NPL
National Physical Laboratory

NPL REPORT IEA 3

ACHIEVING THE 2.4% GDP TARGET: THE ROLE OF MEASUREMENT IN INCREASING INVESTMENT IN R&D AND INNOVATION

DR MIKE KING, EUGENIO RENEDO

MARCH 2020

Achieving the 2.4% GDP target: The role of measurement in increasing investment in R&D and innovation

Mike King, Eugenio Renedo
Analysis and Evaluation, Strategy Directorate

© NPL Management Limited, 2020

ISSN 2633-4194

National Physical Laboratory

Hampton Road, Teddington, Middlesex, TW11 0LW

Extracts from this report may be reproduced provided the source is acknowledged and the extract is not taken out of context.

Approved on behalf of NPLML by
Fiona Auty, Head of Government Relations.

CONTENTS

CONTENTS .....
EXECUTIVE SUMMARY .....
1. INTRODUCTION **1**
2. BACKGROUND AND CONTEXT **4**
A. THE 2.4% TARGET 4
B. TWO TRADITIONAL MODELS OF SUPPORT 5
C. R&D SPENDING IN THE UK 6
3. THE NEED FOR A CHANGE OF FOCUS **7**
A. THE REPRODUCIBILITY OF THE LIFE SCIENCES 7
B. DECLINE IN R&D EFFICIENCY 8
C. DIMINISHING RETURNS FROM THE TWO MODES OF INTERVENTION 9
D. OTHER TYPES OF INTERVENTION 10
4. THE ROLE OF INFRA-TECHNOLOGIES **11**
A. INFRA-TECHNOLOGIES 11
B. UNDERINVESTMENT IN INFRA-TECHNOLOGIES 12
5. A STYLISED MODEL FOR PRIVATE INVESTMENT IN R&D **14**
6. REDUCE THE COSTS OF R&D **16**
7. INCREASE THE BENEFITS FROM R&D **17**
A. BETTER TECHNICAL PERFORMANCE 17
B. FASTER COMMERCIALISATION 18
C. LOWERING NON-TARIFF BARRIERS 19
8. BETTER ALLOCATION FOR R&D RESOURCES **20**
9. CONCLUSION **21**
A. THE CENTRAL ARGUMENT 21
B. NPL'S VISION FOR THE FUTURE 21
C. ONE EXAMPLE: REPRODUCIBILITY IN THE LIFE SCIENCES 21
REFERENCES **23**
ANNEX: USER COST OF R&D **24**

EXECUTIVE SUMMARY

This paper makes the case that achieving the 2.4% target mainly depends on raising the private returns from R&D so that businesses invest more in R&D. However, the UK is close to the limit of what can be achieved through current funding mechanisms. Hence, policy makers should consider other forms of intervention aimed at fundamentally altering the productivity of R&D without just resorting to further subsidies.

Specifically, this paper makes the case for further investment in the nation's measurement infrastructure to ensure good access to research tools, techniques, and standards. Over the last 20 years, investment in such infra-technologies has not kept pace with investment in R&D. There is reason to think that underinvestment has contributed to a decline in the productivity of R&D in areas where relevant infra-technologies either don't exist or need extending into new domains.

Radically updating the stock of infra-technologies requires additional public funding but would increase the efficiency by which private R&D converts generic technologies into proprietary technologies. (Infra-technologies for the life sciences are used as an example but there are a host of new scientific fields in need of support.) Interventions to fundamentally increase the productivity of R&D will necessarily bring business investments in R&D closer the 2.4% target by increasing the proportion of the potential R&D projects that are privately profitable.

1. INTRODUCTION

Reaching the 2.4% target requires interventions to encourage more private R&D spending. Traditionally, the focus has been funding basic research at universities and subsidising applied research and experimental development by businesses.

- Basic research at universities stimulates applied research by companies; because sometimes applied research builds on basic research. (Linear model of innovation.)
- Grants and R&D tax credits reduce the cost of R&D projects. This increases the private return from potential R&D projects: Making R&D more profitable, means that more projects are undertaken, driving up business investment in R&D.

However, there are two reasons why government needs to focus more on interventions that increase the private returns to R&D without just resorting to further subsidies:

1 Successive governments have generously funded both these channels of support. However, the scale of funding is such that diminishing returns have probably set in.[1] That is, the government has nearly reached the limits of what can be achieved through subsidising R&D. Consequently, the time has come to think about other types of intervention.

2 We now have strong evidence that the rate at which R&D spending is converted into new better products has declined over time.[2] Moreover, there is evidence that one factor in the effectiveness of R&D is the limited reproducibility of results in the biological and medical sciences. That is, in these fields, results cannot always be reliably reproduced later by a different organisation. This indicates a need for reproducible and comparable measurements.

Therefore, public investment in the nation's measurement infrastructure would increase the productivity of R&D. This would encourage greater business investment in R&D by making a greater proportion of potential R&D projects privately profitable. (Extra public funding for universities and businesses will, no doubt, be needed but, on its own, this won't resolve the problem of low R&D spending in the UK.) This implies that something needs to be done to make the whole portfolio of potential R&D projects more profitable, by making R&D itself more productive. And, if R&D can be made more productive, then businesses will direct more investment towards the 2.4% target.

