3 lnR_{-it}^{PRI} + \gamma_{3it} \Delta_3 lnR_{t-3}^{PUB} + \epsilon_{it}$.

[16] The data used spans from 1998 to 2019, but with a 5-year lag results could only be estimated using 17 rather than 19 observations for each industry, losing a total of 80 observations across the 40 industries.

- γ_2 is the average elasticity of industry TFP with respect to other-industry R&D – in other words, private sector R&D spillovers from an industry conducting R&D to other industries;
- A_{it} comprise industry- and time-specific factors that cannot otherwise be explicitly accounted for in the quantitative econometric approach (including measurement error in other factors of production that are time- or industry-specific). These are included as controls to ensure more precise estimates for the other coefficients ρ_1, γ_1 and γ_2 rather than to obtain specific numerical estimates of A_{it}. The industry- and time-specific factors are estimated using both:
  - **time dummies** (which account for factors that impact productivity growth which vary over time but not across industries); and,
  - **random effects** (which assist in controlling for unobservable industry-specific factors that affect productivity growth but do not vary over time).[17]

2.1.2 Other approaches used in the literature

The approach taken in this study to estimate the impact of public R&D on productivity – using industry level panel data – is only one methodology. There are other approaches taken in the literature, for example:

- **Haskel and Wallis (2013)** use only time series variation (not cross-sectional e.g. across industries) and find significant spillovers from public sector R&D from Research Councils to private sector productivity growth in the UK. They find a statistically significant rate of return of around 15-30%.
- **van Elk et al. (2019)** exploit time series and cross-country variation for 22 OECD countries to estimate the impact of publicly-performed R&D. In their findings, whether publicly-performed R&D has a positive and statistically significant impact on TFP growth depends on the country-specific context such as institutions and government policies. There is a wide variation in their results across the specifications used; where they find a positive and statistically significant impact of public R&D on TFP the elasticity is generally estimated to be less than 0.1.
- **Sharif et al. (2021)** study the effect of R&D (public and private) on TFP growth on a location-level basis for Hong Kong, Shenzen and Singapore. They find that the impact of both private and public R&D on TFP growth is not uniformly significant or large across the three locations. The impact of public R&D on TFP is significant only for Singapore, with elasticity estimates in the range of 0.03-0.1.
- **Acosta et al. (2015)** use firm-level data for the Spanish food and beverage industry to study the relationship between public R&D, firms' private R&D spending, innovation and productivity. They document how firms that receive public R&D funding invest more in

[17] In the random effects (RE) econometric approach industry-specific factors that do not vary over time are assumed to be unrelated to other predictors of TFP that do not vary over time. In the RE econometric approach industry-specific factors that do not vary over time are assumed to be unrelated to other predictors of TFP that do not vary over time. Fixed effects (FE) specifications are defined similarly, except that there is no assumption made about the relationship between industry-specific factors that do not vary over time and other predictors of TFP that do not vary over time (i.e. whether they are related or not). If the assumption holds, the RE specification allows for a more precise estimation of the rate of return. The methodology follows HHBM/GHHW in using time dummies and random effects.

R&D themselves, which in turn plays a significant role in product and organisational innovation but not in process innovation. They also find a positive relationship between innovation output (the predicted probability of carrying out innovation) and productivity (sales per employee), though they do not estimate an explicit rate of return to R&D.

- **Fieldhouse and Mertens (2023)** study changes in non-defence R&D for five of the US's federal government bodies in the post-war period. They use a system projections with instrumental variables (SP-IV) approach with a production function and find high rates of return of in the range of around 140 to 210%.
- **Dimos and Vorley (2023)** use a firm-level approach to estimate the impact of firms receiving financial support in the form of grants from Innovate UK on firm performance. They find a 73% return, in the form an increase in GVA, to Innovate UK grants invested in business R&D (i.e. funded by the public sector and conducted in the private sector) in the year the investment is made, and further benefits as a result of public R&D stimulating private R&D.[18]

The approach taken in this study is chosen over these other methodologies because it provides an overall return for public R&D that is UK specific (which not all of the above methodologies would) and because it is feasible with the data available for the UK (which not all of the above methodologies are).

2.2 Data used

This section sets out the data sources and key assumptions that inform the econometric estimation.

2.2.1 TFP, private R&D and gross value added

Data for TFP, the stock of private R&D, and gross value-added are all obtained from the UK Intangibles Growth-Accounting dataset produced by The Productivity Institute (TPI).[19] [20] The dataset contains these data for 42 industry groups using the SIC 2007 industrial classification from 1998 until 2019. The industry groups used in this study are described in Annex B . We make use of the full time period of data available for this study.

The TPI data gives a measure of TFP growth based on gross value-added (i.e. industry GVA is used as a starting point to calculate TFP), as opposed to an output-based measure as used

[18] They find a 73p increase in firm GVA for each £1 of grant funding invested in the firm, and further benefits in terms of 14p of additional GVA. They also find further benefits that accrue over longer time periods.

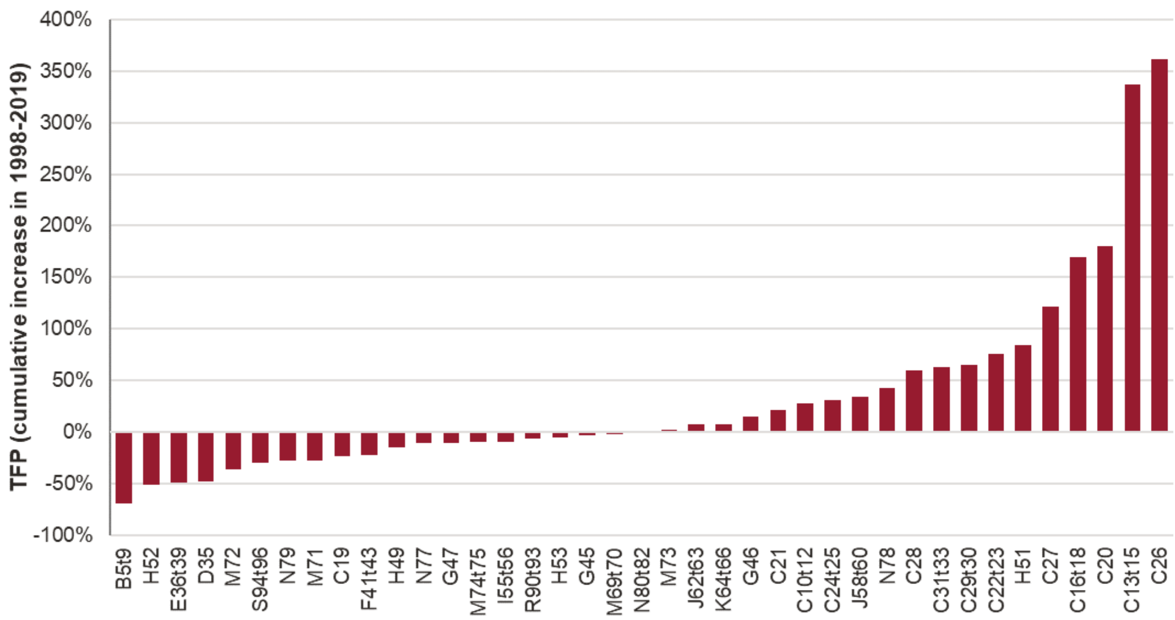
[19] The dataset is available via the 'The Productivity Lab' subgroup of the Figshare platform: TPI UK Intangibles Growth-Accounting data set (manchester.ac.uk). For background, see Goodridge and Haskel (2022). Datasets other than TPI are also available for private R&D and productivity: see from the ONS (only productivity) and EU KLEMS (both productivity and private R&D). TPI offers a more granular industry definition than either of these alternative datasets and is therefore used in this study.

[20] Gross value added is used, for example, in equation (4) as public R&D is defined in the model in proportion to industry-specific gross value added.

in HHBM/GHHW.[21] TFP measures industry GVA relative to the inputs used for production. The TPI data includes two measures of TFP and GVA: one 'narrower' measure that as accounts for inputs that are measured in the national accounts (i.e. labour, tangible assets and some intangible assets such as private R&D), and one 'broader' measure that also accounts for a wider set of intangible assets (such as brand and design) that allow for a more comprehensive picture of industry capital stock.[22] This study uses the 'broader' measure that takes into account a wider set of intangibles.

Figure 4 below shows the cumulative change in TFP for the industry groups in the TPI data between 1998 and 2019. There is a large amount of variation across industries, which is helpful when seeking to identify the effects of public R&D on TFP. See Annex B for a description of the TPI industry groups.

Figure 4 Cumulative TFP growth, by industry group, 1998 to 2019



Source: *Frontier Economics calculations based on TPI: [TPI UK Intangibles Growth-Accounting data set (manchester.ac.uk)](#).*

Note: *J61 "Telecommunications" not shown on the chart. Its TFP increased by over 5,300%. The presence of large upfront investment costs and staggered productivity benefits over time in the sector allows for very large productivity growth. For a discussion of the measurement difficulties related to the sector, see Goodridge et al. (2014).*

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[21] Using an output-based measure has theoretical benefits (e.g. minimising certain measurement biases) while a value added-based measure is more meaningful in the presence of substitution between labour and intermediate inputs over time, e.g. via outsourcing. This present study's long time horizon makes significant substitution between labour and intermediate inputs over time possible. For a discussion of the differences of these approaches, see Australian Government Productivity Commission (2003).

[22] The full set of intangible assets that are capitalised in TFP in the 'broader' approach taken in this study are as follows: software and databases; R&D; artistic originals; mineral exploration; design; financial product innovation; firm-specific training; branding; and organisational capital. For further details, see section 3.4.2 in Goodridge and Haskel (2022). Importantly, it is only the intangible assets *within* an industry that are accounted for as inputs when industry FTP is calculated. R&D conducted by the public sector is therefore not included.

The stock of knowledge in private sector industries is proxied by the stock of private sector R&D conducted in those industries. Data on the stock of private sector R&D is taken from TPI, to ensure consistency with the TFP metric used. The TPI data estimates the stock of private sector R&D in each industry using data on annual R&D spending (from the Business Enterprise Research and Development (BERD) data) and assumptions about depreciation and initial stocks.[23] This measure of private sector R&D includes R&D that is publicly-funded but performed in the private sector. As described below, to avoid double counting, public R&D is defined excluding this privately-performed R&D.

Recent commentary by the Office for National Statistics (ONS) has highlighted how BERD data up to and including 2020 has understated the amount of R&D done in the UK, particularly by small businesses.[24] For the 2021 data, as an interim measure, an 'uplift' was applied to adjust for the understatement. For data relating to 2022 (the latest available, which was published in 2024), the ONS has implemented a new sampling strategy to increase the volume of data collected and ensure that the sample of firms from which R&D data are collected is more representative.[25] The new approach is considered by the ONS to produce the most robust, accurate estimates of R&D, and it does lead to a different picture of R&D across industries. For example, in 2022 the Professional, Scientific and Technical activities; Manufacturing; and Information and communication sectors performed 78.7% of business R&D expenditure, compared to 83.6% of business R&D expenditure in 2020 (prior to the methodological changes). However, at the time of writing there is no updated historical data available for private R&D at an industry level. This study therefore uses the published BERD data, and the implications of the likely mismeasurement of private R&D are discussed in section 3.

2.2.2 Private sector knowledge spillovers

The stock of relevant knowledge from other industries is proxied as the weighted sum of the R&D stock from other industries, where the weights are designed to reflect the likelihood of knowledge spillovers between industries.[26] In this study a relatively simple approach to modelling these knowledge flows is taken, as estimating the spillovers from private R&D is not the focus here. The relative size of knowledge flows is proxied according to supply chain linkages – a common approach in the literature, albeit different to HHBM/GHHW who proxy the relative size of knowledge flows using rates of labour turnover between industries.[27]

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[23] In TPI, initial stocks are obtained using a 'steady-state' growth formula based on previously estimated rates of depreciation – based on research including Goodridge et al. (2016) – and data from the ONS gross fixed capital formation (GFCF) dataset. For the complete set of assumptions underlying the TPI data see the technical note accompanying the dataset via the 'The Productivity Lab' subgroup of the Figshare platform: TPI UK Intangibles Growth-Accounting data set (manchester.ac.uk). For further description of the data, see Goodridge and Haskel (2022).

[24] ONS (2022), Comparison of ONS business enterprise research and development statistics with HMRC research and development tax credit statistics – Office for National Statistics.

[25] ONS (2024), Business Enterprise Research and Development, UK, 2022.

[26] This gives the matrix M for the following term in equation (4) above: $\gamma_2 M \Delta_3 lnR_{-it}^{PRI} = \gamma_2 (\sum_{-i} w_{i,-it} \Delta_3 lnR_{-it}^{PRI})$.

[27] See for example Griliches and Lichtenberg (1984) and Goodridge et al. (2017).

Data is used from ONS input-output tables, which describe industry intermediate consumption by product (corresponding to producing industry).[28] The knowledge flow from industry *-i* to industry *i* (the weights $w_{i,-it}$) is modelled as the share of industry *-i*'s total intermediate demand fulfilled by industry *i*.[29]

2.2.3 Public R&D

Data on public R&D is sourced from Gross Domestic Expenditure on R&D (GERD), and deflated using the GDP deflator.[30]

Public R&D is defined as R&D that is both **funded by and performed by** the public sector. This includes UK R&D that is funded directly by government, by UKRI and by the Higher Education Funding Councils, but excludes R&D that is conducted in the private sector (as this is already captured in the measure of private R&D) and a small amount of R&D that is conducted in the voluntary sector.

Table 1 below illustrates this definition of public R&D using figures for 2019.[31] The top left-hand side box in the table represents R&D that is both funded and performed by the public sector, which amounts to 80% of publicly-funded R&D in the UK (of £10.4 billion of publicly-funded UK R&D, £8.3 billion was also performed by the public sector).

[28] Supply and use tables, "Industries' intermediate consumption" for each year 1997-2019. Available at: Input-output supply and use tables - Office for National Statistics (ons.gov.uk).

[29] Owing to national accounting difficulties (see HHBM/GHHW) and variables with zero values in TPI, we assume zero spillovers from two industry groups to other industries: A1t3 ("Agriculture, Forestry and Fishing") and H50 ("Water transport"). Own-industry spillovers (i.e. from firms within industry *j* to other firms within industry *j*) are also excluded.

[30] GERD includes time series of public R&D spending for the period 1995-2019 split across who funded and who performed the R&D (e.g. universities or government/UKRI). GERD available at: Gross domestic expenditure on research and development time series - Office for National Statistics (ons.gov.uk). GDP deflator: GDP Deflator: Year on Year growth: SA % - Office for National Statistics (ons.gov.uk). While an R&D-specific deflator is available from the ONS, this may not be appropriate for public R&D spending. In line with HHBM/GHHW, we calculate real public R&D spending using the GDP deflator.

[31] Since the publication of this dataset the ONS has revised the estimate for HE self-funded R&D (i.e. performed and funded by HE). For further details, please see: Gross domestic expenditure on research and development, UK - Office for National Statistics (ons.gov.uk). Not adjusting for the revised figures could introduce bias in the estimates. However, is not possible to reliably adjust for HE self-funded R&D because these revised estimates are not available for the entire time period of this study.

Table 1 Annual R&D investment across sectors performing and sectors funding the R&D, 2019

£ million	Sector performing the R&D				
Sector funding	**Government**	**UKRI**	**HE**	Business Enterprise	Private Non-Profit
Government	**1,353**	**151**	**421**	1,202	102
UKRI	**49**	**770**	**2,707**	634	198
Higher Education Funding Councils	**-**	**-**	**2,859**	-	-
Higher Education	4	17	-	28	17
Business Enterprise	15	66	362	20,192	25
Private Non-Profit	28	52	1,247	75	364

Source: *Frontier Economics calculations based on ONS.*

Note: *Data for Private Non-Profit is estimated in non-survey years from survey data. - denotes nil. GERD data also includes R&D funded from, or performed overseas. The table only considers domestic R&D.*

In addition, defence-related R&D is excluded from the measure of public R&D used in this present study. This is because secrecy around such R&D may mean that returns to the wider private sector are very different to the returns that are generated from civilian (non-defence) R&D.[32] This additional exclusion means that the measure of public R&D used in this study captures about 75% of all publicly funded R&D over the period 1998 to 2019.[33]

Figure 5 shows the real level of spending over time on public R&D as defined in this study (publicly funded and performed, excluding defence), and total publicly-funded (including R&D performed privately and including defence). Spending on public R&D as defined in this study (the dashed red line) was £8.2 billion in 2019, out of a total of £10.4 billion in publicly funded R&D (pink line). Annual public R&D spending grew steadily in real terms between (calendar years) 1998 and 2005-6, before remaining relatively steady (in some years declining) between 2006-7 and 2017, and then resuming strong growth in 2018-19.

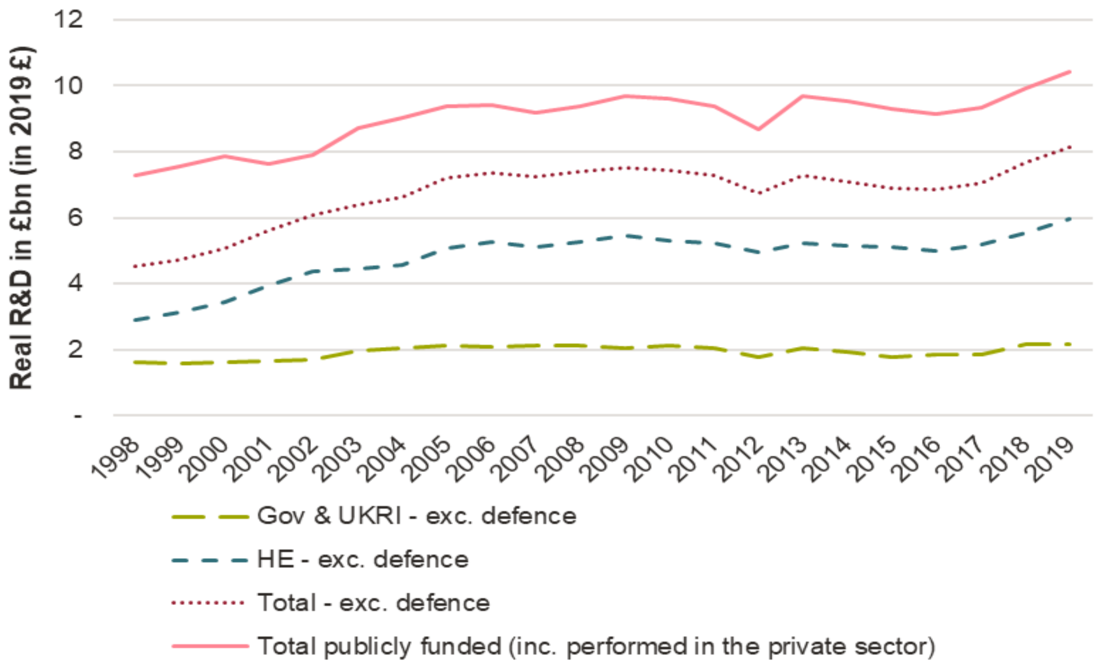
Figure 5 also shows real spending on non-defence public R&D conducted directly by government or by UKRI, and spending on public non-defence R&D conducted in the higher

[32] Due to data limitations a proxy is used for the exclusion of defence-related R&D: for each component in public R&D, defence R&D is excluded based on *performance* by multiplying the given component with the share of civilian R&D within publicly-performed R&D: for example, $\text{R\&D funded by UKRI and performed by HE} * \frac{\text{Civilian R\&D performed by HE}}{\text{Total R\&D performed by HE}}$.

[33] The sensitivity of the main results to alternative definitions of public R&D is tested. The following alternative definitions are used in robustness checks: excluding defence-related R&D based on a the share of civilian R&D within publicly-funded R&D; including defence-related R&D.

education (HE) sector over time. Spending on public R&D conducted by government or by UKRI has been relatively flat over the whole period, while spending on public R&D in the HE sector has increased (particularly between 1998 and 2009).

Figure 5 Trends in UK real-terms public R&D, 1998 to 2019



Source: Frontier Economics calculations based on ONS.
Note: Deflated using the GDP deflator.

2.2.4 Public sector knowledge spillovers

A crucial input to the estimation is a scaling factor that measures the extent of spillovers from public sector knowledge for each industry *i* (X_{it}, see section 2.1.1). Three different approaches are taken for proxying for the relative knowledge flows between the public sector and each industry (in line with the approach of HHBM/GHHW):

- **R&D intensity**: defined for each industry as private R&D spending of the industry divided by industry gross value-added (GVA). R&D intensity, measured by R&D spending relative to size (as measured by GVA) is used as a measure of the industry's absorptive capacity i.e. its ability to understand and use knowledge from public R&D. All else equal, an industry with more absorptive capacity is more likely to benefit from public R&D.
- **Public-private interactions**: the UK Innovation Survey (UKIS) contains firm-level information on interactions with the public sector in relation to innovation.[34] Two metrics are calculated and used to measure public sector spillovers:

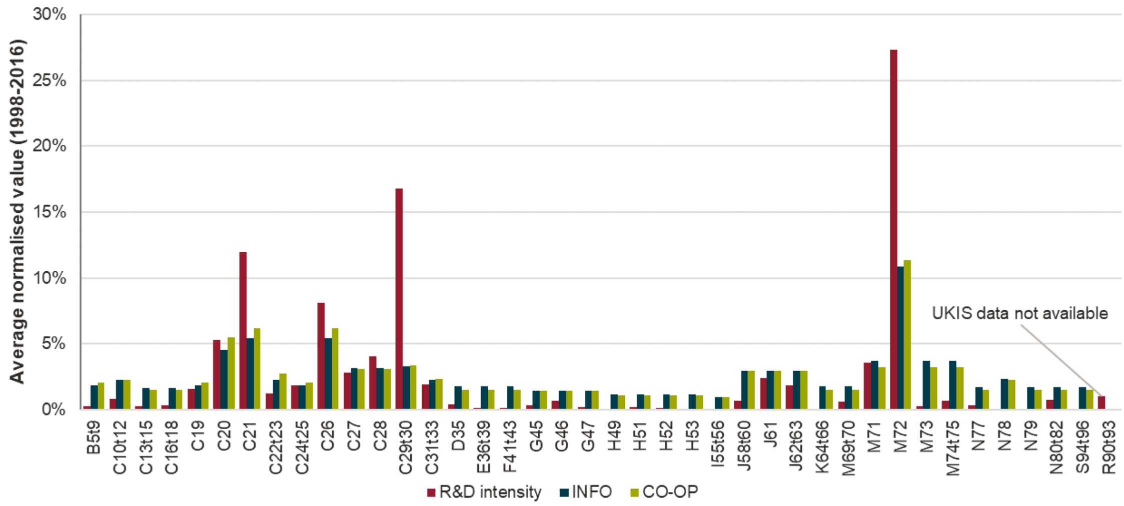
[34] Department for Business and Trade, released 07 June 2022, ONS SRS Metadata Catalogue, dataset, UK Innovation Survey, https://doi.org/10.57906/bs4h-rh59.

- the % share of firms in each industry who report that information from the public sector is important for their own innovation activities ("INFO"); and,
- the % share of firms in each industry who report collaborating on innovation with the public sector ("CO-OP").

More information on the UKIS data, and the assumptions required to calculate the above metrics, is provided in Annex C and in Frontier Economics (2024).

These proxies all vary across industries and years. There are a few industry groups with very high levels of R&D intensity or interaction with the public sector, and many other groups with substantially lower levels. Generally speaking, the different proxies for spillovers from public sector knowledge are highly correlated. Figure 6 shows that industry groups with high levels of R&D intensity also tend to have high levels of interactions with the public sector (Annex B describes the industry groups used in this study).[35] Industry groups with the highest average level of R&D intensity include C21 (Manufacture of basic pharmaceutical products and pharmaceutical preparations), C29t30 (Manufacture of transport equipment), and M72 (Scientific research and development).

Figure 6 Proxies of spillovers from public R&D by industry, average for the period 1998 to 2016



Source: Frontier Economics calculations based on TPI and ONS.

Note: The industry group R90t93 (Arts, Entertainment and Recreation) is not available in UKIS (it is available in TPI), therefore estimation using UKIS data to proxy for the relative size of public sector knowledge spillovers does not include R90t93. 2016 is the last year of this data used in the estimation given a 3-year lag (the smallest) between public R&D and its impact on productivity. Annex B describes the industry groups used in this study.

[35] The values for these proxies are shown in normalised form, that is, the value for a given industry and year X_{it} is divided by the sum of X_{it} across all industries in that year. See section 2.1.1.

3 Quantifying the rate of return: results

Summary

The results suggest a substantial positive impact of public R&D on private sector productivity.

Rates of return are inherently challenging to estimate, and the quantified rates of return should be interpreted cautiously. The range of results across different specifications in this report underline the uncertainty that is present in any single estimate. In addition, the estimates produced in this work may be biased upwards if:

- they capture the impact of other factors of production that are subject to measurement error (there is known mis-measurement of private R&D, for example);[36]
- there are other omitted factors that positively correlate with both productivity and R&D investment.

With such caveats in mind**, the current estimates suggest an average rate of return to public R&D of around 40% could be enjoyed 6 years after the investment is made.** In other words, £100m of public R&D investment could be expected on average to yield, in 6 years' time, an increase in annual private sector productivity worth £40m; annual gross value added (GVA) in the private sector is £40m higher as a result of the £100m public R&D investment.

The rate of return is estimated to be greater with a longer (10 year) lag between the R&D and productivity impact. This is consistent with the benefits of public R&D taking time to feed through into private sector productivity.

These returns are higher than previously estimated for public R&D in the UK using a similar methodology. **This is believed to be mainly due to revisions to the underlying macro-economic data** since the previous estimates were produced, particularly measures of industry level productivity (TFP).

The estimated results suggest that the returns to public R&D have increased since the financial crisis but the results are not conclusive. Furthermore, it is unclear what the drivers of this are, and therefore this is worthy of further exploration.

It has not been possible to estimate separate rates of return for public R&D conducted by the higher education sector and R&D conducted by central government or research institutes.

[36] Office for National Statistics (2024) Business Enterprise Research and Development, UK: 2022.

3.1 Main results

3.1.1 Returns to public R&D

The main estimation results for the rate of return to public R&D are summarised in Table 2. This shows the impact public R&D is expected to have on annual private sector productivity.

Each column in Table 2 contains the results for a different approach to measuring the relative size of public sector R&D spillovers across different industries (see section 2.2.4). The first row shows the results when the impact of public R&D on private sector productivity is modelled with a 3-year lag, while the other rows show how the estimates change when the lag length is modelled as 6 years and 10 years. The results are to be interpreted as the increase in annual private sector gross value added (GVA) relative to the public R&D investment, as a result of increased private sector productivity. Detailed results are shown in Table 5 further below.

Table 2 Baseline estimates of the rate of return to public R&D

Lag for public R&D	R&D intensity	INFO (UKIS)	CO-OP (UKIS)
3 years	77%*	100%	87%*
6 years	4%	36%***	41%***
10 years	45%***	99%***	80%***

Source: Frontier Economics calculations.

Note: Econometric model estimated with time dummies and random effects (results for these are not reported). (*) statistically significant at 10% / (**) at 5% / (***) at 1%.

The results suggest substantial positive impacts of public R&D investment on private sector productivity, even though the precise estimate of the return varies significantly across different specifications. The estimated rate of return to public R&D with a 3-year lag varies between 77% (when R&D intensity is used to proxy for the relative size of public sector spillovers) and 100% (when the “INFO” measure is used). These results are not precisely estimated, and are either statistically insignificant, or significant only at a 10% confidence level.

With a 6-year lag, the estimated rate of return is not significantly different from zero in the “R&D intensity” specification, but is around 40% for the “INFO” and “COOP” specifications, and in each case significant at the 1% level.

With a 10-year lag, the estimated rate of return is around 45% for the “R&D intensity” specification and around 80-100% for the CO-OP and INFO specifications. These results are all significant at the 1% level.

The range of rate of return estimates is generally robust to various different specifications used as sensitivity checks.[37] The results are summarised in Table 13 in Annex D .

Rates of return are inherently challenging to estimate, and these quantified rates of return should be interpreted cautiously. In particular, these estimates may be biased upwards if:

- There are omitted factors (that vary over time for particular industries) that correlate positively with industry TFP and either public R&D or the measures used to proxy for the relative size of spillovers from public R&D to different industries (R&D intensity, "INFO" and "COOP"). This might be a particular concern for the 3-year lag model if there is a cyclical relationship between private R&D investment, innovation activity and productivity (e.g. if private sector firms' innovation interaction with the public sector tends to be high when TFP growth is also high because of the stage of the business cycle).
- The coefficient on public R&D is capturing an omitted positive impact of private R&D on productivity. This is a concern because private R&D is known to be underestimated in the official R&D data used in this study (see section 2.2.1). If private R&D is underestimated in a time-varying way for individual industries, and if this correlates with self-reported innovation behaviour (as seems likely) then this would cause an upward bias in the estimated rate of return. Unfortunately without data on the size and pattern of the sectoral mis-measurement of private R&D over time it is not possible to quantify the likely size of this bias.

The variation in the results across different specifications in Table 2, and the caveats above, suggest one should be cautious about focusing too confidently on any particular estimate of the rate of return. However, in terms of a preferred specification, the results for the **6-year lag** with the **"INFO" or "COOP" specifications** may be the most informative. This is because:

- the 3-year lag models are more prone to bias from cyclical factors, while with the 10-year lag models it is harder to control for other changes that occur over time; and,
- the "INFO"/"COOP" specifications may be at greater risk of upward bias than the "R&D intensity" specification due to the mismeasurement of private R&D. However, the "INFO"/"COOP" variables are intuitively better proxies for how public R&D spillovers vary across industries, as they are constructed from self-reported data from businesses in different industries on the importance of the public sector for their own innovation. (Specifically: the importance of information from the public sector for own innovation (in the case of "INFO"), and the proportion who collaborate with the public sector on innovation (in the case of "COOP".).

In these specifications the estimated rate of return is around 40% with a 6-year lag between public R&D and the impact on productivity. In other words, £100m of public R&D

[37] The baseline estimates are obtained by excluding defence-related public R&D that is performed in the public sector (see 2.2.3 for further details) and including a term to model private sector spillovers in the specification. The sensitivities comprise the following alternative specifications: (i) excluding defence-related public R&D that is funded by (rather than performed in) the public sector; (ii) including defence-related public R&D; and, (iii) excluding private sector spillovers.

investment is estimated to yield on average an increase in annual private sector productivity of £40m in 6 years' time.

There is some evidence that the rate of return is even higher when a longer lag of 10 years is modelled. However, direct comparisons in the rates of return must be made carefully, as the period over which TFP growth is measured (and the period over which public R&D is measured) varies between the 6-year lag and 10-year lag specifications because of the different data periods available when estimating with different lag lengths.

If attention is restricted to a specific time period over which TFP growth is measured (2008 to 2019) it is possible to calculate the returns using the same period for each lag specification.[38] This yields a different pattern of results (shown in Table 3, further details in Table 14 in Annex D). The rate of return estimates for the 6-year lag specifications are somewhat higher across all three models compared with the baseline estimates shown in Table 2. The estimated returns with a 10-year lag are still higher than 6-year returns based on the “R&D intensity” and the “INFO” specifications, but are slightly smaller based on the “CO-OP” specification.

Table 3 Public R&D rate of return estimates with TFP growth measured over a common period (2008 to 2019) across all lag lengths

Lag for public R&D	R&D intensity	INFO (UKIS)	CO-OP (UKIS)
3 years	102%**	234%***	206%***
6 years	14%	65%**	84%***
10 years	45%***	99%***	80%***

Source: Frontier Economics calculations.

Note: Econometric model estimated with time dummies and random effects (results for these are not reported). (*) significant at 10% / (**) at 5% / (***) at 1%.

Alternatively, focus can be restricted to public R&D performed in a common period (1998 to 2009), and results estimated for different lag lengths.[39] This produces similar estimates as in the baseline (Table 2) for the rate of return to public R&D for the 6-year lag specifications (results are shown in Table 4, further details in Table 15 in Annex D). That is, analysis over an equivalent period for public R&D investment suggests higher 10-year returns compared to 6-year returns.

[38] That is, we estimate the 3-year, 6-year and 10-year lag models where TFP growth is measured in 2008, 2009 … 2019.

[39] That is, we estimate the 3-year, 6-year and 10-year lag models where public R&D takes place in 1998, with impact on TFP in 2001 with a 3-year lag, 2004 with a 6-year lag and 2008 with a 10-year lag, and similarly for when public R&D takes place in 1999-2009.

Table 4 Public R&D rate of return estimates with public R&D measured over a common period (1998 to 2009) across all lag lengths

Lag for public R&D	R&D intensity	INFO (UKIS)	CO-OP (UKIS)
3 years	69%***	66%***	55%***
6 years	21%	37%***	43%***
10 years	45%***	99%***	80%***

Source: Frontier Economics calculations.

Note: Econometric model estimated with time dummies and random effects (results for these are not reported). (*) significant at 10% / (**) at 5% / (***) at 1%.

3.1.2 Returns to private R&D

Across the various specifications, the estimated coefficient on private R&D is not significantly different from zero (shown in Table 5). This does not indicate that there is no return to private R&D – rather that there is no 'excess return', since a normal return to private R&D is already taken into account when TFP is calculated (as discussed in section 2.2.1).

The results in Table 5 also suggest no impact on productivity from private R&D in other industries (i.e. no spillovers from private R&D). This is perhaps surprising, given there is evidence in other studies for positive spillovers.[40] However, the proxy used to estimate spillover flows – supply chain links – is a relatively simple measure, since estimating spillovers from private R&D was not the main focus of this study. It is possible that more sophisticated approaches to estimating spillovers from private R&D would detect positive impacts of spillovers from private R&D. Other approaches include Goodridge et al. (2017) who use proxies such as the transition of workers between industries, whereas Lucking et al. (2019) exploit technological proximity. Separately, it is also not obvious that this choice of proxy biases the estimated return to public R&D.

[40] Frontier Economics (2023) provides a review of this evidence, including Lucking et al. (2019) and Goodridge, Haskel and Wallis (2017). HHBM/GHHW find differing levels of significance depending on the specification used for spillovers from private R&D.

Table 5 Baseline results – by lag length of public R&D investment and measure of public knowledge spillovers

Lag for public R&D	3 years			6 years			10 years		
	R&D	**INFO**	**CO-OP**	**R&D**	**INFO**	**CO-OP**	**R&D**	**INFO**	**CO-OP**
Coefficient estimates									
Private R&D	0.075	0.063	0.066	0.098	0.103	0.101	0.129	0.125	0.122
Private spillovers	-0.245	-0.257	-0.274	-0.29	-0.263	-0.258	-0.298	-0.246	-0.263
Public R&D	**77%***	**100%**	**87%***	**4%**	**36%*****	**41%*****	**45%*****	**99%*****	**80%*****
P-value (Public R&D)	0.066	0.102	0.085	0.848	<0.01	<0.01	<0.01	<0.01	<0.01
Summary statistics									
Sample size	760	741	741	640	624	624	480	468	468
Industry groups	40	39	39	40	39	39	40	39	39
R squared	0.246	0.464	0.474	0.053	0.507	0.525	0.314	0.653	0.635

Source: Frontier Economics calculations.