---

1 (Guellec & Van Pottelsberghe, 2003) show an increased effectiveness of R&D subsidies up to a threshold of 13%, after which further increases in generosity start to decrease the leverage rate; beyond the 25% threshold, further increases have a negative effect on the level of private funding committed to R&D (see page 16 of this paper for an analysis of crowding-out and crowding-in). Currently, about the 23% of the UK's BERD (Business Expenditure on Research and Development) is publicly funded, strongly suggesting the UK is already close to the limits of what can be achieved by R&D subsidies.

2 (Bloom, et al., 2017) present a wide range of evidence from various industries, products, and firms showing that research effort is rising substantially while research productivity is declining sharply.

Often policy makers divide scientific and technological knowledge into three categories: basic science (blue skies research); applied research (generic technologies); and experimental development (proprietary technologies).[3] However, (Tassey, 2004) argues that there is a much overlooked fourth type of technological knowledge, which determines the productivity of R&D spending. But the efficiency with which generic knowledge is converted into proprietary knowledge depends on having access to research tools, techniques, and standards. These public goods determine the productivity of private R&D (Tassey names this fourth category 'infra-technologies').

A lack of awareness about the role of infra-technologies means that there has been underinvestment in these public good technologies. Chief amongst these infra-technologies is measurement science (metrology). Hence, this document claims that interventions that strengthen the measurement infrastructure, will raise the private returns from R&D and so lead to more privately funded R&D. The central argument of this document can be summarised as follows:

1. R&D will be made more productive if one of its sub-activities can be made more productive.

2. Performing experiments or developing prototypes involves taking many measurements. Employment data collected by the ONS (Office of National Statistics) suggests that, in terms of the hours committed to various sub-activities, taking measurements (testing, analysis, calibration) accounts for at least 14.3% of R&D activity. This estimate comes from an analysis of roles among employees working in the scientific research and development industry.[4]

3. If R&D were to be made more productive, then a greater proportion of potential R&D projects would become privately profitable and so be undertaken by businesses even without further subsidies.

Therefore, if measurements taken during R&D projects can be made more effectively, then R&D itself becomes more productive and attracts greater private investment. One route to achieving this, is for government to invest in both the public and private parts of the nation's measurement infrastructure. For example, to fund advances in the field of metrology (the science of measurement) that extend the reproducibility found in the physical sciences to the biological and medical sciences.

---

3 Donald E. Stokes, in his book *Pasteur's Quadrant: Basic Science and Technological Innovation*, advocates that understanding and use are two characteristics of research. Thus, all research can be classified in terms of its '*quest for fundamental understanding*' and its '*consideration for use*' – basic research (Niels Bohr); use-inspired research (Louis Pasteur), applied research (Thomas Edison).

4 The Standard Occupation Codes (SOCs) are: 5224 for precision instrument makers and repairers; and 3111 for laboratory technicians. The Standard Industrial Code (SIC) for business R&D and biotechnology is 72.

OVERVIEW OF THE DOCUMENT

Section 2	Describes and explains the background to this paper. It highlights the importance of the 2.4% target to future growth and outlines the two main modes of public support for R&D: funding for universities; and R&D subsidies for businesses.
Section 3	Makes the argument that there is a growing need for interventions aimed at fundamentally raising the returns from private R&D spending. The section begins by discussing the problem of research reproducibility in the life sciences. Next, it reviews evidence that the productivity of R&D has been declining. Lastly, it discusses the existence of diminishing returns from ever more generous R&D subsidies for businesses, and the need to implement other types of intervention.
Section 4	Introduces the concept of infra-technologies (a fourth type of technological knowledge which role is to speed up the rate at which generic technologies are converted to proprietary technologies). Next it describes the problematic of underinvesting in infra-technologies.
Section 5	Presents a stylised model that analyses the main factors affecting the level of private investment. The model shows that there are three ways of increasing the number of R&D projects thet firms carry out: (1) reduce the costs of R&D, (2) increase the benefit from R&D, and (3) provide better information about returns on each project in the portfolio.
Section 6	Explains why advances in measurement science can reduce the cost of R&D projects. Since making measurements accounts for a large fraction of researchers' time, being able to make more effective measurements could directly reduce the cost of running experiments.
Section 7	States that there are three ways in which infra-technologies increase the benefits from R&D. Firstly, there is the better technical performance of instruments and process control equipment. Secondly, the existence of appropriate protocols for testing safety and performance, enables faster commercialisation and adoption of new technologies. Lastly, supporting the development of clear performance-based product standards lowers non-tariff barriers and makes it easier for new entrants to compete with incumbents.
Section 8	Explains why infra-technologies support better allocation of R&D resources. This is about lowering technological uncertainty to reduce the risk premium; and providing investors with better information so that funds are targeted at projects with the highest potential.
Section 9	Concludes by first summarising the central argument of this document. Next, it presents NPL's vision for the future, and how it can support BEIS's aspirations. Lastly, it highlights the main takeaways from the case study presented in this note: the problem of scientific reproducibility in life sciences.

2. BACKGROUND AND CONTEXT

This section explains the importance of the 2.4% target and describes the two main modes of support: funding for universities and R&D subsidies for businesses.

A. THE 2.4% TARGET

Long-term economic growth is driven by technological change. Although in the short run any economy can grow by increasing the capital stock per worker, this mechanism soon runs out. This is because as the capital stock grows larger, it takes more and more investment to produce an additional unit of output, and at some point, the economy only invests to keep up with effective depreciation. Therefore, investment in R&D is key because it drives the technological change needed for productivity growth, and thus, long-term economic growth.