Note: Econometric model estimated with time dummies and random effects (results for these are not reported). (*) significant at 10% / (**) at 5% / (***) at 1%. The coefficient estimates for "Public R&D" are rates of return while the other coefficient estimates are elasticities. The first three columns show the results when the impact of public R&D on private sector productivity is modelled with a 3-year lag, with each column containing the results for a different approach to measuring the relative size of public sector spillovers across industries. The other panels in the table set out how the estimates change when the length of time between public R&D and productivity is modelled as 6 years and 10 years, respectively. The estimates for the rate of return to public R&D are highlighted yellow and bold.

3.2 Comparison to previous estimates

The rates of return to public R&D estimated here are higher than those estimated previously for the UK in HHBM/GHHW, which have largely been interpreted as suggesting a rate of return to public R&D of around 20%. The main reason for the difference is due to changes in the underlying data.

The methodology used in this paper broadly replicates that of HHBM/GHHW but there are a few key differences, including:

- **Different industry definitions**. HHBM/GHHW use data for 6 industries. We use more granular data covering 40 industries in our baseline specification.
- **Different time periods**. HHBM/GHHW use data on TFP and R&D between 1992 and 2007. We use data between 1998 and 2019.
- **Differences in the underlying data**. As discussed in section 1.2, there have been significant revisions in particular to industry-level GVA and TFP.

To understand the extent to which these factors are driving the differences in estimated rates of return, the main quantitative econometric analysis in this paper is repeated (i) as closely as possible to the same time period (we cannot replicate the exact same time period as studies in HHBM/GHHW as our dataset starts in 1998 rather than in 1992) and (ii) with the industry data aggregated to the same broad industry groups that were used in HHBM/GHHW.

TFP growth is aggregated using Domar weights based on gross value added (GVA):[41] TFP growth in a broad industry group *A* is equal to the weighted sum of TFP growth in the broad industry group's *N* constituent granular industries *i*, where the weights are the granular industries' share of GVA as a proportion of total GVA for the broad industry. See equation (5):

$$\Delta_3 lnTFP_{At} = \sum_{i=1}^{N}(\Delta_3 lnTFP_{it} * \frac{GVA_{it}}{\sum_{i=1}^{N} GVA_{it}}) \quad (5)$$

Other data available for granular industries in TPI are aggregated up to broad industry groups using unweighted sums.

The estimated returns to public R&D are set out in Table 6, alongside the most comparable results from HHBM/GHHW. Table 16 in Annex D contains the full set of estimation results.

[41] Domar (1961).

Table 6 Public R&D rate of return previous estimates and estimates from this study when using a similar time period and industry groupings as previous estimates

Lag for public R&D	R&D intensity		CO-OP (UKIS)	
	HHBM/GHHW	This study	HHBM/GHHW	This study
3 years	41%***	193%**	36%*** (21%***)+	197%*
6 years	82%***	227%**	(20%**)+	-177%***

Source: Frontier Economics calculations, page 15 in Goodridge et al. (2015).

Note: (+) Models in HHBM/GHHW that yield 21% (3-year lag, significant at 1%) and 20% (6-year lag, significant at 5%) rate of return to public R&D do not include private R&D spillovers. Estimates in this study include private R&D spillovers, excluding these does not meaningfully change the results (see Table 17 in Annex D). Econometric model estimated with time dummies and random effects (results for these are not reported). (*) significant at 10% / (**) at 5% / (***) at 1%.

These estimates for the rate of return produced using today's data do not align with the estimates of HHBM/GHHW, and the new estimates are large and volatile across specifications and therefore do not appear to have meaningful interpretations. This is perhaps not surprising given that panel data estimation from a sample of only 6 industries and 4 to 7 years of outcome data would be expected to be challenging.[42] While there remain some minor methodological differences between the approach in this work and that taken by HHBM/GHHW, this suggests that **the main reason for the difference in estimates produced is due to changes in the underlying data.**

As noted in section 1.2, over the past decade methodological improvements have resulted in revisions to industry GVA, which feed through into revisions to industry level TFP (as estimates of the factors of production, capital and labour, are not affected by the main revisions). The November 2021 Monetary Policy Report from the Bank of England provides a discussion of changes to the measurement of GVA, and Chart A in that publication provides an illustration of the significant impact on the calculated GVA of some industries.[43]

Differences in the underlying data can also been seen in descriptive statistics for TFP growth. Table 7 summarises the average change in TFP in the data used in HHBM/GHHW and the average change in TFP in the data used in this study (for as similar a period as possible). There is a significantly different pattern across industries, illustrative of the data revisions. In particular there is more variation at broad industry level in the revised data, notwithstanding the shorter time period available in the current underlying data when the time period is restricted to end at the same time as HHBM/GHHW.

[42] Time period of 1998-2007 using 3-year and 6-year lags.

[43] Available at: Bank of England Monetary Policy Report November 2021

Table 7 Broad industry estimates of 3-year average TFP growth

Industry group	HHBM/GHHW 1995-2007	This study 2001-2007
Manufacturing	0.53%	5.16%
Electricity, Gas & Water Supply	0.58%	-3.21%
Construction	0.04%	-1.21%
Distribution; Hotels & Restaurants; Transport, Storage and Communications	0.77%	0.58%
Financial Services	0.69%	2.70%
Business Activities (excluding real estate)	0.89%	-0.45%

Source: Frontier Economics calculations; page 14 in Goodridge et al. (2015).

3.3 Variation in rates of return

3.3.1 Changes in rates of return over time

One of the motivations for this present work was to understand whether the rate of return to public R&D might have changed over time, given the slowdown in UK productivity growth since 2008 at a time when public R&D spending has been relatively high by historical standards (as was shown in Figure 2). To explore this, the data were split into two time periods – 2001 to 2007 and 2008 to 2019 – and the impact of public R&D on productivity in each time period estimated separately.[44] Only the 3-year and 6-year lag models can be estimated for these sub-periods as there is insufficient data to estimate the 10-year lag model for the earlier time period.

Table 8 summarises the results for when the relative size of spillovers from public R&D across industries are proxied using the "INFO" and "COOP" measures (see detailed results in Table 18 in Annex D). The results suggest an increase in the rate of return to public R&D after 2008. For example using the "INFO" measure, the rate of return with a 3-year lag is estimated to have been 100% before 2008 and 234% since 2008, while the rate of return with a 6 year lag is estimated to have been 55% before 2008 and 65% since 2008. The "INFO" and "COOP" measures give qualitatively similar results.

[44] Excluding 2008-9 due to the financial crisis does not change the results qualitatively.

Table 8 Public R&D rate of return estimates for the pre-crisis (1998 to 2007) and post-crisis (2008 to 2019) period, UKIS measures of public knowledge spillovers

Lag for public R&D	INFO (UKIS)		CO-OP (UKIS)	
	Pre-crisis	Post-crisis	Pre-crisis	Post-crisis
3 years	100%***	234%***	96%***	206%***
6 years	55%***	65%**	50%***	84%***

Source: *Frontier Economics calculations.*

Note: *Econometric model estimated with time dummies and random effects (results for these are not reported). (*) significant at 10% / (**) at 5% / (***) at 1%.*

The results for when the relative size of spillovers are proxied using R&D intensity is shown in Table 9 (see detailed results in Table 19 in Annex D). The estimates in the first panel exhibit a different picture to those in Table 8: there is no increase in the estimated rate of return over time.

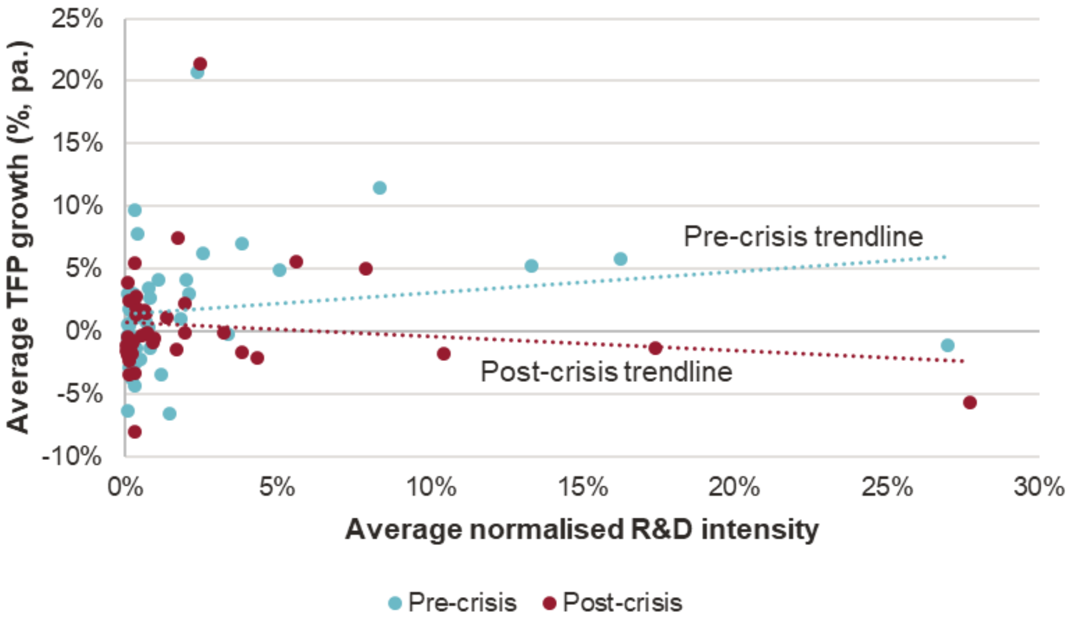
Other research, however, has shown that the slowdown in TFP growth since the financial crisis has been larger in more intangible- and knowledge- intensive industries.[45] Figure 7 shows that normalised R&D intensity, one of the public sector knowledge spillover proxies used in this study, is positively correlated with TFP growth in the pre-crisis period, as shown by the upward slope of the trendline for this period.[46] However, the correlation is negative in the post-crisis period as shown by the downward sloping trendline for the post-crisis period. The “INFO” and “COOP” public sector knowledge spillover measures show similar relationships with TFP growth but of a smaller magnitude. For these, the correlation with TFP growth changes from 0.15 and 0.19 to -0.05 and -0.02, respectively for “INFO” and “COOP”, from the pre-crisis to the post-crisis period.[47] For R&D intensity, the correlation changes from 0.18 to -0.13.

[45] The use of intangible assets (such as patents and brand) across industries displays a similarly negative correlation with TFP growth post-crisis. Goodridge and Haskel (2022).

[46] Normalisation involves dividing R&D intensity X_{it} at time *t* for industry group *i* by the sum of X_{it} across all industries in year *t*. See further details in section 2.1.1.

[47] The industry group R90t93 (Arts, Entertainment and Recreation) is not available in UKIS (it is available in TPI). As such, correlation calculations exclude this group for “INFO” and “COOP”.

Figure 7 Scatter plot of TFP growth and R&D intensity separately for the pre-crisis (1998-2007) and post-crisis (2008-2016) periods



Source: *Frontier Economics calculations based on TPI: [TPI UK Intangibles Growth-Accounting data set (manchester.ac.uk)](#).*

Note: *2016 is the last year data on R&D intensity is used in the estimation given a 3-year lag (the smallest) between public R&D and its impact on productivity. Using data until 2019 leads to similar results as on Figure 7. Average TFP growth is calculated as the geometric average growth rate within each period. Average normalised R&D intensity is the simple average.*

While the reasons for this are not well understood, this does raise a caution that the estimated rate of return to public R&D may be biased by omitted factors that correlate with R&D intensity, and that this bias changes over time. As a simple exploration of this, the second panel of Table 9 adds as an additional control in the estimation the level of the R&D intensity in the industry relative to other industries.[48] These results suggest an increase in the estimated rate of return since 2008 for most specifications, though the estimated returns using 6-year lags are not always statistically significant.[49]

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[48] The model with the additional control: $\Delta_3 lnTFP_{it} = A_{it} + \gamma_1 \Delta_3 lnR^{PRI}_{it-3} + \gamma_2 M \Delta_3 lnR^{PRI}_{-it} + \rho_1 \frac{X_{it-3}}{\Sigma X_{it-3}} \frac{N^{PUB}_{t-3}}{V_{it-3}} + \gamma_3 \frac{RDint_{it-3}}{\Sigma RDint_{it-3}} + \epsilon_{it}$ (6)

[49] Modelling the relative size of spillovers from the public sector with "INFO" or "CO-OP" with an additional control for the level of the R&D intensity in the industry relative to other industries is also consistent with an increase in the rate of return to public R&D since the financial crisis, similar to the results in Table 8. See Table 20 in Annex D .

Table 9 Public R&D rate of return estimates for the pre-crisis (1998 to 2007) and post-crisis (2008 to 2019) period, R&D intensity measure of public knowledge spillovers

Lag for public R&D	R&D intensity		R&D intensity with additional control	
	Pre-crisis	Post-crisis	Pre-crisis	Post-crisis
3 years	99%***	102%**	101%***	172%***
6 years	48%***	14%	46%***	55%

Source: Frontier Economics calculations.

Note: Right hand panel includes as an additional control the level of R&D intensity in the industry relative to other industries. Econometric model estimated with time dummies and random effects (results for these are not reported). (*) significant at 10% / (**) at 5% / (***) at 1%.

Taken at face value the results suggest that there may have been an increase in the rate of return to public R&D since 2008. However, it is unclear what the drivers of this are, and therefore this is worthy of further exploration in future before conclusions are drawn. It is possible that some of the causes of possible upward bias in the estimates identified in section 3.1.1 could have become larger post-crisis.

3.3.2 Variation in rates of return according to who conducts the R&D

Given the granularity of the GERD data used for public R&D investment it is theoretically possible to examine whether the rate of return differs between R&D funded and conducted by universities (“HE”) and by central government or UKRI (“GOV”).

Table 10 presents the results where these two sources of public R&D are entered separately into the baseline model specification (see detailed results in Table 21 in Annex D). This gives two separate coefficient estimates for the corresponding rate of return: one on HE R&D and another on GOV R&D. For the model in the first column, R&D intensity is used as the proxy for the spillover from both HE and GOV R&D. For the “INFO“ and “CO-OP“ models, specific proxies are used for the spillover from HE and the spillover from GOV using the underlying UKIS data to derive different measures of the intensity of engagement of different industries with HE or GOV. See Annex C and Frontier Economics (2024) for further information.

Table 10 Public R&D rate of return estimates separately for "GOV" and "HE"

Lag for public R&D	R&D intensity		INFO (UKIS)		CO-OP (UKIS)	
	HE	GOV	HE	GOV	HE	GOV
3 years	120%	-17%	467%***	-606%**	388%**	-628%*
6 years	-89%	242%	44%	32%	82%	-51%
10 years	138%	-116%	230%*	-132%	235%	-277%

Source: *Frontier Economics calculations.*

Note: *Econometric model estimated with time dummies and random effects (results for these are not reported). (*) significant at 10% / (**) at 5% / (***) at 1%.*

The R&D intensity model leads to estimates that are not significant whereas the "INFO" and "CO-OP" models lead to sometimes significant, but either very large positive (HE) or very large negative (GOV) estimates. This is likely because of the high correlation between the measures of spillovers from HE and GOV for each industry, which means that it is hard to correctly attribute the separate impact of these on TFP.

Based on these results it is not possible to confidently estimate separate rates of return for public R&D funded and conducted by the higher education sector and by central government.

3.4 Summary and interpretation

This work has estimated high rates of return to R&D funded and performed by the public sector, in terms of its impact on private sector TFP. The results depend, to some extent, on the precise specification and the range of results across different specifications in this report underline the uncertainty that is present in any single estimate. Any exact numerical estimate in this study should be interpreted with caution due to the methodological challenges involved in estimating the rate of return to public R&D and the variation in estimates across specifications. That said, using the preferred measure of how different industries engage with public R&D the results suggest, a return of around 40% six years after the public R&D investment is made.

The results imply higher returns than those found in the previous literature, whose approach is (broadly) replicated and extended with this work. While differences to the previous literature are believed to be due primarily to revisions to the underlying data, and while the longer time series and more granular sector-level data used in this work give confidence that the new findings are an improvement on past results, these new estimates should still be interpreted with caution. There is considerable variation in TFP growth across industries, particularly since 2008, and it is possible (even likely) that there are unobservable factors that are causing upward bias in estimates of the rate of return. Given the specification used, to cause upward bias these factors would need to be (i) changing over time and (ii) positively correlated with both TFP and the measures used to proxy for knowledge spillovers from the public sector. One known potential issue is the measurement of private sector R&D, which ONS has acknowledged has been under-estimated historically. This mismeasurement could lead to the rate of return to public R&D being over estimated. In interpreting the implications of the estimated rate of return, a few other key factors should also be kept in mind:

- **The estimated rate of return is an average, and not the rate of return that would be expected from any individual R&D investment**. Some R&D investments will turn out to have little to no benefit, while some will turn out to be groundbreaking and generate significant productivity improvements relative to the initial investment.
- **The estimated rate of return is an average across the level of R&D undertaken in the public sector, and not the return that would necessarily be expected on average for a much higher (or lower) level of investment**. If returns are non-linear then the return that could be expected for additional R&D may be higher or lower than the average across the existing level of R&D.
- **The estimated rate of return is an underestimate if public R&D also stimulates private sector R&D which itself has positive returns**. Such an impact on TFP is not attributed to public R&D in the methodology used. There is existing literature that provides evidence that public R&D spurs private R&D, and that private R&D on average has positive returns.
- **The estimated returns do not capture wider social benefits that are not reflected in private sector productivity, such as beneficial impacts on the environment or health**.

The estimates of the rate of return generated in this work should therefore be used in government appraisals as valuable context, but appraisal of individual public R&D projects should still be based on specific evidence of the likely returns most relevant to those projects.

The potential impact of public R&D in terms of wider social benefits is explored further in the next section.

4 Mechanisms through which returns to public R&D are generated

The econometric analysis reported in the previous sections provides estimates of the return to public R&D in terms of private sector productivity. However, one drawback of that approach is that it cannot explain the mechanisms through which public R&D influences private sector productivity. Furthermore, it cannot capture returns which accrue through other mechanisms such as returns to wider society or labour productivity, and for that reason those estimates should be treated as a lower bound on the total return to public R&D.

In this section, we draw on evidence from two qualitative case studies to provide real-world examples which characterise mechanisms linking public R&D to private sector productivity and other returns to public R&D.

4.1 The case studies

The case studies examined are:

- "Beyond Blue": A £1 million grant from the Engineering and Physical Sciences Research Council (EPSRC) for semiconductor research conducted at the Centre for Gallium Nitride at the University of Cambridge between 2015 and 2020.
- "SPRINT": The Space Research and Innovation Network for Technology, a £7.5 million project funded primarily by Research England between 2018 and 2022, that sought to connect SMEs with space-related expertise in participating UK universities and provided small grant funding to enable SMEs to purchase universities' input on collaborative R&D projects.

The case studies were chosen based on a desk review of the UKRI Gateway to Research database, and published impact statements from across UKRI.[50] Many other excellent examples of public R&D that have led to private sector impacts and wider social benefits can be found in those sources. The criteria for selection were for the case studies to relate to R&D conducted in the public sector, with an impact on private sector productivity. Consideration was also given for the case studies to help demonstrate a range of mechanisms through which public R&D impacts private sector productivity, and that this impact is realised in different economic sectors.

Full narrative case studies are provided respectively in annexes Annex E and Annex F . In this chapter we synthesise the findings to briefly summarise the mechanisms through which R&D generates returns that are evidenced by these case studies.

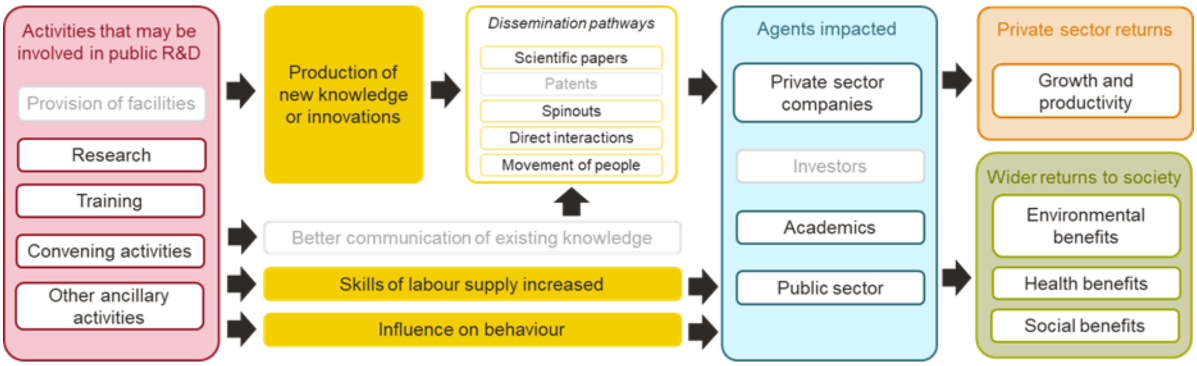
[50] The Gateway to Research database is available at https://gtr.ukri.org/. Research outcomes and impact statements are available on the UKRI website at https://www.ukri.org/who-we-are/how-we-are-doing/research-outcomes-and-impact/. Case studies on Aerospace Technology Institute projects are available through an online portal accessed via https://www.ati.org.uk/projects/.

4.2 Returns to public R&D

An overarching illustration of the main mechanisms through which public R&D can potentially generate returns was illustrated in Figure 1. Public R&D investment can fund many different types of activities, including most obviously research, but also the provision of equipment or facilities, training, convening activities or other ancillary activities that support R&D. These activities may produce new knowledge or innovations, but they may (as well or instead) increase awareness of existing knowledge, increase the skills of the workforce, or otherwise influence the behaviour of other organisations – be that private companies, investors, academics or the wider public sector. This can feed through into private sector returns or wider returns to society (or both).

The case studies examined provide real-world examples of these potential pathways through which returns may be generated. Figure 8 repeats Figure 1 but only colours those pathways that have been exemplified by the two case studies; those pathways that have not been evidenced here are greyed out.

Figure 8 Overview of mechanisms through which public R&D may generate returns



Source: *Frontier Economics.*

Each of the following mechanisms are evidenced, and are discussed in more detail below, with specific examples drawn from the two case studies:

1. The R&D produces new knowledge, or new applications of knowledge, that is transmitted to the private sector through the direct collaboration of a private partner in the R&D project.
2. The R&D produces new knowledge that is transmitted to the private sector without the involvement of a private sector project partner.
3. The R&D involves training and skills development which increases the productivity of workers in the public or private sectors.
4. The R&D results in end products or services that have wider benefits to society, such as benefits to the environment or to health.
5. The R&D has other influences on behaviour that result in wider benefits to society.

6. The R&D has other influences on behaviour that increases the production of new knowledge or the faster adoption of knowledge, or may do so in future.

One potentially important pathway that has not been explicitly evidenced through the two case studies included in this work is that public R&D may lead to better communication of existing knowledge. Public R&D may increase awareness of existing technologies that are already out there (potentially abroad), enabling private companies, academics and/or the public sector to better absorb existing technology and knowledge, which may feed through to productivity benefits or wider returns to society. The fact that this pathway is not explicitly evidenced should not be interpreted as this mechanism being non-existent or even less important than the other mechanisms that are evidenced, simply that this was less explicit from the case studies considered. In practice, there are also likely aspects of this pathway captured under pathway 1 above, as it is challenging for CR&D projects in particular to truly distinguish between 'new knowledge' and the absorption of existing knowledge that is given a new application.

4.2.1 R&D produces new knowledge that generates private sector returns through the involvement of a private sector collaborator

This pathway is most relevant for collaborative R&D (CR&D) projects that involve a direct collaboration on a piece of research between academic and private sector partners. As is illustrated in Figure 9, the general pathway can be described as:

- The research conducted by the academic partner generates some new knowledge.
- The collaborating private company is directly aware of this, and there is a return for the collaborator which (depending on the stage of development) might come through the new knowledge enabling production, increasing the efficiency of production, improving the quality of output, or improving access to finance.
- The product of the collaborator may also be used by wider private sector firms to increase their productivity or improve their output, adding to the private sector return.

Figure 9 Illustration of the pathway through which R&D produces knowledge that generates a private return through involvement of a collaborator

Source: Frontier Economics.

The SPRINT programme funded many CR&D projects, bringing together SMEs with universities that had space-related expertise or facilities, which demonstrate this pathway. For example:

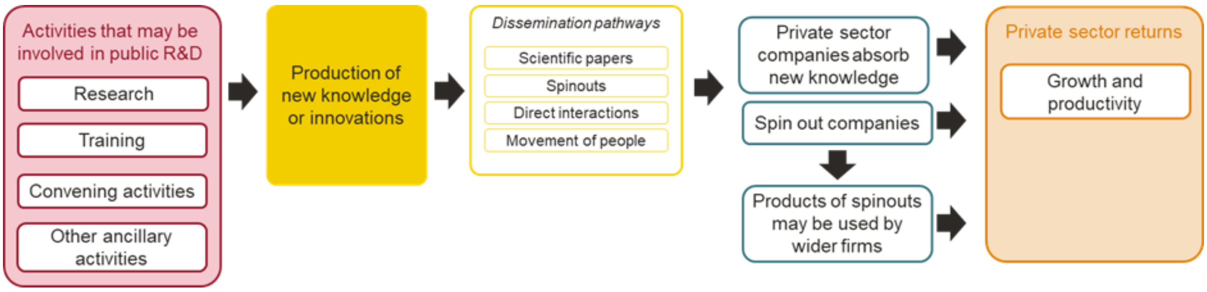
- Mafic Ltd is a construction company that uses machine learning and connected sensors to improve working environments. SPRINT supported three CR&D projects involving Mafic and the University of Southampton, and enabled Mafic to leverage academic expertise to save development time: one estimate suggests SPRINT participation halved Mafic's time spent on product development.[51]
- Mafic has not only grown as a private company as a result, but their products have had wider benefits. Their wearable sensors for construction workers have improved worker productivity for adopting firms (for example, by identifying bottlenecks and increases motivation by rewarding workers for productivity). One company saw a 8% increase in productivity as a result of a new shift pattern introduced by insights including from Mafic; introduction of an incentive scheme improved productivity by 13%.[52]

4.2.2 R&D produces new knowledge that generates private sector returns without the involvement of a private sector collaborator

This pathway is most relevant for public R&D projects that are conducted in university departments. As is illustrated in Figure 10, the general pathway can be described as:

- The academic research conducted generates some new knowledge.
- Firms in the private sector may become aware of this knowledge through academic papers, or interactions with researchers at field-specific conferences, or from the movement of people. This knowledge could then be used to improve their own production processes or improve the quality of their products.
- More likely, new knowledge with commercial application may be taken forwards by a spinout company, that seeks to demonstrate the commercial viability of the knowledge.
- Spinout companies contribute directly to private sector output, but they also become part of the supply chain offering innovative and productivity-enhancing products to other firms, further increasing the private sector return.

Figure 10 Illustration of the pathway through which R&D produces knowledge that generates a private return without involvement of a collaborator



Source: Frontier Economics.

[51] For further details please see section F.3 of the SPRINT case study.

[52] According to Mafic.

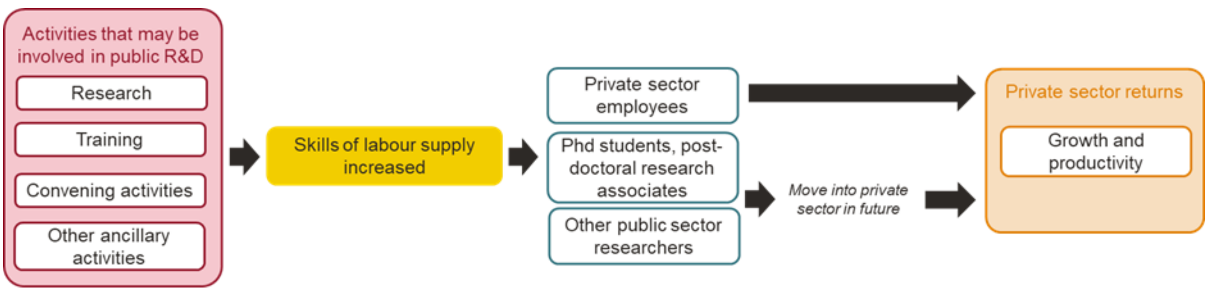
The Beyond Blue case study provides evidence of this pathway. The R&D produced new technological innovations and insights. These were communicated in many academic papers, and through engagement between the research team and a handful of private companies. The researchers involved in the Beyond Blue research were confident that their innovations impacted on the private sector through these channels, although the link is hard to demonstrate explicitly. The R&D also contributed to three spinout companies, and the private sector returns generated through these companies is evident. For example:

- Paragraf Ltd is a spinout company from the University of Cambridge that took forward the discovery of how to produce device-quality graphene at large scale. Through additional (private) funding, Paragraf has developed graphene-based electronic devices, and is producing magnetic sensors, biomedical sensors, and other semiconductor technologies, with applications in automotive, agri-tech, healthcare, automation, cryogenics and telecoms. This has resulted in increased private sector productivity through the output of both Paragraf itself and the wider companies adopting its technology.
- Poro Technologies Ltd is a spinout company from the University of Cambridge that took forwards the development of a process to create porous gallium nitride, and has since developed the technology to produce the first all-in-one microLED. This has resulted in private sector returns for both Porotech, and wider companies that are able to utilise this new technology and its associated manufacturing benefits, or build on this technology in their own R&D.

4.2.3 R&D upskills individuals in the public and private sectors

A third pathway identified through which public R&D generates returns in the private sector is through the upskilling of individuals. In some cases training and skill acquisition is implicit (obtained through conducting the research in question), but in many cases R&D funding contains explicit provision for training activities, such as support for PhD students or post-doctoral positions. Figure 11 illustrates that the R&D may increase the skills of people who are currently employed in industry, or it may increase the skills of people who are currently in academia but will go on to work in industry in future.

Figure 11 Illustration of the pathway through which R&D generates private sector returns by upskilling individuals



Source: Frontier Economics.

This pathway is demonstrated by the Beyond Blue case study. The research programme involved explicit training of individuals in industry (for example, employees of Plessey Semiconductors). It also included training for PhD students and post-doctoral research associates, around half of whom could be estimated to have gone on to work in directly related industry, taking their skills with them.

4.2.4 R&D results in end products or services that have wider benefits to society

The case studies examined provided evidence of wider social benefits arising from the public R&D. One of the main pathways to such benefits is through the products or services produced as a result of the R&D. This is illustrated in Figure 12.

Figure 12 Illustration of the pathway through which R&D produces products or services with wider benefits to society

Source: Frontier Economics.

There are multiple examples of this, including:

- Satellite Vu is a company that uses infrared technology to monitor objects on earth to determine their energy use and efficiency. SPRINT supported Satellite Vu in its work with The University of Surrey to validate the technology using advanced image analysis techniques. In addition to increasing private sector output through the growth of Satellite Vu, the company is also having wider environmental benefits by providing data that enables businesses to make decisions that are more environmentally friendly. For example, their technology is used to understand the environmental footprint of buildings and identify where retrofitting to improve energy efficiency would be efficient.
- Paragraf is producing graphene-based electronic devices with a wide variety of applications. These have environmental benefits where they are leading to a reduction in energy use, and health benefits where they are being used in medical applications (such next generation Magnetic Resonance Imaging (MRI) scanning, and biosensors).

4.2.5 R&D influences behaviour in ways that generate wider social benefits

The case studies also provided examples where the research involved ancillary activities that have other direct impacts on social outcomes. For example:

- Media training conducted as part of the Beyond Blue research project led to members of the research team increasing their profile, which led to an impact on policy. In particular, related to the impact of science funding policy on equality, diversity, inclusion and accessibility, and with regard to the development of the UK semiconductor strategy.

- Outreach activities conducted as part of the Beyond Blue project are believed by the research team to have increased the profile of science among children, which will help ensure a pool of productive workers in future.

These are illustrated in Figure 13.

Figure 13 Illustration of the pathway through which R&D may influence behaviour in ways that have wider benefits for society

Source: Frontier Economics.

4.2.6 R&D influences behaviour in ways that will increase the production or adoption of new knowledge in future

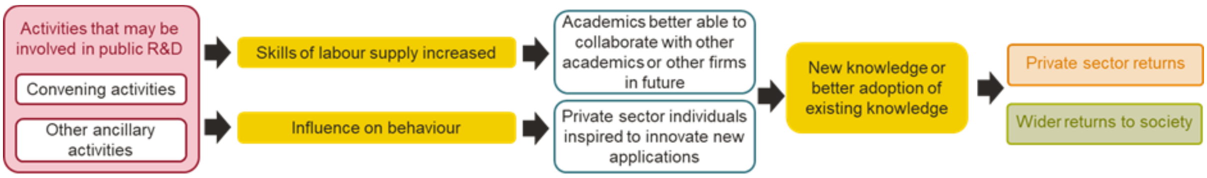
Finally, the case studies provided some examples where the research impacted the behaviour of different groups in ways that has either increased innovation, or could be expected to increase innovation (or the adoption of new innovations) in future.

Two different examples of this include:

- The advertisement of the SPRINT programme highlighted the potential application of ‘space technology’ across a vast range of applications. This is believed to have fostered innovation in the private sector, with firms developing and applying technology to new uses that they might not otherwise have thought of.
- The SPRINT programme improved academics’ ability to collaborate with each other and with companies. This is expected to benefit firms who seek to collaborate with academic partners in future.

These are illustrated in Figure 14.

Figure 14 Illustration of the pathway through which R&D may increase the production of knowledge in future



Source: Frontier Economics.

5 Conclusion

This study estimated the rate of return to public R&D investment, through its impact on private sector productivity. Previous studies quantified this relationship for the UK based on data up until the financial crisis. Changes since the crisis (declining productivity growth and sustained high levels of public R&D investment), and revisions to macro-economic data mean producing updated estimates is of key importance.

The focus of the study is on R&D that is both funded and performed by the public sector, which makes up about 80% of publicly-funded R&D in the UK. The findings suggest a positive and economically meaningful return to this public R&D. The exact estimates produced by this study should be interpreted with caution. Estimating the rate of return on public R&D investment is methodologically challenging. The estimates vary across specifications, and unobserved factors not captured in the this study could impact the rate of return estimates. In particular, concerns are raised by the fact that private sector R&D is known to be mis-measured, which may cause upward bias in the estimated rate of return to public R&D. Bearing these caveats in mind, the results suggest a rate of return of around 40% when a six year lag between public R&D and the impact on productivity is modelled. In other words, on average £100m of public R&D investment could be expected on average to yield an increase in annual private sector productivity of £40m in 6 years' time. Returns may be even greater over a longer period.