Between 1948 and 2002, the UK economy (GDP) grew at around 2.5% per year. Growth in conventional inputs (labour and capital) together account for around 1.5 percentage points; and technological change accounts for about 1.0 percentage points.[5] This implies that 40% of the GDP growth over this period is due to technological change. (In the language of economists, this is growth in total factor productivity.)[6] At the end of this 54-year period (1948-2002) the economy was 70% larger due to technological change than it would have been without it.[7] (GDP is currently £2,182 billion; with no TFP growth it would be £1.284 billion.) This is a huge impact when one considers that, at best, 2% of GDP was invested in R&D compared to, say, 17% in GFCF (Gross Fixed Capital Formation).

Growth from technological change is based on people creating ideas, and long-run growth rate is the product of two terms:

Economic Growth = Research Productivity × Number of Researchers.[8]

Although the private sector is responsible for the majority of R&D, government can intervene in various ways to influence both the **number of researchers** and their **productivity**. Romer's work on endogenous growth theory, gave economic credibility to the notion that countries can improve their underlying performance if they concentrate on supply-side measures such as R&D, innovation, and skills. His work encouraged economists to move away from classical models that rely mainly on the private sector to boost investment in capital goods; and urged governments to intervene to boost R&D and skills.

Currently, the UK is below the OECD (Organisation for Economic Cooperation and Development) average in terms of the proportion of GDP that it invests in domestic R&D, which will negatively affect its comparative economic growth in the future. (The UK invests 1.7% of its GDP in R&D, whereas, Germany invests 2.9% of its GDP in R&D.)

---

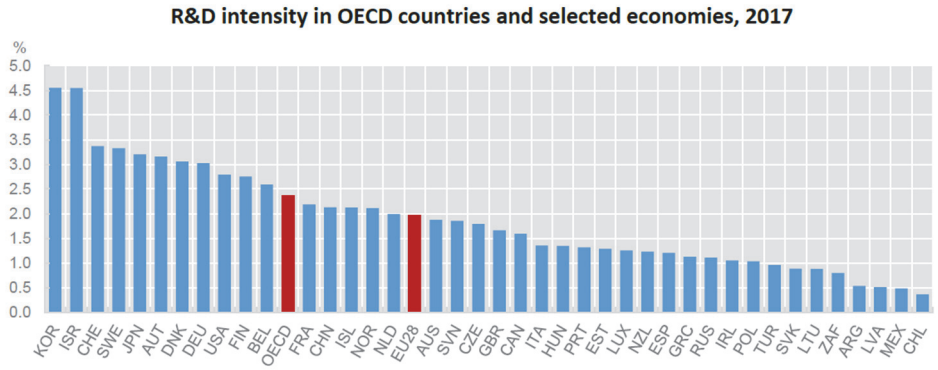
5 (Department of Trade and Industry, 2005) (see page 4).

6 The production function for the economy is $Y = AL^{\alpha}K^{\beta}$, where Y is output, L is employment, and K is gross capital stock. A denotes total factor productivity; and TFP growth is given by $\dot{A}/A$, where $\dot{A} = \frac{dA}{dt}$.

7 The size of the economy at the end of the 1948-2002 period is $Y = Y_0(1 + 0.025)^{54}$ ($Y_0 \equiv$ UK's GDP in 1948). Without total factor productivity growth, we would have $Y' = Y_0(1 + 0.015)^{54}$ instead. We can compute the increased size of the economy due to total factor productivity growth as $(Y' - Y)/Y = Y'/Y - 1 = [(1 + 0.025)^{54}/(1 + 0.015)^{54}] - 1 \approx 69.8\%$

8 In this context, 'economic growth' means TFP growth.

To remedy this the government has committed to raising the R&D spending, so that by 2027, the **UK spends 2.4% of GDP on R&D**. Although, some additional funding for public R&D is definitely required, this ambitious target can only be met (and sustained) by encouraging business to invest more in R&D by the government supporting interventions aimed at increasing the private returns from R&D.[9]



Source: OECD Main Science and Technology Indicators Database, February 2019. http://oe.cd/msti

B. TWO TRADITIONAL MODELS OF SUPPORT

Funding universities

Funding basic research at universities helps to stimulate business R&D (1) by providing new knowledge about phenomena and laws of nature, and (2) by turning university research into exploitable technologies.[10]

Generally, advances are cumulative, in that an advance today enables another further advance in the future; as demonstrated by a flow of citations from one article or patent to another. Sometimes knowledge created by academic research can be used as the basis of a new technology; meaning that the research spending at universities has the ability of leveraging private funding from businesses.

However, the transmission and absorption of this knowledge is often **slow and costly**.[11] And, thus, the Catapult Centres play an important role lowering barriers, so that new scientific knowledge flows.

Subsidising businesses

R&D subsidies delivered through R&D tax credits and grants are clearly one mechanism for lowering the cost of business R&D. The user cost of R&D is the minimum pre-tax rate of return on an investment required by an investor. (The economic intuition behind this concept is that investors will only commit resources if they expect to receive at least the same amount they could earn on other equally risky investments – this is the investor's *opportunity cost* of capital.)