These returns are higher than some of the previous estimates for the UK – notably those published in HHBM/GHHW which suggested a rate of return of around 20%. This is largely believed to be due to revisions to macro-economic data (particularly official data on gross value added) since those estimates were produced. However, the cautions about potential sources of upward bias in the estimates mentioned above remain.

In interpreting the estimates, it is important to bear in mind two factors that mean that the rate of return quantified here actually understates the full benefit of public R&D investments. First, public R&D may stimulate private sector R&D, which itself has positive return in terms of productivity. This is not captured in the return to public R&D estimated here, which controls for private R&D separately (and in the calculation of TFP itself). Second, the estimated returns do not capture wider social benefits that are not reflected in private sector productivity, such as beneficial impacts on the environment or health.

This study complements the quantitative methodology with qualitative analysis of two case studies of past public R&D projects and the impacts they have had. These illustrate the mechanisms through which public R&D investment can lead to increased private sector productivity, and demonstrate that there can be important wider impacts on health and environmental outcomes.

Overall this study has provided quantitative and qualitative evidence in support of the value of public R&D spending. This is valuable context that should be used to support future appraisal of public sector spending. However, the quantitative results relate to average returns and not the return that every marginal public R&D investment would be expected to generate, while the qualitative findings illustrate possible mechanisms to returns and do not guarantee that any particular mechanism will be relevant for any individual investment. This evidence should therefore be used alongside, and not in any way in place of, thorough individual project appraisal in line with Green Book guidance.[53]

[53] The Green Book (2022) - GOV.UK (www.gov.uk).

Peer review by Gavin Wallis

The effect of both public and private R&D on UK economic growth and productivity remains a key economic and policy question. While there are different methods for studying the impact of R&D on growth and productivity all are essentially a challenge of measurement. This is particularly true when estimating the total economy wide return to R&D – including the spillovers to the broader economy and not just the direct return received by those conducting the R&D.

This study focuses on estimating the rate of return to public R&D investment through its impact on private sector productivity. It does so using the sources-of-growth plus spillovers framework – estimating the impact of the stock of public R&D on total factor productivity (TFP) in the private sector. This is the same approach used in my own work to try and tackle this difficult question.

In Goodridge et al. (2015) we found a statistically significant rate of return to public R&D of about 20%. The measurement challenges with that work were significant, much more so than with the data now available. Specifically:

- We had to construct our own measures of TFP growth to ensure that the contribution of intangible assets, including R&D, was properly accounted for. This study benefits from the extensive work since then, most recently by The Productivity Institute, to improve the underlying growth-accounting dataset.
- We were limited to a dataset covering just 13 years and 6 industries. As we noted at the time, most of the variation in our dataset was between-industry variation suggesting our estimates might be an understatement. This study benefits from a much longer time-series and for 40 industries, meaning much greater time and industry variation with which to try and estimate spillovers from public R&D.

In addition to the improvements in data noted above, there has also been significant revisions to the UK National Account data on the back of methodological improvements. Revisions to industry gross value added, and hence TFP, have been significant. This means an update to our previous work has a lot of value.

I agree with the conclusion that the exact estimates produced in this study should be interpreted with caution, given the measurement challenges that remain. However, I believe the study provides important additional evidence of a positive and economically meaningful return to public R&D. The estimated return is somewhat higher at 40% but is based on a much better dataset than was available to us almost a decade ago.

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Annex A – Underlying model derivations

This section provides additional information on the econometric specification used and in particular the derivation of the RoR on public R&D in equation (2) in Section 2.1.1.

Equation 1 in Section 2.1.1 provided a behavioural assumption for $\Delta lnTFP_{it}$:

$$\Delta lnTFP_{it} = A_{it} + \gamma_1 \Delta lnR_{it}^{PRI} + \gamma_2 M \Delta lnR_{-it}^{PRI} + \gamma_{3\text{it}} \Delta lnR_t^{PUB} + \epsilon_{it} \quad (1)$$

To estimate the rate of return directly, note that:

- γ_{3i} is an elasticity: $\gamma_{3it} = \frac{\delta TFP_{it}/TFP_{it}}{\delta R_t^{PUB}/R_t^{PUB}}$;
- $\Delta lnR_t^{PUB} \approx \frac{\Delta R_t^{PUB}}{R_t^{PUB}}$;
- The rate of return is defined as $\rho_{it} = \frac{\delta TFP_{it}}{\delta R_t^{PUB}}$, that is, the change in private sector TFP in industry *i* as a result of a change in the public sector knowledge stock. Assuming other inputs and their prices are not sensitive to R_t^{PUB}, this can be expressed using value added i.e. $\rho_{it} = \frac{\delta V_{it}}{\delta R_t^{PUB}}$
- If depreciation of public R&D (θ) is zero: $\Delta R_t^{PUB} = N_t^{PUB} - \theta R_{it-1}^{PUB} = N_t^{PUB}$; and,
- ϵ_{it} is an error term.

Then, from equation (1):

$$\Delta lnTFP_{it} = A_{it} + \gamma_1 \Delta lnR_{it}^{PRI} + \gamma_2 M \Delta lnR_{-it}^{PRI} + \gamma_{3it} \Delta lnR_{it}^{PUB} + \epsilon_{it}$$

$$\Delta lnTFP_{it} = A_{it} + \gamma_1 \Delta lnR_{it}^{PRI} + \gamma_2 M \Delta lnR_{-it}^{PRI} + \gamma_{3it} \frac{\Delta R_t^{PUB}}{R_t^{PUB}} + \epsilon_{it}$$

$$\Delta lnTFP_{it} = A_{it} + \gamma_1 \Delta lnR_{it}^{PRI} + \gamma_2 M \Delta lnR_{-it}^{PRI} + \frac{\delta V_{it}/V_{it}}{\delta R_t^{PUB}/R_t^{PUB}} \frac{\Delta R_t^{PUB}}{R_t^{PUB}} + \epsilon_{it}$$

$$\Delta lnTFP_{it} = A_{it} + \gamma_1 \Delta lnR_{it}^{PRI} + \gamma_2 M \Delta lnR_{-it}^{PRI} + \frac{\delta V_{it}}{\delta R_t^{PUB}} \frac{\Delta R_t^{PUB}}{V_{it}} + \epsilon_{it}$$

$$\Delta lnTFP_{it} = A_{it} + \gamma_1 \Delta lnR_{it}^{PRI} + \gamma_2 M \Delta lnR_{-it}^{PRI} + \rho_{it} \frac{\Delta R_t^{PUB}}{V_{it}} + \epsilon_{it}$$

$\Delta lnTFP_{it} = A_{it} + \gamma_1 \Delta lnR_{it}^{PRI} + \gamma_2 M \Delta lnR_{-it}^{PRI} + \rho_{it} \frac{N_t^{PUB}}{V_{it}} + \epsilon_{it}$ i.e. equation (2) in Section 2.1.1:

$\Delta lnTFP_{it} = A_{it} + \gamma_1 \Delta lnR_{it}^{PRI} + \gamma_2 M \Delta lnR_{-it}^{PRI} + \rho_{it} \frac{N_{t-3}^{PUB}}{V_{it-3}} + \epsilon_{it}$ using a 3-year lag between an increase in the public sector knowledge stock and any impact on private industry TFP.

The industry-specific rate of return ρ_{it} is modelled as a 'common' return ρ_1 scaled across industries according to the extent of spillovers from the public sector to each industry X_{it}. This is also normalised (i.e. divided) by the sum of X_{it} across all industries in that year: this ensures that the 'common' or average return ρ_1 can be observed when estimating the relationship modelled in equation (4). Using a 3-year lag, as above:

$$\Delta_3 lnTFP_{it} = A_{it} + \gamma_1 \Delta_3 lnR_{it-3}^{PRI} + \gamma_2 M \Delta_3 lnR_{-it}^{PRI} + \rho_1 \frac{X_{it-3}}{\Sigma X_{it-3}} \frac{N_{t-3}^{PUB}}{V_{it-3}} + \epsilon_{it} \quad (4)$$

Equation (6) below demonstrates that ρ_1 can be interpreted as the average rate of return to public R&D across all industries:

$$\sum \rho_{it} = \sum \rho_1 \frac{X_{it-3}}{\sum_{i=1}^{N} X_{it-3}} = \rho_1 \frac{\sum_{i=1}^{N} X_{it-3}}{\sum_{i=1}^{N} X_{it-3}} = \rho_1 \quad (6)$$

Annex B – Industry groups

Table 11 shows the composition of the granular industry groups. Table 12 shows the composition of the broad industry groups used to compare the estimated rate of return to public R&D investment with previous estimates.

Table 11 Granular industry groups

Industry group	Description	SIC 2007 groups contained
B5t9	Mining and Quarrying	B5 to B9
C10t12	Manufacture of food, beverages & tobacco	C10 to C12
C13t15	Manufacture of textiles, wearing apparel & leather products	C13 to C15
C16t18	Manufacture of wood & paper products; printing and reproduction of recorded media	C16 to C18
C19	Manufacture of coke and refined petroleum products	C19
C20	Manufacture of chemicals and chemical products	C20
C21	Manufacture of basic pharmaceutical products and pharmaceutical preparations	C21
C22t23	Manufacture of rubber, plastic and non-metallic mineral products	C22 to C23
C24t25	Manufacture of basic & fabricated metals	C24 to C25
C26	Manufacture of computer, electronic and optical products	C26
C27	Manufacture of electrical equipment	C27
C28	Manufacture of machinery and equipment n.e.c.	C28
C29t30	Manufacture of transport equipment	C29 to C30
C31t33	Manufacture of furniture; other manufacturing; repair and installation	C31 to C33
D35	Electricity, Gas, Steam and Air Conditioning Supply	D35
E36t39	Water Supply; Sewerage, Waste Management and Remediation Activities	E36 to E39
F41t43	Construction	F41 to F43
G45	Wholesale and retail trade and repair of motor vehicles and motorcycles	G45
G46	Wholesale trade, except of motor vehicles and motorcycles	G46
G47	Retail trade, except of motor vehicles and motorcycles	G47
H49	Land transport and transport via pipelines	H49
H51	Air transport	H51
H52	Warehousing and support activities for transportation	H52
H53	Postal and courier activities	H53
I55t56	Accommodation and Food Service Activities	I55 to I56
J58t60	Publishing; Motion picture, video and television, sound recording and music publishing; Programming and broadcasting	J58 to J60

Industry group	Description	SIC 2007 groups contained
J61	Telecommunications	J61
J62t63	Computer programming, consultancy and related activities; Information service act.	J62 to J63
K64t66	Financial and Insurance Activities	K64 to K66
M69t70	Legal and accounting activities; Activities of head offices; management consultancy activities	M69 to M70
M71	Architectural and engineering activities; technical testing and analysis	M71
M72	Scientific research and development	M72
M73	Advertising and market research	M73
M74t75	Other professional, scientific and technical activities	M74 to M75
N77	Rental and leasing activities	N77
N78	Employment activities	N78
N79	Travel agency, tour operator and other reservation service and related activities	N79
N80t82	Security and investigation; Services to buildings and landscape; Office administrative and other business support	N80 to N82
R90t93	Arts, Entertainment and Recreation	R90 to R93
S94t96	Other Service Activities	S94 to S96

Source: Frontier Economics calculations based on TPI: TPI UK Intangibles Growth-Accounting data set (manchester.ac.uk).
Note: R90t93 is not available in UKIS.

Table 12 Broad industry groups

Industry group	Description	SIC 2007 groups contained
D	Manufacturing	C10 to C33
E	Utilities (electricity; gas and water supply)	D35, E36 to E39
F	Construction	F41 to F43
GHI	Distribution; hotels and restaurants; transport, storage and communications	G45 to G47, H49 to H53, I55 to I56, J58 to J63
J	Financial services	K64 to K66
K	Business activities	M69 to M75, N77 to N82

Source: Frontier Economics calculations based on HHBM/GHHW.
Note: The SIC 2007 groups R90t93 and S94t96 are not included in any of the broad industry groups. The Business activities broad industry group excludes real estate.

Annex C – Relative size of public sector spillovers from UKIS

Two of the approaches taken for proxying for the relative knowledge flows from the public sector to each industry use measures of interactions between the public and private sector in their innovation activities calculated from the UK Innovation Survey (UKIS).

UKIS collects data from firms about their innovation activities to document trends in UK innovation.

Two metrics are calculated:

- the % share of firms in each industry who report that information from the public sector is important for their own innovation activities ("INFO"); and,
- the % share of firms in each industry who report collaborating on innovation with the public sector ("CO-OP").

In this study data is used from the following UKIS waves (with corresponding time windows in parenthesis: wave 3 (1998-2000); wave 4 (2002-4), 5 (2004-6), 6 (2006-8), 7 (2008-10), 8 (2010-12), 9 (2012-14), 10 (2014-16) and 11 (2016-18).[54] The above metrics are calculated for each wave of UKIS.

To calculate annual measures as required for the estimation in this study, the average is calculated across all of the waves that cover a given year. For example, both wave 10 and 11 cover 2016, therefore the average is taken across wave 10 and 11 to obtain the value for 2016.

The desired metrics cannot always be calculated from the UKIS data at the same level of industry granularity as the other data sources (e.g. TPI) used in this study, due to the sample sizes available in UKIS.[55] Where this is the case, the desired metrics are calculated for a broader industry group, and it is assumed that all the more granular industries included in that group have the same interaction levels as the wider group itself.

Variation in rates of return according to who conducts the R&D

The analysis in section 3.3.2 examines whether the rate of return to public R&D differs according to who conducts the R&D. For this, separate metrics for interactions with universities ("HE") and with central government/UKRI ("GOV") are calculated.

It is not possible to calculate these separately for each *granular* industry in each wave of UKIS due to insufficient sample sizes in the UKIS data. Instead, these are calculated at a *wider*

[54] Data for wave 3 is only used when estimating the rate of return using broad industry groups (in section 3.2). There is insufficient sample size in wave 3 to calculate the required metrics for the granular industries used in this study and therefore data is used from wave 4 (2002-2004) for the years 1998-2001.

[55] Due to issues such as changes in the sampling frame (the industries included in each UKIS survey) over time and to avoid statistical disclosure. Data is available on 19 industry groups for waves 4-11 for INFO and CO-UP for the % share of firms who report interactions with the public sector.

industry aggregation, and for the public sector overall ("PUB") rather than separately for HE and GOV.

To obtain the HE and GOV-specific interaction levels adjustments are made for the difference in interaction levels between the public sector (i.e. "PUB") and HE, and between the public sector and GOV. Data is available for these adjustments, separately for HE and GOV, for each UKIS wave aggregated across all industries and for 30 *granular* industry groups aggregated across all waves.

Adjustments are made for **time-specific differences** (via the difference in interaction levels between PUB and HE, and separately between PUB and GOV, for a given wave). For example, assume that for the "CO-OP" interaction metric, the wave 4 average across all industries of the interaction level for HE is 5% and the level for PUB is 10%.[56] In this case, the PUB interaction level for *wider* industry *i* in wave 4 is multiplied by the ratio of the HE and PUB levels estimated across all industries in wave 4, that is, by 5% / 10% = 0.5.

Similar adjustments are made for **industry-specific differences** (via the difference in interaction levels between the HE / PUB and separately the GOV / PUB ratios for (i) *granular* industry *j*, where the interaction levels are aggregated across all waves, and for (ii) the simple average across all waves of wave-specific interaction levels). If for *granular* industry *j* across all waves the ratio of the interaction level for HE to that of PUB is 0.75, but the ratio across all industries is 2.25, the PUB interaction level for industry *i* in wave 4 (for example) is multiplied by 0.75 / 2.25 = 0.33.

In this example, the total adjustment applied is equal to 0.5 * 0.33 = 0.167 where *granular* industry *j* is included in *wider* industry *i* (in some cases a *granular* industry is itself a *wider* industry).

Further details of the calculations presented in this Annex are provided in Frontier Economics (2024).

[56] In other words, 5% of firms in a given industry report collaboration with the universities on innovation while 10% report collaboration with the public sector overall.

Annex D – Further econometric results

Table 13 Sensitivity results for the rate of return to public R&D – by lag length of public R&D investment and measure of public knowledge spillovers

Lag for public R&D	3 years			6 years			10 years		
	R&D	INFO	CO-OP	R&D	INFO	CO-OP	R&D	INFO	CO-OP
Coefficient estimates									
Funder defence adjustment	82%*	108%	93%*	4%	39%***	44%***	48%***	106%***	86%***
No defence adjustment	68%*	81%	71%*	6%	31%***	34%***	38%***	80%***	66%***
Excluding private spillovers	78%*	102%	88%*	5%	39%***	43%***	47%***	102%***	83%***

Source: Frontier Economics calculations.

Note: Econometric model estimated with time dummies and random effects (results for these are not reported). (*) significant at 10% / (**) at 5% / (***) at 1%. The table summarises the estimated rate of return to public R&D from various specifications. The first three columns show the estimated rate of return to public R&D when the impact of public R&D on private sector productivity is modelled with a 3-year lag, with each column containing the results for a different approach to measuring the relative size of public sector spillovers across industries. The other panels in the table set out how the estimates change when the length of time between public R&D and productivity is modelled as 6 years and 10 years, respectively. The rows test the sensitivity of the estimated rate of return to the following alternative specifications: (i) excluding defence-related public R&D that is funded by the public sector, rather than defence related R&D performed in the public sector; (ii) including defence-related public R&D; (iii) excluding private sector spillovers.

Table 14 Econometric results with TFP growth measured over a common period (2008 to 2019) – by lag length of public R&D investment and measure of public knowledge spillovers

Lag for public R&D	3 years			6 years			10 years		
	R&D	INFO	CO-OP	R&D	INFO	CO-OP	R&D	INFO	CO-OP
Coefficient estimates									
Private R&D	0.116	0.06	0.075	0.132	0.142	0.137	0.129	0.125	0.122
Private spillovers	-0.227	-0.219	-0.245	-0.31	-0.261	-0.241	-0.298	-0.246	-0.263
Public R&D	**102%****	**234%*****	**206%*****	**14%**	**65%****	**84%*****	**45%*****	**99%*****	**80%*****
Summary statistics									
Sample size	480	468	468	480	468	468	480	468	468
Industry groups	40	39	39	40	39	39	40	39	39
R squared	0.047	0.217	0.227	0.071	0.362	0.379	0.314	0.653	0.635

Source: Frontier Economics calculations.

Note: Econometric model estimated with time dummies and random effects (results for these are not reported). (*) significant at 10% / (**) at 5% / (***) at 1%. The coefficient estimates for "Public R&D" are rates of return while the other coefficient estimates are elasticities. The first three columns show the results when the impact of public R&D on private sector productivity is modelled with a 3-year lag, with each column containing the results for a different approach to measuring the relative size of public sector spillovers across industries. The other panels in the table set out how the estimates change when the length of time between public R&D and productivity is modelled as 6 years and 10 years, respectively. The estimates for the rate of return to public R&D are highlighted yellow and bold.

Table 15 Econometric results with public R&D measured over a common period (1998 to 2009) – by lag length of public R&D investment and measure of public knowledge spillovers

Lag for public R&D	3 years			6 years			10 years		
	R&D	INFO	CO-OP	R&D	INFO	CO-OP	R&D	INFO	CO-OP
Coefficient estimates									
Private R&D	0.066	0.071	0.071	0.229	0.225	0.223	0.129	0.125	0.122
Private spillovers	-0.218	-0.25	-0.256	-0.275	-0.269	-0.264	-0.298	-0.246	-0.263
Public R&D	**69%*****	**66%*** **	**55%*** **	**21%**	**37%*** **	**43%*** **	**45%*** **	**99%*** **	**80%*** **
Summary statistics									
Sample size	480	468	468	480	468	468	480	468	468
Industry groups	40	39	39	40	39	39	40	39	39
R squared	0.306	0.345	0.351	0.078	0.247	0.282	0.314	0.653	0.635

Source: Frontier Economics calculations.

Note: Econometric model estimated with time dummies and random effects (results for these are not reported). (*) significant at 10% / (**) at 5% / (***) at 1%. The coefficient estimates for "Public R&D" are rates of return while the other coefficient estimates are elasticities. The first three columns show the results when the impact of public R&D on private sector productivity is modelled with a 3-year lag, with each column containing the results for a different approach to measuring the relative size of public sector spillovers across industries. The other panels in the table set out how the estimates change when the length of time between public R&D and productivity is modelled as 6 years and 10 years, respectively. The estimates for the rate of return to public R&D are highlighted yellow and bold.

Table 16 Econometric results using broad industry groups as in HHBM/GHHW and data from 1998 to 2007 only – by lag length of public R&D investment and measure of public knowledge spillovers

Lag for public R&D	3 years			6 years		
	R&D	INFO	CO-OP	R&D	INFO	CO-OP
Coefficient estimates						
Private R&D	0.267***	0.327**	0.274***	0.483***	0.347***	0.403***
Private spillovers	1.788***	3.223**	2.82*	2.042***	1.381**	1.405**
Public R&D	**193%****	**384%****	**197%***	**227%****	**-266%*****	**-177%*****
Summary statistics						
Sample size	42	42	42	24	24	24
Industry groups	6	6	6	6	6	6
R squared	0.847	0.083	0.227	0.827	0.812	0.810

Source: Frontier Economics calculations.

Note: Econometric model estimated with time dummies and random effects (results for these are not reported). (*) significant at 10% / (**) at 5% / (***) at 1%. The coefficient estimates for "Public R&D" are rates of return while the other coefficient estimates are elasticities. The first three columns show the results when the impact of public R&D on private sector productivity is modelled with a 3-year lag, with each column containing the results for a different approach to measuring the relative size of public sector spillovers across industries. The other panel in the table sets out how the estimates change when the length of time between public R&D and productivity is modelled as 6 years. The estimates for the rate of return to public R&D are highlighted yellow and bold.

Table 17 Econometric results using broad industry groups as in HHBM/GHHW and data from 1998 to 2007 only, and excluding private spillovers – by lag length of public R&D investment and measure of public knowledge spillovers

Lag for public R&D	3 years			6 years		
	R&D	INFO	CO-OP	R&D	INFO	CO-OP
Coefficient estimates						
Private R&D	0.121	0.137	0.154	0.234*	0.229**	0.226**
Public R&D	**204%**	**334%*** **	**220%*** **	**133%**	**-229%*** **	**-151%*** **
Summary statistics						
Sample size	42	42	42	24	24	24
Industry groups	6	6	6	6	6	6
R squared	0.564	0.172	0.170	0.475	0.696	0.699

Source: Frontier Economics calculations.

Note: Econometric model estimated with time dummies and random effects (results for these are not reported). (*) significant at 10% / (**) at 5% / (***) at 1%. The coefficient estimates for "Public R&D" are rates of return while the other coefficient estimates are elasticities. The first three columns show the results when the impact of public R&D on private sector productivity is modelled with a 3-year lag, with each column containing the results for a different approach to measuring the relative size of public sector spillovers across industries. The other panel in the table sets out how the estimates change when the length of time between public R&D and productivity is modelled as 6 years. The estimates for the rate of return to public R&D are highlighted yellow and bold.

Table 18 Econometric results for the pre-crisis (1998 to 2007) and post-crisis (2008 to 2019) period, UKIS measures of public knowledge spillovers – by lag length of public R&D investment and measure of public knowledge spillovers

Lag for public R&D	3 years		3 years		6 years		6 years	
	INFO		CO-OP		INFO		CO-OP	
	Pre-crisis	Post-crisis	Pre-crisis	Post-crisis	Pre-crisis	Post-crisis	Pre-crisis	Post-crisis
Coefficient estimates								
Private R&D	-0.015	0.06	-0.016	0.075	-0.054	0.142	-0.056	0.137
Private spillovers	-0.415	-0.219	-0.417	-0.245	-0.531	-0.261	-0.542	-0.241
Public R&D	**100%*****	**234%*****	**96%*****	**206%*****	**55%*****	**65%****	**50%*****	**84%*****
Summary statistics								
Sample size	273	468	273	468	156	468	156	468
Industry groups	39	39	39	39	39	39	39	39
R squared	0.324	0.217	0.335	0.227	0.265	0.362	0.264	0.379

Source: Frontier Economics calculations.

Note: Econometric model estimated with time dummies and random effects (results for these are not reported). (*) significant at 10% / (**) at 5% / (***) at 1%. The coefficient estimates for "Public R&D" are rates of return while the other coefficient estimates are elasticities. The first four columns show the results when the impact of public R&D on private sector productivity is modelled with a 3-year lag, with each column containing the results for a different approach to measuring the relative size of public sector spillovers across industries (using the UKIS measures) and time period (pre-crisis and post-crisis). The last four columns in the table set out how the estimates change when the length of time between public R&D and productivity is modelled as 6 years. The estimates for the rate of return to public R&D are highlighted yellow and bold.

Table 19 Econometric results for the pre-crisis (1998 to 2007) and post-crisis (2008 to 2019) period, R&D intensity measure of public knowledge spillovers including with additional control for R&D intensity – by lag length of public R&D investment and measure of public knowledge spillovers

Lag for public R&D	3 years		3 years		6 years		6 years	
	R&D intensity		R&D intensity & control		R&D intensity		R&D intensity & control	
	Pre-crisis	Post-crisis	Pre-crisis	Post-crisis	Pre-crisis	Post-crisis	Pre-crisis	Post-crisis
Coefficient estimates								
Private R&D	-0.017	0.116	-0.017	0.131	-0.06	0.132	-0.061	0.131
Private spillovers	-0.369	-0.227	-0.379	-0.218	-0.484	-0.31	-0.482	-0.308
Public R&D	**99%*** **	**102%** **	**101%*** **	**172%*** **	**48%*** **	**14%**	**46%*** **	**55%**
Summary statistics								
Sample size	280	480	280	480	160	480	160	480
Industry groups	40	40	40	40	40	40	40	40
R squared	0.373	0.047	0.379	0.220	0.261	0.071	0.256	0.396

Source: Frontier Economics calculations.

Note: Econometric model estimated with time dummies and random effects (results for these are not reported). (*) significant at 10% / (**) at 5% / (***) at 1%. The coefficient estimates for "Public R&D" are rates of return while the other coefficient estimates are elasticities. The first four columns show the results when the impact of public R&D on private sector productivity is modelled with a 3-year lag, with each column containing the results for a different time period (pre-crisis and post-crisis). R&D intensity is used to mease the relative size of public sector spillovers across industries; in the "R&D intensity & control" columns the level of R&D intensity in the industry relative to other industries is added as a control variable to the estimating equation (see equation (4) in section 2.1.1). The last four columns in the table set out how the estimates change when the length of time between public R&D and productivity is modelled as 6 years. The estimates for the rate of return to public R&D are highlighted yellow and bold.

Table 20 Econometric results for the pre-crisis (1998 to 2007) and post-crisis (2008 to 2019) period, UKIS measures of public knowledge spillovers and additional control for R&D intensity – by lag length of public R&D investment and measure of public knowledge spillovers

Lag for public R&D	3 years		3 years		6 years		6 years	
	INFO & control		CO-OP & control		INFO & control		CO-OP & control	
	Pre-crisis	Post-crisis	Pre-crisis	Post-crisis	Pre-crisis	Post-crisis	Pre-crisis	Post-crisis
Coefficient estimates								
Private R&D	-0.012	0.066	-0.053	0.138	-0.013	0.08	-0.055	0.13
Private spillovers	-0.371	-0.228	-0.494	-0.252	-0.379	-0.255	-0.509	-0.227
Public R&D	**97%*****	**242%*****	**54%*****	**77%*****	**92%*****	**219%*****	**49%*****	**98%*****
Summary statistics								
Sample size	273	468	156	468	273	468	156	468
Industry groups	39	39	39	39	39	39	39	39
R squared	0.351	0.298	0.285	0.447	0.353	0.316	0.279	0.483

Source: Frontier Economics calculations.

Note: Econometric model estimated with time dummies and random effects (results for these are not reported). (*) significant at 10% / (**) at 5% / (***) at 1%. The coefficient estimates for "Public R&D" are rates of return while the other coefficient estimates are elasticities. The first four columns show the results when the impact of public R&D on private sector productivity is modelled with a 3-year lag, with each column containing the results for a different approach to measuring the relative size of public sector spillovers across industries (using the UKIS measures) and time period (pre-crisis and post-crisis). The level of R&D intensity in the industry relative to other industries is added as a control variable to the estimating equation (see equation (4) in section 2.1.1). The last four columns in the table set out how the estimates change when the length of time between public R&D and productivity is modelled as 6 years. The estimates for the rate of return to public R&D are highlighted yellow and bold.

Table 21 Econometric results separately for "GOV" and "HE" – by lag length of public R&D investment and measure of public knowledge spillovers

Lag for public R&D	3 years			6 years			10 years		
	R&D	**INFO**	**CO-OP**	**R&D**	**INFO**	**CO-OP**	**R&D**	**INFO**	**CO-OP**
Coefficient estimates									
Private R&D	0.074	0.049	0.061	0.096	0.104	0.102	0.133	0.128	0.125
Private spillovers	-0.234	-0.190	-0.250	-0.299	-0.259	-0.252	-0.29	-0.206	-0.238
HE R&D	**120%**	**467%**	**388%**	**-89%**	**44%**	**82%**	**138%**	**230%**	**235%**
GOV R&D	**-17%**	**-606%**	**-628%**	**242%**	**32%**	**-51%**	**-116%**	**-132%**	**-277%**
Descriptive statistics									
Sample size	760	741	741	640	624	624	480	468	468
Industry groups	40	39	39	40	39	39	40	39	39
R squared	0.237	0.192	0.335	0.271	0.481	0.487	0.300	0.536	0.550

Source: Frontier Economics calculations.

Note: Econometric model estimated with time dummies and random effects (results for these are not reported). (*) significant at 10% / (**) at 5% / (***) at 1%. The coefficient estimates for "HE R&D" and "GOV R&D" are rates of return while the other coefficient estimates are elasticities. The first three columns show the results when the impact of public R&D (separately for "HE" and "GOV") on private sector productivity is modelled with a 3-year lag, with each column containing the results for a different approach to measuring the relative size of public sector spillovers across industries. The other panels in the table set out how the estimates change when the length of time between public R&D and productivity is modelled as 6 years and 10 years, respectively. The estimates for the rate of return to public R&D are highlighted yellow and bold.

Annex E – Case Study: Beyond Blue

Executive summary

Beyond Blue was a £1 million grant for semiconductor research conducted at the University of Cambridge between 2015 and 2020. The research contributed directly to significant technological advancements, including the development of graphene-based electronic devices suitable for mass production, porous gallium nitride and red micro LEDs.

Three spinout companies were the main initial mechanism through which this technological knowledge has been transferred to the private sector. These companies have continued to develop their technologies, which are finding applications in different sectors, with consequences for the growth of other companies. Two of these companies, Paragraf Limited and Poro Technologies Limited, between them now employ over 180 individuals with offices both in the UK and internationally.

Through their applications the technologies are having environmental benefits (for example, by reducing energy use and supporting the development of electric vehicles) and health benefits (for example, through improved medical diagnostics). In addition, the Beyond Blue research grant supported wider activities, alongside core research, that can be traced to societal benefits including an increased awareness of equality, diversity and inclusion in science, and a greater appreciation of science among young people.

E.1 Introduction

This case study focuses on a £1 million platform grant "Beyond Blue: New Horizons in Nitrides" from the Engineering and Physical Sciences Research Council (EPSRC) that funded research conducted at the Centre for Gallium Nitride at the University of Cambridge over the period 2015 to 2020.

The case study explores the routes through which the research fed through into the private sector, and wider social benefits.

The case study is based on desk research of related materials (including the project information and reported outcomes in the Gateway to Research database[57]) and interviews with stakeholders (including academics involved in the research and representatives from spinout companies).

[57] https://gtr.ukri.org/projects?ref=EP%2FM010589%2F1

E.2 The ‘Beyond Blue’ research

Platform grants were a form of competitive grant made available by EPSRC at that time that provided underpinning funding for large research groups and allowed some flexibility in the research that was done. The nature of the grant means that the funding covered core planned research activities, as well as allowing researchers the flexibility to explore extra research avenues that appeared and seemed promising. Researchers at the Centre for Gallium Nitride also obtained additional public funding for specific research projects that built on the research ideas being supported by the platform grant. Platform grants are no longer offered by EPSRC, which the stakeholders all viewed as a shame given the perceived benefits of the flexibility they afforded.

> *“The thing about the platform grant is it gives you a bit of space and time. And I think probably I would say that does incentivise commercialization because it means that by taking the pressure off, the continual need to write the next grant proposal and apply for the next grant, it gives you time to spend on these other aspects of your job.”*

> *“[The nature of the platform grant] allowed us to recruit some slightly unusual people who came out of industry. Having those people embedded made a difference to our thinking. But we would not necessarily have employed them onto very defined standard postdocs positions because they didn't necessarily have the very neat skill set.”*

> *“It was very much about underpinning the ecosystem we had running at the time, being able to give postdocs freedom to go sideways rather than just kind of stay on the track of the project they were on.”*

> *“[The platform grant] really enabled him to [pursue what turned out to be a ground-breaking idea] because we didn't have to go back to put a grant application in, which probably would have failed because we had no experience with the area.”*

The grant had a number of scientific themes, including the growth of light emitting diodes (LEDs) on large area substrates, developing efficient light transmitters at longer and shorter wavelengths than the established gallium nitride blue LEDs (green and amber at one end of the spectrum, and ultraviolet at the other), exploring more exotic light sources (such as single photon sources and laser diodes), exploring different growth methodologies for growing nitride crystals, and developing new electronic devices (transistor devices).

The research supported by the grant was very successful and contributed directly to significant technological advancements, including the development of porous gallium nitride, red micro LEDs, and graphene-based electronic devices suitable for mass production.

E.3 Mechanisms through which the R&D generated a return in the private sector

There are two high-level routes by which the research funded by the ‘Beyond Blue’ grant fed through directly into the private sector. The first was the production of knowledge that had, or was subsequently developed to have, commercial applications. The second was the training of personnel who worked in, or went on to work in, the private sector.

Production of knowledge

The case study explored the particular mechanisms through which the knowledge generated by the 'Beyond Blue' research reached the private sector. Four potential mechanisms were discussed in detail:

- **Scientific publications.** Scientific publications are a key output of academic research, and are important for early career researchers to establish their reputations. The research funded by the Beyond Blue grant contributed to at least 150 academic publications. Stakeholders varied in their views on the importance of scientific papers as a mechanism for the transfer of knowledge from academia to the private sector.
  - The academic researchers were confident that research they have published in this field (though not necessarily from this grant) had, on occasion, been picked up by industry, though they believed that this was more often than not with international industry rather than UK industry.