9 Currently, 73% of the UK's Gross domestic expenditure on R&D (GERD) is financed using private funding, as opposed to public funding.
10 (Shane, 2004) provides a comprehensive literature review on how spin-offs encourage economic growth by several mechanism (see pages 20-28)
11 Investments in R&D are needed for firms to build up their absorptive capacity. That is, generally, firms can't benefit from knowledge spillovers without having some internal R&D activities. This is second aspect of R&D is analysed in (Cohen & Levinthal, 1989).

The user-cost of R&D, u, is defined by the following expression: u + δ = (B-index)(r + δ), where the 'B-index' depends on taxes and subsidies; δ is an annual depreciation rate for knowledge assets; and r is the interest rate or general-purpose financial cost of capital. The typical parameter values, used in economic analysis, are δ = 15% and r = 10%.

The B-index = 1 when there are no subsidies for R&D; and in this case the expression above clearly reduces to u = r = 10%, meaning that the user cost of R&D equals the interest rate. If firms can claim payable credits under R&D Expenditure Credit (RDEC), amounting to 12% of their R&D expenditure, then the B-index is given by B-index = 1 – 0.12 = 0.88. (This assumes the credit is taxable.) Hence, the user cost becomes u = 0.88 × (10% + 15%) – 15% = 7%. This means that, compared to the case of no R&D subsidies, having a credit rate of 12% decreases the user cost of R&D by 30%.[12] (The formula for the user-cost of R&D is discussed in more detail in the annex.)

Subsidies increase returns from R&D and so brings in to being marginal R&D projects that would not otherwise be undertaken. (Bloom, et al., 2002) found that the short-run elasticity of private R&D spending against the user-cost of R&D is about -0.14 and the long run elasticity is about -0.96. Meaning that in the short term, a 30% decrease in the user cost of R&D would increase R&D spending by 4.2%. However, in the long term such a subsidy would lead to a 28.8% increase in R&D spending.

C. R&D SPENDING IN THE UK

1.7% In 2016, the UK's GERD (Gross Expenditure on R&D) amounted to about 1.7% of GDP (£33.1 billion).

About 73% of the UK's GERD (£24 billion) is funded by the private sector: businesses, charities, and overseas firms. Since total public spending accounts for around 40% of GDP, this implies that the R&D intensity of the private sector is around 2%, whereas, that of public sector is around 1%.[13]

Many econometric studies have explored the relationship between changes in output and changes in the level of R&D spending at a range of levels (firms, industry, country).

- Reasonable estimates of the (short term) private rate of return from R&D investments range from 20% to 30%. (Spillover benefits mean that social returns are typically 2 or 3 times larger than the private returns.)
- Combining this with an R&D intensity of 1.9%, suggests that the R&D elasticity of output ranges from 0.023 to 0.025.[14] This implies that if companies were to double their R&D spending, their output (sales) would rise by a bit over 2%.

---

12 With no subsidy (B-index = 1) the user cost of capital is given by: $u = 1 \cdot (10\% + 15\%) - 15\% = 10\%$, thus an additional 3% return is needed.

13 The UK's GDP in 2016 was £1,960bn. The total public spending (~40% GDP) was then around £784bn, and the total private spending was £1176bn. The UK's GERD in 2016 amounted to approximately 1.69% of GDP (£33.1 bn); 73% of it was funded by the private sector (£24.3bn) and the rest (£9.0bn) by the public sector. Therefore, the R&D intensity of the private sector was $24.3/1{,}176 \approx 2\%$, whereas that of the public sector was $9.0/784 \approx 1.2\%$,

14 Let 'Y' denote output (e.g. sales) and 'R' denote R&D spending. Since 'Rate of Return' = (ΔY – ΔR)/ΔR, it must be the case that: ΔY/ΔR = 'Rate of Return' + 1. Secondly, by definition, 'Elasticity'= (ΔY/Y)/(ΔR/R), which can be re-expressed as 'Elasticity' = (ΔY/ΔR) × (R/Y), where R/Y is the R&D intensity. Thus, a return of 20%, with a R&D intensity of 1.9%, implies an elasticity of 1.20 × 0.019 = 0.023.

3. THE NEED FOR A CHANGE OF FOCUS

This section begins by reviewing evidence that the productivity of R&D has been declining. Next, it argues there is likely to be diminishing returns to the two traditional modes of intervention. Thus, policy makers need to think beyond universities and R&D tax credits.

A. THE REPRODUCIBILITY OF THE LIFE SCIENCES

There is limited reproducibility of results in the biological and medical sciences. That is, in these fields, there's an urgent need for results that are stable over time and can be reproduced reliably by different organisations. This issue is exemplified by the following case studies:

	An inadequate focus on the developing of appropriate research tools for advancing complex generic technologies could undermine attempts to leap from advances in basic science to the development of specific innovations (new drugs or therapies). As an example of this phenomenon, (Tassey, 2004) points to the very low success rate of biotechnology firms in the 1980s and 1990s. He claims that 25 years after Genetech became the first biotech company, only 12 of the 50 largest companies were profitable and the biotech industry was still losing money in 2005.
	Theranos (Real-Time Cures) raised $700 million from venture capitalists, resulting in a $10 billion valuation at its peak in 2014. Investors and the media hyped Theranos as a breakthrough in the blood-testing market, where the U.S. diagnostic-lab industry has annual sales of over $70 billion. Theranos claimed its technology was revolutionary and that its tests required only about 1/100 of the amount of blood that would ordinarily be needed and cost far less than existing tests. However, evidence emerged that they had greatly exaggerated the accuracy and sensitivity of its testing technique. The Wall Street Journal exposed Theranos and published a book-length treatment of the fraud in May 2018.[15] Ian Gibbons, chief scientist, committed suicide in 2013; and the CEO, Elizabeth Holmes, is due to face trial on serious fraud charges.
	(Freedman, et al., 2015) found that only 50% of preclinical research is reproducible, costing the US $28 billion a year in wasted R&D. It's important to note that this paper is a contentious and not always accepted among researchers working in the life sciences, but it does suggest the potential for a large cost from poor reproducibility. Moreover, the biological world is much more complex than the physical world; and biological processes are difficult to track and measure.