    "I can think of, not necessarily from this grant, from my research broadly, situations where I know that industry have taken on stuff that was first in our publications and I'm pretty sure that they are doing so because they read the publications, but there's no direct link at all. That's more often than not with international industry than with UK industry."

  - The view from a spinout company representative was that while academic papers might be a useful starting point, concepts would typically take significant development work to have practical applications for industry. It was also highlighted by stakeholders that there is an inherent tension surrounding academic papers between a desire to publish research findings to share knowledge and gain reputation and a desire to capture any commercial potential from research findings. Research findings with the most immediate and direct commercial applications (and therefore benefits for private firms) are therefore least likely to appear in scientific publications.

    "Early career researchers, in particular, they need publications. That's what needs to be on their CV. But if you sit on them while patents are written and made as effective in protecting your IP as possible, and then you potentially want to choose your moment when to submit the patent and maybe sit on information like know how around the patent… it genuinely prevents publications and it causes huge tensions."

- **Direct industry interactions.** The researchers involved in the grant highlighted that they had a number of direct interactions with industry relating to the research they were conducting. Sometimes these connections were made as a result of industry representatives reading a scientific paper or attending a field conference and making an approach to discuss the research further. In other instances the researchers had an established connection with companies and would regularly meet with the company to discuss the direction of their research and any areas of mutual interest that could be explored through future collaboration. This was the case with Plessey Semiconductors for example, whom the research group had an existing relationship with before the Beyond Blue grant. These relationships enabled the co-production of knowledge that fed directly to engaged private sector companies.

"Industries will get in touch: 'we can see that you have expertise in X, can you help us with Y?' That may be via publications and perhaps more often because industries come to conferences in our field. So you'll deliver a presentation and then some will say to you at the end 'okay you can do that, could you do this for us?'"

"Engagement with [a private company] came from me giving a talk at a conference where there was a scientist from this company in the audience."

While this is believed to have been an important mechanism for knowledge transfer in the past, one stakeholder interviewed raised concerns about the ability of industry to engage with many universities today. Specifically, there are increasing costs and roadblocks for companies that want to engage with universities, as a result of universities increasingly trying to monetise their research (for example, through university knowledge transfer offices). This could result in a reduction in the extent to which research being produced in universities actually ends up being utilised in the private sector.

"A lot of universities now have caught onto this concept of the knowledge transfer offices or tech transfer offices. They are actively roadblocks to knowledge getting out into the outside world. I'll give you an example. There was an academic at a university who wanted to work with us. But their tech transfer office said they could not without us paying a significant sum. Before even licensing any IP, just to work with the Professor. It's completely disincentivizing any company to go and work with a university. That's why knowledge transfer network projects are actually quite good, because they put a heavy stamp on it that the industry partner must own the IP at the end. I shudder to think how much fantastic research there is in universities that's not being utilised in the real world."

- **Patents**. Patents are a form of intellectual property (IP) that gives the owner the legal right to exclude others from making, using, or selling an invention for a limited period. While the licensing of patented technology to private sector firms could, theoretically, be a key way for the knowledge produced by R&D in universities to be taken up by the private sector, the researchers involved in the Beyond Blue grant indicated that in their experience this rarely happens in practice, and it did not happen for the IP generated from the Beyond Blue grant. Companies potentially interested in the IP would want to have confidence that the technology or innovation could be operated at scale before licensing it. Instead it is far more common for academics who have developed technology to create a spinout company that can generate and demonstrate scale from patented IP and then attract interest from larger industry.

"When I first started writing patents, I had a very naive view whereby they would sit in the patent database and people come along and pick them out, do brilliant things with them and pay me money. But to the extent that that was ever true, it is less and less true. Often you go the spinout company route once you've got patented IP as a way of getting the idea to a scale where you can interest larger industry."

- **Spinout companies**. Spinout companies were seen by all those as involved in the Beyond Blue grant as the most effective way of seeing the knowledge generated from university research through to private sector application. Spinout companies could either be sold off to another company once the potential for the technology had been demonstrated, or could continue to be grown as companies.

  Spinout companies lead to private sector returns in several ways. They are companies in their own right, employing people and producing output themselves. They are also typically elements in a supply chain, buying from and selling to other companies and thereby influencing the productivity of those firms. Many spinouts continue to invest and produce further innovations, thus increasing the productivity benefits they enjoy arising from the original innovation. The innovations and productivity benefits can be shared with wider firms through the licencing of IP, or could even be generated by other firms building on the technology of the spinout. In either case this would have productivity benefits for wider firms.

  “You're not just spinning out a company, you're spinning out an element in a supply chain.”

  “The devices we make are really high performance, transformative devices. The application spaces we're selling into, we're enabling other people to create their own applications and technologies in ways they couldn't do before. Our technology is enabling their own technologies and these range across many, many different spaces.”

  “Quite often we’ll develop new products together [the spinout and another company], through collaborative projects. Because we're bringing our technology, they don't really understand. They're trying to develop an application space that we don't understand. So working together is only the only real way of getting it to fundamentally work.”

  There were three spinout companies that stakeholders attributed (at least in part) to the Beyond Blue grant: Kubos Semiconductors, Paragraf and Porotech. The latter two are discussed in more detail below.

Spinout: Paragraf (Paragraf Limited)

The Beyond Blue grant did not initially envisage supporting research on graphene. However, the flexibility of the grant meant that the principal investigator could support a small project looking to create a graphene gallium nitride device (combining graphene and gallium nitride). This led the research group to the problem of how to obtain device quality large area graphene, which it was not known how to manufacture at the time, and consequently to the idea that their equipment being used to make gallium nitride could be used to make graphene. This resulted in a successful project to develop a new method for making high quality large area graphene.

In 2017 the researchers involved decided to pursue the use of graphene in industry and spun out a company Paragraf. The IP generated from the university research was to create graphene, and Paragraf subsequently developed the technology to turn graphene into electronic solid-state devices. Since it was established Paragraf has raised over $85 million in funding. Today the company employs around 130 people at two sites in the UK and one in the

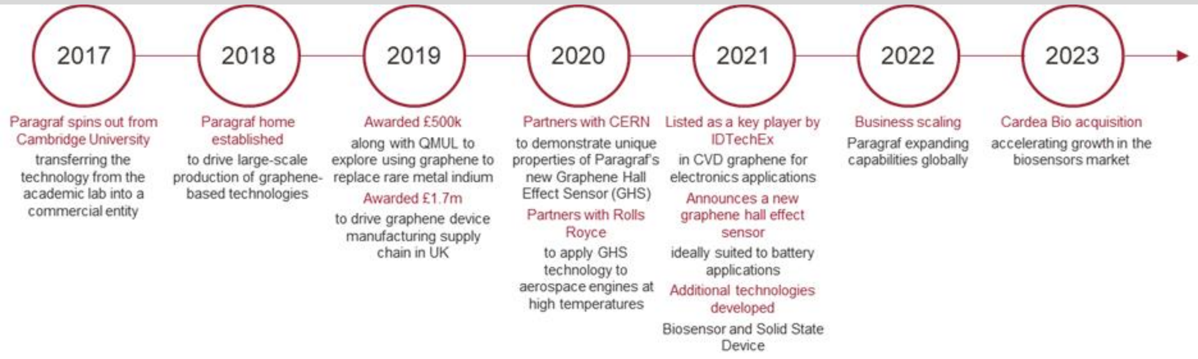
US. Paragraf is the only company in the world that can produce graphene at a scale that allows commercially viable graphene electronics.

The potential of graphene semiconductors is considerable. Graphene is considered to be the world's most conductive material, and therefore electronics using graphene semiconductors could potentially operate many thousands of times faster than today's electronics and with a thousandth of the energy requirement.

More immediately, the benefits of Paragraf's technology can be found in the products being manufactured. These include magnetic sensors, biomedical sensors, and other semiconductor technologies, with applications in automotive, agri-tech, healthcare, automation, cryogenics and telecoms (amongst other sectors). For example, Paragraf is developing next generation Magnetic Resonance Imaging (MRI) technology, and is improving the safety of electric vehicle batteries.

The products that Paragraf make are enablers of technologies for other companies, and therefore the benefits of the technology (that can be traced back to the original Beyond Blue research) continue to permeate through the private sector. Furthermore, the applications of the technology has wider social benefits, including to health and the environment.

Paragraf company timeline:



Source: https://www.paragraf.com/.

Spinout: Porotech (Poro Technologies Limited)

Researchers at the Cambridge Centre for Gallium Nitride developed a process to create porous gallium nitride, which was a new technology that could be included in large scale manufacturing for gallium nitride devices. While this research was directly supported by another grant from EPSRC, the researchers involved stressed the importance and value of the supportive ecosystem that was being provide by the Beyond Blue platform grant in ensuring that the research was a success.

Having patented the new manufacturing process, the spinout company Poro Technologies Limited was founded in 2018, initially aiming to demonstrate the structures that could be produced with the new process and selling that IP to other manufacturers to use. By 2020, Porotech was selling material to Osram and other electronics companies around the world to try out their ideas. However the company continued to develop the applications for porous gallium nitride, which led to the development of the first gallium nitride based red micro display. The company has subsequently developed the first all-in-one microLED (which is one pixel that can take whatever colour needed, rather than the traditional way of generating colours using red, green and blue pixels). This has many manufacturing advantages for display technology.

Porotech now has over 50 members of staff, and is based in the UK, Taiwan and the US. The company interacts with other companies, as part of the supply chain in the semi-conductor industry, as well as interacting with other companies (such as Plessey Semiconductors) on further R&D ideas involving porous gallium nitride. This could lead to further innovations among wider industry firms in future.

Source: https://www.porotech.com/.

Training personnel

Another route through which the R&D conducted under the Beyond Blue grant led to private sector benefits was through the training of people. The grant directly funded PhD students and post-doctoral research students. One of the researchers involved in the grant estimated that around half of their PhD students (supported by the Beyond Blue and other grants) have gone on to work in nitride-related industries, directly taking their technical knowledge and expertise into the private sector. Furthermore, the Beyond Blue grant also funded direct training interactions with industry, such as some training activities conducted with Plessey Semiconductors. This will have increased the productivity of these private firms.

> *"We benefit industry by training people who then go and work in companies. Across multiple grants, about half of my PhD students have gone into relevant industry. That's, people going to do properly nitride or nitride related things."*

> *"We learn to do things, and then we sent people to teach [Plessey] how to things practically. And it goes both ways. Industry sends us people to help us with stuff as well."*

E.4 Mechanisms through which the R&D generated wider social returns

In addition to the private sector growth and productivity benefits arising from the Beyond Blue research, there are also demonstrable wider social returns.

- **Environmental benefits.** The research programme improved the technology of LED lighting and high power electronics. This has and will continue to improve the LEDs ultimately used by consumers, reducing energy requirements and thus saving the production of large amounts of carbon dioxide. Similar environmental benefits are expected to arise in future from graphene based electronic devices, which require lower power than silicon semiconductors.

  > *"On LEDs I know have influenced the industry profoundly. That has knock on effects for how they make LEDs which will be altering the LEDs you screw into your ceiling. You can't necessarily always go 'this paper did this', but I know the work was of interest to industry,*

was taken up by industry, changed the way industry did things and that will eventually have battled all the way through."

- **Health benefits.** The graphene based devices being developed by Paragraf have applications in health technologies that will ultimately save lives. For example, Paragraf is currently developing next generation MRI technology, as well as biosensors with potential applications such as cancer monitoring and disease detection.

  "The products we make are having global benefits. Our current magnetic field sensor is being used in diverse fields from EV's to medical diagnostics. Today, we're working on next generation MRI, which is an application that will save lives. More importantly we are about to launch a biosensor technology, which in years to come, will save millions of lives."

- **Influence on policy.** Some of the activities under the Beyond Blue research programme also led to members of the research team increasing their profile and going on to have an impact on policy – both within the industry and more broadly. For example, researchers involved in the Beyond Blue grant contributed to the development of the UK semiconductor strategy.[58]

  "I could draw you the red line from one to the other. The grant proposal specifically talks about developing social media strategy and using that to raise profile and influence policymakers. I can trace back to the platform grant how I came to go on the UK delegation to the USA about the semiconductor strategy and a load of other things."

Impact on ED&I policies

The research programme included funding for a workshop on social media strategies. This was aimed at helping the research team to improve their outreach and science communication strategies but also their policy engagement. This led to Professor Oliver (one of the co-investigators of the Beyond Blue grant) using Twitter, becoming more aware of Select Committee inquiries, and as a result submitting a pitch to the 'My Science Inquiry' on the impact of science funding policy on equality, diversity, inclusion and accessibility, which led to an inquiry by a parliamentary committee on the topic.

- **Influence on society.** The research team also highlighted their outreach activities – particularly engaging with school children and generating an interest in science. This was seen as an important activity to generate a productive and innovative future labour force.

  "We gave a lot of presentations to schools and have turned lots of school children onto science, and this is very important for the future of the UK. We desperately need more people in STEM subjects."

[58] Institute of Physics/Royal Academy of Engineering (2022) 0402_semi-conductor-report_v2.pdf (raeng.org.uk)

Annex F – Case Study: SPRINT

Executive summary

The **Space Research and Innovation Network for Technology** (SPRINT) was a £7.5 million programme that sought to support the commercialisation efforts of small companies by tapping into space-related knowledge at UK universities. The programme connected companies with universities, and provided small grant funding to enable companies to use academic time and university facilities.

SPRINT had a direct impact on the private sector though increased commercialisation for supported companies (e.g. the private company Mafic). There were also indirect benefits to a wider set of private companies who use the technology or products of SPRINT-supported companies.

Technologies developed by some of the supported companies also exhibit the potential for wider social benefits. These include environmental (e.g. monitoring rainforest preservation) and societal outcomes (e.g. supporting humanitarian interventions).

F.1 Introduction

This case study focuses on SPRINT – the Space Research and Innovation Network for Technology. This project was funded primarily by Research England through their Connecting Capability Fund (CCF) Programme, a programme that sought to strengthen universities' ability to use their knowledge base to deliver commercial applications with economic and societal benefits. The SPRINT programme was aimed at tapping into space-related knowledge at UK universities to support the commercialisation efforts of companies (mainly SMEs) and the UK's space sector.

The case study explores the routes through which the research funded by SPRINT fed through into the private sector, and wider social benefits.

It is based on desk research of related materials (including SPRINT website materials[59] such as news items, case studies, a SPRINT report[60] and two reviews of the CCF programme conducted by Research England[61]); and interviews with stakeholders who have relevant experience with the programme's impact on supported companies (including a former senior leader of the SPRINT programme, former Innovation Advisors who worked with companies, and a representative from a SPRINT-supported company).

[59] Accessed via: SPRINT Guide > SPRINT (archive.org).

[60] SPRINT (2021).

[61] Available at: Connecting capability fund – UKRI.

F.2 The SPRINT programme

The SPRINT programme operated between 2018 and 2022, with a total value of £7.5m.[62] It was primarily supported by £6.8m of funding from Research England through the CCF programme,[63] with additional funding from the UK Space Agency and the Scottish Funding Council.[64]

SPRINT connected companies with partner universities and provided companies small grant funding (mostly grants of £25,000 to £50,000, but sometimes up to £150,000) that paid for university input on their research projects.[65] Companies were required to provide match funding for the grant, but this could be in kind. University input was mostly in the form of time from academics or research staff, but it could also include access to technology, equipment or data.

Companies often sought help with solving a technological problem or improving the efficiency of a process in a way that was important for commercialisation. SPRINT typically supported companies who had already conducted some R&D and had a product that they wanted to bring closer to commercialisation (often with a product or technology at Technology Readiness level (TRL) 2 or above).

"SPRINT was designed to support the growth and sustainability of SMEs in the space businesses by allowing them access to university resources. It could be ideas to help them design a new business line, or it could be support that helps them move ideas they have to a sustainable level, and particularly a technology level that makes them marketable."

The scope of SPRINT support included both upstream ('traditional' space sector e.g. satellite components) and downstream (application of space technologies and data in sectors including non-space) applications, as well as companies with technology transfer solutions (e.g. 'transferring' a given technology from the space to other sectors).[66] Figure 15 shows the range of sectors that interacted with SPRINT.

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[62] Total income (programme value). Page 7 of SPRINT (2021). See also SPRINT website archive, available at: Statistics > SPRINT (archive.org).

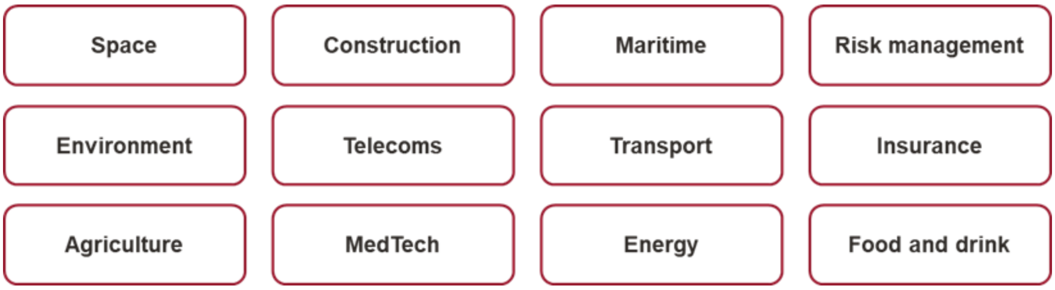
[63] An initial grant of £4.8m in 2018, followed by a £2m extension in 2021.

[64] The UK Space Agency provided funding to support five particular SPRINT projects, and to support collaborations with a wider set of higher education institutions, including in Northern Ireland, Scotland and Wales. The Scottish Funding Council funded the participation of the University of Edinburgh: About SPRINT > SPRINT (archive.org).