15 *Bad Blood: Secrets and Lies in a Silicon Valley Start-up.*

The examples above relate to the medical and biological sciences. However, similar issue might be found other relatively new areas of science (e.g. climate science); which means the examples discussed above should be seen in the wider context of people working at the frontiers of scientific knowledge. For example, in the last decade new generic technologies have emerged from the physical sciences, such as, quantum technology. In time, the commercialisation and regulation of these areas will require new infra-technologies: research tools, techniques, and standards.

B. DECLINE IN R&D EFFICIENCY

(Bloom, et al., 2017) provides strong evidence that the rate at which research spending is converted into innovative products has declined over time. Their analysis is based on the notion that the long-term output of research is economic growth. According to this conceptual framework, the percentage change in research productivity can be found by subtracting the percentage change in the number of researchers from the percentage change in economic growth.

$$\left(\frac{\Delta Research_Productivity}{Research_Productivity}\right) = \left(\frac{\Delta Economic_Growth}{Economic_Growth}\right) - \left(\frac{\Delta Number_of_Researchers}{Number_of_Researchers}\right)$$

Bloom and colleagues observe that if the economic growth rate is lower than the rate of employment growth for researchers, then research productivity is declining. They explore a wide range of empirical evidence indicating that in many contexts, research effort is rising substantially, while research productivity has been declining significantly. (Steady economic growth, when it occurs, results from the offsetting of these two trends.) This issue is exemplified by the following case studies:

	‘Chip density’ relates to the number of components per integrated circuit; and in past decades Moore’s Law held that the number of transistors in a dense integrated circuit doubles about every two years. However, the number of researchers required to double chip density today is more than 18 times larger than the number required in the early 1970s. At least as far as semiconductors are concerned, commercially valuable technological ideas are getting ever more difficult to discover. Research productivity in semiconductors is declining sharply, at a rate that averages about 6.8% per year.
	Research productivity for seed yields declines at about 5% per year. They find a similar rate of decline when studying the mortality improvements associated with cancer and heart disease.
10%	They find substantial heterogeneity across the population of firms but research productivity is declining in more than 85% of the sample. Averaging across firms, research productivity declines at a rate of 10% per year.

It should be noted that the decline research productivity is slightly contestable as some of the benefits of research may not be being picked up in the economic data used in this analysis. That is, the presence of non-market goods (e.g. clean air and security) and associated benefits, mean that the measurement of economic output is an active area of economic research. Also, the principal factors leading to a decline in R&D efficiency are not too well understood.

However, (Bloom, et al., 2017) is an important study by four leading economists that can't be easily dismissed. Hence, despite the article's, somewhat, awkward conclusion, those working in the area science policy might want to reflect on its findings. In particular, at least according to NPL, it may be helpful to focus on two underlying issues:

1 It is becoming harder to find valuable new technologies based on the mature physical sciences because a lot of potential innovations have already been found. That is, engineering and the mature physical sciences have been extensively mined for profitable innovations. (The phenomenon is analogous to the early exploration of new territories; and the cultivation of ever more marginal land because the most fertile land had already been occupied.)

2 Over the last 30 years, a lot of R&D has gone into the life sciences given the huge potential of this area for new technologies. However, the commercialisation rates have been relatively poor because of the lack of an appropriate intra-technology. Hence, the life sciences need public support to develop their own infra-technology, which suites the analysis of living systems. (Overly reductive thinking might lead one to think that chemistry could be derived from physics; and biology could be derived from chemistry. Actually, new phenomena emerge from simpler parts, which can't be fully understood in terms of the behaviour of those components. Hence, new units and standards will be needed for the life sciences and medicine and these can't necessarily be derived from existing standards for the physical sciences.)

C. DIMINISHING RETURNS FROM THE TWO MODES OF INTERVENTION

As discussed, the two main modes of support are funding for universities and R&D subsidies for businesses. However, in both cases, there are reasons to expect diminishing returns from further increases in the amount of public money spent on these modes of support.

Funding universities

Beyond a certain point, the flow of new scientific knowledge exceeds the absorptive capacity of businesses. (In any case, firms have access to research from all the world's great universities. Hence, doubling funding for UK's universities could only increase the overall stock of articles by a modest amount.[16])

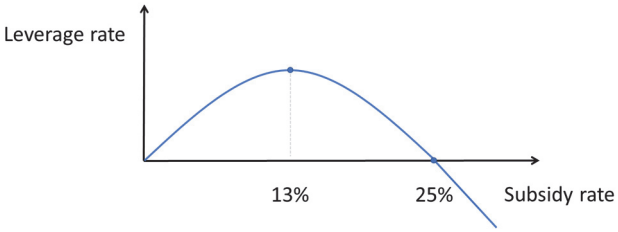
16 The UK's universities are very efficient at producing articles, contributing about 7% of the global stock of articles; which is good given that the UK accounts for 3% of the World's GDP and 1% of its population. For comparison, the UK only accounts for about 2% of the World's patent applications.