[65] As of 2021, university partners included the University of Leicester; University of Edinburgh; The Open University; University of Southampton and; University of Surrey. Associate Members selected in July 2021 included: City University of London; Durham University; Kingston University; University of Bristol; University of Exeter; University of Glasgow; University of Leeds and; University of Strathclyde.

[66] The European Space Agency (ESA) provides an overview of these different types of applications: Measuring the Space Economy (esa.int).

Figure 15 Sectors covered by SPRINT



Source: SPRINT (2021), page 7.
Note: Three further unidentified sectors are in the 'Other' category.

Over the four years it operated, SPRINT financially supported over 80 SMEs (out of the total over 500 with whom SPRINT held consultation on business requirements) in 140 projects.[67] The stakeholders we spoke to noted that generally companies received support for short periods, typically up to about 6 months.

The SPRINT programme was supported by Innovation Advisors (IAs) at participating universities, who connected companies to the academic(s) in the SPRINT network who were most suited to the companies' needs. IAs helped companies apply for SPRINT support[68] and introduced them to non-university partners including prospective investors, larger companies (who might work with SPRINT-supported companies in their supply chains) and business support organisations (incubation and accelerator programmes, business development agencies, and science and technology parks).[69]

IAs also sought to improve industry understanding at their universities, for example, by leveraging their connections and through networking events. This was aimed at improving academics' understanding of the commercial applications and companies' development needs in working towards these applications, and how academic research can contribute to this.

SPRINT also benefitted from central marketing and further events to raise awareness about the programme among both academics and industry.

F.3 Mechanisms through which the R&D generated a return in the private sector

The main route through which the research activities funded through SPRINT fed through into the private sector was through **improving the development of technologies in companies**

[67] Page 3 and 7 of SPRINT (2021).

[68] Applications were reviewed by a panel of SPRINT IAs and independent advisers.

[69] More information about the different types partners is available at: About SPRINT > SPRINT (archive.org).

directly supported. However, stakeholders also identified mechanisms through which there were indirect impacts on a wider set of companies:

- **Supported companies' interactions with other companies**: for example, through supply chain interactions.
- **Improved cross-academia collaborations enabling better support for companies**: SPRINT acted as an example of, and allowed academics to gain experience in effective collaboration with each other in supporting private sector firms. Improved collaboration enables public sector R&D to increasingly benefit private sector companies in the future.
- **Increased awareness among companies of the potential wide commercial relevance of academic knowledge in space sectors**: SPRINT had a broad scope in its sectoral focus and applications supported, which help facilitate the development of such applications.

Direct impact on supported companies

The SPRINT programme funded collaborations between academics and private companies. The main impact of SPRINT on the private sector was therefore through the direct benefits to the supported companies.

Supported companies could leverage **prior knowledge** developed by academics and/or create **new knowledge** as part of the collaboration.

SPRINT helped some companies **increase the speed of commercialisation and be better prepared for its next stage** (e.g. by having a better sense of business strategy).

SPRINT also helped companies **continue R&D** where, without support, the R&D would potentially not have been viable.

Two of the stakeholders mentioned that SPRINT mostly helped companies access and apply existing academic knowledge to improve their products. SPRINT often helped companies with the testing, validation and development of a working product. SPRINT collaborations increased the Technology Readiness Level (TRL) of supported companies' technology, with one stakeholder estimating a typical increase of 1 to 2 levels.

Half of the respondents to a 2021 survey of SPRINT-supported projects reported that collaborations they had participated in would not have happened in the absence of SPRINT support.[70] One of the stakeholders emphasised the large positive impact of even small, time-limited support such as SPRINT can have on early-stage companies who have limited access to finance. Another stakeholder pointed out that the required R&D facilities (e.g. for testing) can be prohibitively expensive for small companies.

[70] Page 6, SPRINT (2021).

"[Universities] have clean rooms, laboratories, test facilities. SMEs need access to that kind of thing because one of the big problems, particularly for SMEs, is that they often cannot afford the equipment that sometimes they need."

SPRINT was also reported by stakeholders to have helped some companies secure follow-on funding after the programme, mainly via the R&D outcomes achieved in SPRINT and via introductions with investors.

There are examples of different types of academic inputs among the supported companies:

- **Mafic** worked with the University of Southampton as part of SPRINT. Mafic benefitted from SPRINT support by improving its movement recognition technology used in construction sites and saving product development time. See the box below for a case study of Mafic.
- SPRINT collaboration with the University of Southampton enabled **Protolaunch** to develop a new low-cost rocket engine for small satellites. Protolaunch benefitted from the use of facilities (e.g. chemical propulsion labs and testing facility).[71]
- **Satellite Vu** is a company that uses infrared technology to monitor objects on earth to determine their energy use and efficiency.[72] SPRINT supported Satellite Vu in its work with The University of Surrey to validate the technology using advanced image analysis techniques.[73]

Supported company: Mafic Ltd.

Mafic provides technologies for construction and industrial environments to enhance productivity, safety and wellbeing. The company offers wearable sensors (e.g. fixed onto hard hats) that capture data from movements. Such data is then used to improve productivity in construction sites by motivating workers with increased salary based on performance. It can also be used by construction companies to optimise their workflow (e.g. find the optimal working hours or schedules). Figure 16 below shows an overview of Mafic's technology.

Mafic had not initially seen themselves as a 'space company'. They were able to apply for SPRINT support due to their use of Global Navigation Satellite System (GNSS) sensors for location data tracking, a downstream space technology application.[74]

Mafic took part in three separate SPRINT projects to help with their machine learning algorithm and inertial navigation system used to understand movements, and their induction charger and energy harvesting solution to make the device efficient and easy to use.

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[71] Southampton astronautics expertise boosts UK small satellite propulsion technologies | Engineering | University of Southampton.

[72] SatVu (satellitevu.com).

[73] Page 13-14, SPRINT (2021).

[74] Mafic signs up for new SPRINT project to optimise power management of new Safeguard solution for industrial construction workplaces > SPRINT (archive.org).

SPRINT helped Mafic validate their technology and improve the accuracy of movement recognition. Dr Alex Weddel at the University of Southampton also guided Mafic in energy harvesting based on previous research and experience. Mafic highlighted the close collaboration with university partners through the SPRINT programme:

"… you have to be very close. You have to understand the work yourself. This is not outsourcing the work by any means. You have to be deeply involved with the work that they're doing. And manage and work with them."

Mafic also highlighted the value of SPRINT as a tool to find talent who can use the latest tools (e.g. in machine learning) and are able to learn quickly, even without many years of professional experience, and *"bring new things to the table".* Bringing new talent on board also contributed to a *"culture which is about learning new stuff"*, mainly as a result of SPRINT:

"And I think that's come predominantly from our experiences with the university, and a large part of that is of course SPRINT."

SPRINT generally allowed Mafic to save time: one estimate suggests that SPRINT participation halved product development time.[75] Academic input allowed Mafic to make rapid decisions about development that, in the absence of SPRINT, could have taken the company potentially months. In particular, Mafic highlighted the value from knowing which of several development options the company should explore when solving a problem:

"This doesn't work because of that. Draw a line through it. Off we go. So that's hugely valuable because we have four or five different options for solving one problem, and if we can obviously knock off three of them, then that's progress."

SPRINT support through the validation of their technology enabled Mafic introductions to, and investment from, Errigal Contracts and other construction and engineering companies.[76] Mafic worked on R&D with Errigal to develop its movement recognition technology through 'live' implementations in construction sites.[77] Errigal used Mafic's technology to identify the sources of disruptions to workers' productivity including management and training bottlenecks, decrease in motivation, worker fatigue and quality control issues.

Errigal changed its operations based partly on these insights e.g. introducing a new shift pattern and Mafic's incentive scheme. This in turn led to significant improvements in employee morale, reduced project costs and completion times.[78] The change in shift pattern increased productivity by 8%, whereas the incentive scheme increased it by about 13%, according to Mafic.

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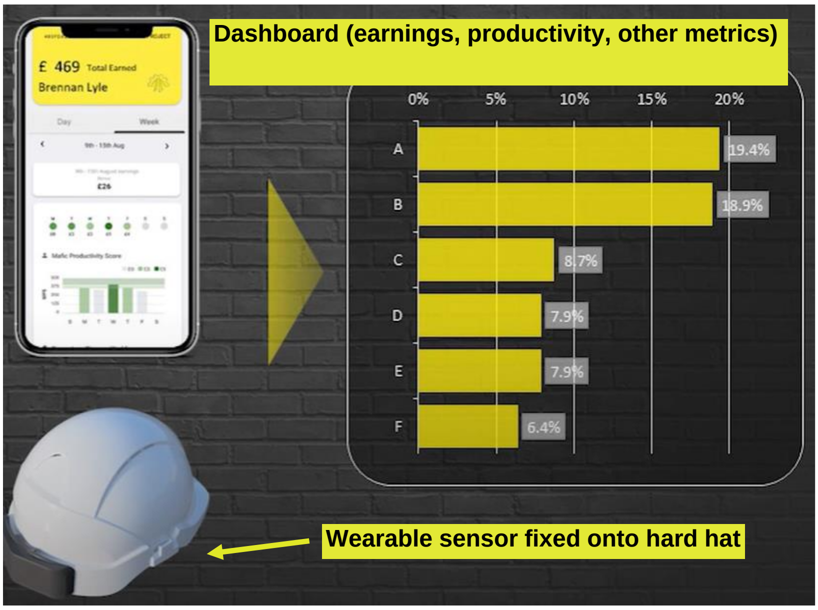
[75] Applying machine learning to improve the safety of heavy industry workforces > SPRINT (archive.org).

[76] Ibid.

[77] Mafic secures major investment for development of innovative, wearable safeguard devices (satelliteevolution.com).

[78] Page 39-42 of Lean Construction Ireland Annual Book of Cases 2022. Available at: Book of Cases 2022 - LCi Lean Construction Ireland.

Figure 16 Overview of Mafic's technology



Source: Mafic Demo Day Pitch, available at: [Mafic Demo Day Pitch - YouTube](#).

Indirect impact on companies who interacted with SPRINT-supported firms

SPRINT also had positive benefits on firms other than those directly supported through interactions with SPRINT-supported companies.

Companies supported by SPRINT successfully **launched products that other companies use**. Through this pathway a **wide set of firms across the private sector benefit from the public R&D** conducted under the SPRINT programme (e.g. a firm could make its output with a more efficient method of production).

SPRINT-supported companies reported that the support they received helped them develop commercial relationships. Most of the company and university respondents to a 2021 survey reported that they benefitted from SPRINT through new collaborations.[79] Most of the companies also reported positive impact on finding suppliers and customers.[80]

Particular examples where SPRINT-supported projects had subsequent benefits for other private sector firms include:

[79] Page 8 of SPRINT (2021).

[80] Ibid.

- **Theyr** worked with the University of Southampton to develop a route optimisation tool for commercial vessels using real-time space satellite weather data and AI algorithms.[81] The tool enables fuel and time savings, and improvement in vessel revenue performance. It has been integrated into commercial applications, therefore companies using this technology (e.g. shipping company Euronav and its customers) indirectly benefit from the SPRINT support Theyr received.[82]
- **Oxford Satellite Systems** received support from the University of Surrey in testing its new antenna technology in an environment designed to simulate conditions in space. The collaboration allowed Oxford Satellite Systems to demonstrate the performance of its antenna design and increase the speed of future product development.[83] Multiple products developed by the company have been launched into orbit, with applications in areas such as Internet of Things (IoT) connections.[84]

Legacy for academic collaboration and work with private companies

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SPRINT improved academics' ability to collaborate with each other in ways that better support companies. Over the longer term this is expected to benefit firms supported through collaborative programmes similar to SPRINT.

One of the stakeholders mentioned that academics across different universities are now more aware of what others are doing, and how they can combine and complement competences or pool resources across universities (e.g. as part of a 'cluster' of academic and industry partners), and that SPRINT made a major contribution to this outcome:

"… academics will carry on with the same sort of research and area, but I think there's more room for, well, let's work on this project together or let's bring in the university. ***We are naturally aware of what's going on****. There is a steering committee that looks over the three universities now*[85] *to say how we are* ***combining our resources*** *so we don't duplicate or miss things that perhaps is already on our doorstep. I wouldn't say this was wholly about SPRINT but certainly* ***SPRINT is held up always as that was a really good thing****. We shouldn't lose that sense of collaboration and support. We're* ***not in competition*** *because I mean academics they are always competing for funding."* (emphasis added)

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81 Microsoft Word - Theyr_UoS_ Sprint Press release 200320.docx.

82 Theyr.com - News.

83 Space antennas developed more quickly through collaboration – UKRI.

84 Oxford Space Systems.

85 University of Portsmouth, University of Southampton and the University of Surrey as part of the Space South Central cluster (the cluster has further members): Space South Central - Satellite Applications Catapult.

Another stakeholder mentioned that universities became "very agile" [86] at collaborating with each other as a result of SPRINT.

"… because of Sprint, we are very agile at doing that. All the people that were in SPRINT, talk to each other still. So you still have this kind of habit of talking to other universities and collaborating with them on bids."

Improved cross-academia collaboration can help better support companies: for example through improved co-ordination on resources (e.g. facilities) made available for supported companies, and through drawing on a wider network of academic knowledge.

One of the stakeholders also pointed out that SPRINT taught academics the importance of having formal processes (e.g. for liability issues, insurance, equipment) in place when working with companies. This can further improve academics' ability to interact with private companies in the future.

The same stakeholder also highlighted the initial perception that there was a big disconnect between academic research and commercial applications (e.g. that many academics don't necessarily know about the potential commercial applications of their work), and that the experience from SPRINT helped to challenge this perception given the successful relationships between academics and companies.

"… the nature of the collaborations were very tight and very, very specific. And I think the relationships that formed between the academics and some of the companies, it was really a first step into a more longer term and deeper collaboration."

Stakeholders gave several examples of **cross-academia** and **industry-academia** collaborations that continued after the end of the SPRINT programme:

- The UK has space-related clusters of academia and industry aimed at facilitating innovation and business development.[87] According to one stakeholder the **Space South Central** cluster has "grown out of the SPRINT activity", while another stakeholder added that collaboration in the same cluster is a "natural legacy" of SPRINT.[88]
- There are several examples of companies that had further academic collaborations beyond the SPRINT programme. For example, **Clutch Space** continued working with academics at the University of Surrey after their participation in the SPRINT programme.

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[86] SPRINT had a fast application process which can be important given rapid technological change. However, one of the stakeholders also mentioned that this was challenging for universities to deliver this from a resourcing point of view. The fast pace of SPRINT relative to other similar programmes is also highlighted by the CCF review: "*At SPRINT, the whole process from initial approach to funded project takes 6-8 weeks, which is **much quicker than many other funding streams, and fits well with SME timeframes**."* (emphasis added). Page 20 of "Update to the interim review of the Connecting Capability Fund". Available at: Update to the interim review of the Connecting Capability Fund – UKRI.

[87] Space Enterprise Community - Satellite Applications Catapult.

[88] Space South Central - The largest regional space cluster in the UK..

Prompting innovation with wider applications of space technology

SPRINT's broad sectoral focus (e.g. downstream applications) could promote innovation by **raising awareness of the diverse set of commercial applications of space assets, technology, research and data.**

Stakeholders suggested that the SPRINT programme benefitted the private sector through raising awareness of the diverse use and value of space assets, technology, research and data. SPRINT was very broad in the sectors and applications that it supported, and in doing so has advertised the vast range of potential commercial applications – compared to applications that might previously have been thought of as only being relevant for the narrow space sector. This could increase innovation across the wider private sector.

"A lot more companies now are perfectly aware that they're part of the space sector and they might not have previously thought that they were. Particularly in the downstream section of space - in data analysis, telecoms and other fields. Funders as well have started to target those kind of areas and make it more obvious that they're now funding those kind of things."

F.4 Mechanisms through which the R&D generated wider social returns

In addition to the private sector benefits, there are also demonstrable wider social returns from the SPRINT programme and the research it supported. These are identified as coming about from the products and services provided by supported companies.

- **Environmental benefits**. Examples of supported companies with a positive impact on sustainability and the climate as a result of their SPRINT-supported technology include:
  - **Satellite Vu**'s technology monitors objects on Earth to determine their energy use and efficiency. It has use cases in building efficiency, sustainable finance, the energy industry, and plastic detection and clean-up.[89]
  - **Ecometrica** provides a forest-loss detection tool that penetrates cloud cover. This can help decision makers to improve the monitoring and preservation of rainforests. The technology has been used for example by forest rangers.[90]
  - **Raymetrics** developed a laser-based detection system for the monitoring of atmospheric pollution. The technology has urban and marine applications.[91]

89 SatVu (satellitevu.com).

90 Sustainability Reporting and Climate Risk Monitoring - Ecometrica.

91 Environment – raymetrics.

- **Societal benefits**. Examples of supported companies with a positive impact on resource use, food security, and humanitarian issues as a result of their SPRINT-supported technology include:
  - **Mantle Labs** uses satellite data to track the health, quality and environmental impact of farmland to facilitate decision-making and risk management in agriculture.[92]
  - **Alcis** combines satellite data with geospatial datasets and field data for humanitarian and development interventions. It can help better understand and tackle issues such as illicit trade, seal level rise, draught and others. Alcis works with clients including governments, NGOs and multilateral organisations.[93]

[92] Mantle Labs (mantle-labs.com).

[93] Geographic Information Services (GIS) | Alcis | United Kingdom.