Analysis in the Global Innovation Index 2019 suggests that the UK is excellent at knowledge creation (research) but less good at enabling the diffusion and commercialisation of knowledge.[17] This strongly suggests that the UK may have reached the limits of what can be achieved by putting more public money into the universities, excellent as they are.

Subsidising businesses

Aside from the fiscal constraints, there are limitations to what can be achieved with R&D subsidies, at least, in the short term. That is, there is a limited number of researchers, as well as, a limited number of nascent R&D projects that firms would be interested in undertaking.

Consequently, at some point, ever higher R&D subsidies start to crowed-out private R&D spending. That is, extra public funding just drives up the wages of researchers and also firms start to substitute public funding for private funding. (Guellec & Van Pottelsberghe, 2003) show an increased effectiveness of R&D subsidies up to a threshold of 13%, after which further increases in generosity start to decrease the leverage rate; beyond the 25% threshold, further increases have a negative effect on the level of private funding committed to R&D.[18]



Currently, about the 23% of the UK's BERD (Business Expenditure on Research and Development) is publicly funded, strongly suggesting the UK is already close to the limits of what can be achieved by R&D subsidies.

D. OTHER TYPES OF INTERVENTION

This analysis suggests that there is a need to think beyond the two traditional modes of intervention and consider other factors (technical and legal infrastructure) that fundamentally change the costs and benefits of private R&D.

One example is the important role that the IPO (Intellectual property Office) plays in ensuring that patents and copywrites can be used by innovators to protect inventions or software. It is widely understood that developing a system for creating and enforcing intellectual property rights boosts returns from R&D by protecting the private benefits from innovation. Innovation friendly regulations (e.g. CE marking) and easier access to data (e.g. relaxing GDPR) might also lower the cost of R&D projects but could be quite contentious.

Less well known than the system for protecting intellectual property, but no less important, is the technical infrastructure of artefacts, protocols, and standards needed to make effective and reliable measurements when experimenting and prototyping. This paper explains the important role that NPL can play in raising the returns from R&D by maintaining and updating this infrastructure.

17 In 2019, the UK ranked 5th in terms of knowledge creation. (1st in terms of citable documents H-index.) However, it ranked only 12th in terms of knowledge diffusion. (18th in terms of high-tech net exports as a % of trade; and 28th in terms of ICT services exports as a % of trade.)
18 See page 16 of this paper for an analysis of crowding-out and crowding-in.

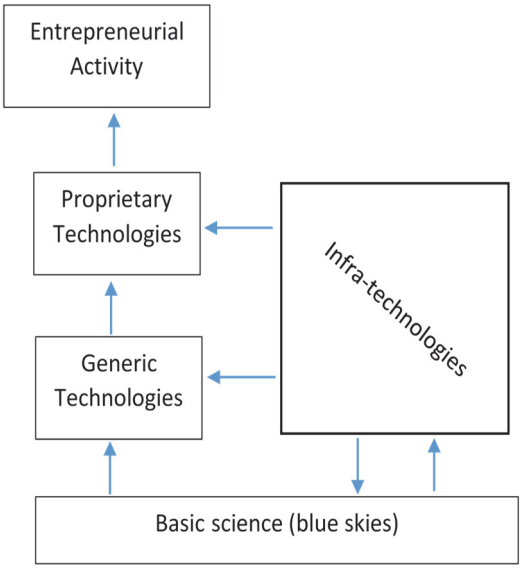
4. THE ROLE OF INFRA-TECHNOLOGIES

This section introduces the concept of infra-technologies as a fourth type of technological knowledge that is often overlooked by conventional taxonomies. The role of infra-technologies is to speed up the rate at which generic technologies are converted to proprietary technologies. Then, this section explains the effect of underinvestment in infratechnologies.

A. INFRA-TECHNOLOGIES

Often technological knowledge is discussed as if it is homogeneous but, according to (Tassey, 2004), it is more useful for policy makers to think in terms of four distinct types of knowledge:

Basic Science	Basic knowledge about phenomena in the world (e.g. quantum physics)
Generic technologies	Generic or general-purpose technologies with an established proof of concept (e.g. medical scanning technique like NMRI)
Proprietary technologies	Specific proprietary technologies that might be patentable (e.g. medical imaging devices)
Infra-technologies	Infra-technologies, reference data, and research tools (e.g. primary standard or reference data)



According to Tassey, science leads to generic technologies, which in turn leads to proprietary technologies. But the efficiency or speed with which one type of knowledge is converted into another type of knowledge depends on having good access to appropriate research tools, techniques, and standards. These elements form the infra-technology needed for the reproducibility of experimental phenomena.[19]

To reproduce an empirical result means being able to observe it again under circumstances like those that existed during its previous occurrence. This assumes that the relevant conditions must be known, and controlled to such an extent, that they can be recreated in future attempts to reproduce a given phenomenon. If the conditions are known well enough, the aspect of control is typically guaranteed by suitable experimental designs. A proper experimental set-up enables a precise and reproducible observation of a selected

19 This is discussed in more detail in (King, et al., 2017).

feature of a system. The collection of research tools, techniques, and standards that together gives this level of experimental control is the relevant infra-technology.

The degree of controllability is also important for clinical trials and experimental prototyping. When optimising the design of a component or system it is often necessary to have large amounts of experimental data. Sometimes when the relevant infra-technology does not yet exist, cutting-edge inventors invent a new research tool so that data can be collected more efficiently.[20] The success of experimental development often depends on access to tools that allow datasets to be assembled quickly and accurately.

The accuracy of a measurement can be improved by calibration against a trustworthy reference. This might be a national standard or a reference instrument that has been calibrated against a national standard directly, or indirectly via one or more steps. This method of ensuring a measurement's accuracy, through an unbroken chain of calibrations, is called 'measurement traceability'. NPL and its sister labs (LGC and NEL) are responsible for maintaining, and sometimes updating, these national standards.[21]

To assure the quality of measurements, instruments should be compared against a standard of higher accuracy. And, if this reveals errors, then corrections can be applied. Calibration is the comparison of an instrument against a reference or standard, to find any errors in the instrument's readings. In some cases, calibration identifies a relationship (equation) linking the input and output of an instrument. The outcome of a calibration is typically a certificate reporting instrument errors or corrections to be applied, and the uncertainties in these corrections.

B. UNDERINVESTMENT IN INFRA-TECHNOLOGIES

Underinvestment in R&D can take the form of both the wrong amount and the wrong composition of R&D activities. Hence, it is important to consider how the production of each type of knowledge is sustained and stimulated. Infra-technologies, like metrology (tools, standards, protocols, reference data), increase the productivity of research and innovation activities.[22] Similarly, refurbishment of generic technologies increases the likelihood of developing proprietary technologies.

The trouble with both infra-technologies and generic technologies is that they are both expensive to develop and hard to commercialise, as well as being subject to extensive spillovers; which mean that private investment will be less than optimal because of the

20 For example, in 1900 the Wright brothers tried to design aircraft wings based on theoretical models (early aerodynamics) and limited experimental data from Lilienthal who had sadly died a few years earlier in a test flight. However, during the autumn of 1901, the Wright brothers began to question the aerodynamic data on which they were basing their designs. They decided to measure their own values of lift and drag with a series of wind tunnel tests. At the end of their wind tunnel tests, the Wright brothers had the most detailed data in the world for the design of aircraft wings. In 1902, they returned with a new aircraft that performed much better than the 1901 aircraft and so the development of wind tunnels lead directly to their famous flight in 1903.

21 For example, NPL's Louis Essen built the first working atomic clock in 1955; with caesium clocks being used to change the definition of the second in 1965. (This meant switching from defining the passage of time using the Earth's passage round the Sun, to a better definition based on the oscillation of atoms.) Subsequently, this switch in the definition of the second enabled time to be measured much more accurately; which was later needed for the emergence of GPS services.

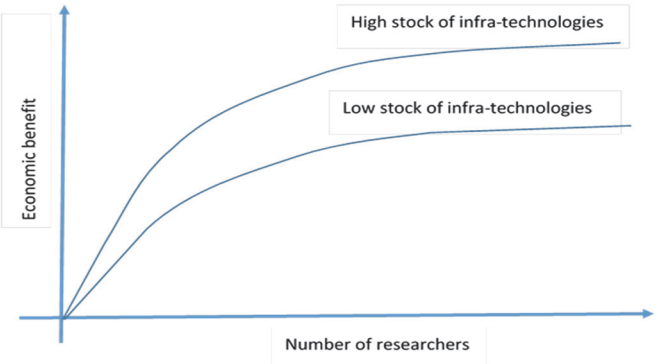
22 NPL calibrates instruments for commercial calibration labs, who then calibrate instruments for end-users on a massive scale. Thus, the benefits of new or improved calibration services are transmitted down the chain. In economic terms, 'pecuniary externalities' mean that end-users benefit from improvements in calibrations despite have very little direct interaction with NPL.

temptation to free-ride on the efforts of others. This means that public support is needed to remedy underinvestment in infra-technologies by the private sector.[23]

Investment in both the UK's measurement infrastructure and the science of measurement (metrology) has taken place over 100+ years. [24] (Note that for much of its history the focus was physical science and engineering.) As discussed, there are strong reasons to believe that the national measurement laboratories (NPL, LGC and NEL) and the commercial measurement sector (instrument manufacturers and testing laboratories)[25] play an important role in both reducing the cost of R&D and increasing the benefit that comes to firms from investing in R&D by maintaining this technical infrastructure.

Infra-technologies can be thought of as a complementary asset which raise the productivity of R&D. The relationship might be represented by the following production function for the economic benefit generated by R&D: $Y = A.K^{\alpha}.L^{\beta}$, where Y = economic benefits, K = stock of infra-technologies, and L = number of researchers. The parameters α, β and A are positive constants that determine how a percentage change in one of the inputs (K or L) translates into a change in the amount of economic benefit that is generated. Diminishing returns for both inputs are to be expected (α < 1 and β < 1) – note that no assumption on returns to scale (α + β) is needed for the purpose of this model.[26] The productivity of research is $Y/L = A.K^{\alpha}L^{\beta-1}$, which declines as L increases unless there is a corresponding increase in K.

The implication of such a model is that raising the number of researchers lowers the productivity of R&D unless there is a corresponding investment in complementary infra-technologies. That is, if government were to increase the funding for science, then there would need to be a commensurate increase in the investment in infra-technologies, otherwise, there will be a decrease in the productivity of researchers.



However, the relationship sketched above is based purely on theoretical arguments rather than a systematic statistical analysis. Hence, further economic analysis is needed to explore the relationship and estimate parameters in the model. This is something that might be investigated in the future using a cross country econometric analysis.

23 The four types of R&D have different amounts of public good content. Hence, different degrees of underinvestment by the private sector.
24 The National Physical Laboratory (NPL) was founded in 1900 with the mission to provide the measurement capability that underpins the UK's prosperity and quality of life. It is the UK's National Measurement Institute and is at the heart of UK's measurement infrastructure supporting and enabling confident R&D and innovation decisions in business, the public sector and academia to meet current and future needs and deliver the Industrial Strategy.
25 The boarder measurement requirements of the UK are huge and NPL, LGC and NEL directly support over 1500 UKAS accredited laboratories enabling UK industry to deliver millions of critical measurements every year. 'UKAS' stands for the United Kingdom Accreditation Services.
26 There are two main strands in the economic growth literature. On the one hand, there is the exogenous theory of economic growth which is based on the accumulation of capital. Capital is a rival good (e.g., if a worker is using a machine, it cannot be used by other workers). This leads to constant returns of scale. On the other hand, there is the endogenous theory of economic growth. This line of thought assumes that productivity growth is due to the generation of new "ideas" (i.e: new goods or new processes), which in essence are non-rival (i.e., can be used by many at the same time). The accumulation of non-rival "knowledge capital" can sustain growth in the long-term. This leads to increasing returns to scale. Infra-technologies are midway between conventional physical (instrumentation) capital and ideas (standards), so some sort of increasing returns to scale are to be expected.

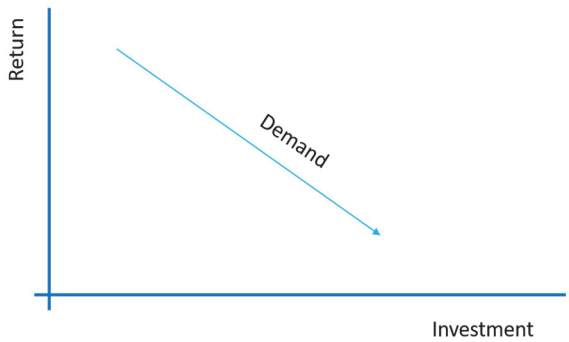
5. A STYLISED MODEL FOR PRIVATE INVESTMENT IN R&D

For large high-tech businesses, an R&D project is viable if its expected benefits exceed its expected costs. R&D projects generate new products and processes: new products increase sales and sometimes create new markets; and new processes reduce the cost of making or supplying products (goods or services).

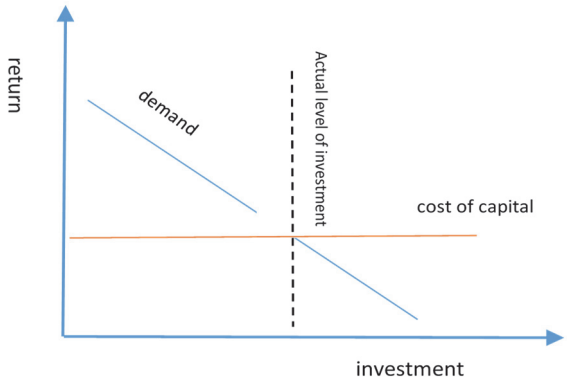
Before explaining how advances in measurement science affect R&D spending, it's helpful to review the classic stylised model, often used by economists, when thinking about the aggregate level of private investment in the economy. According to this model, the level of investment is determined by the expected private rate of return.

The costs and benefits of a project will typically occur over a period of years; and these costs and benefits can be compared using the concept of present values.[27] Thus, the private rate of return on a project is defined as its net benefit (private income minus private cost) as a percentage of the private cost of the project. Hence, a project's expected rate of return can be expressed as follows: 'rate of return' = 100*('total benefit' – 'total cost')/'total cost'.

Businesses have a portfolio of potential projects, each with differing expected returns. To prioritise funding these projects are put in descending order of the expected return. When only a little money is available for investment, only projects with the highest returns will receive funding. But as more money for investment is made available, projects with ever lower rates of return will be brought into existence. In the aggregate economy the decisions of one firm will be writ large. Hence, the rate of return on the last project funded decreases as investment increases; which is the basis of the downwards sloping demand curve. The figure on the right-hand-side, represents the demand for investment, showing the rate of return on the last project funded (vertical axis) for a given level of aggregate investment (horizontal axis).



Lastly, the actual level of investment (or equivalently the last project funded) is determined by the cost-of-capital – that is, the rate at which a business can borrow money. Essentially, the cost-of-capital is the opportunity cost of foregoing investment in something else; and is determined outside the model by factors like the interest rate set by a central bank. Therefore, the cost-of-capital determines the hurdle rate for potential projects. Projects with a high rate of return will be funded first; but all projects with rates of return above the hurdle rate will be funded. Hence, the level of private investment is determined by the point where the cost-of-capital (hurdle rate) intersects the



27 This is based on a rate of time preference - money now is worth a bit more than money in the future. Summing the present values of the expected costs (benefits) across future years enables the total cost (benefit) to be estimated. (HM Treasury, 2018) stresses the importance of discounting. (This document, known as the Green Book, provides a comprehensive central government guidance on appraisal and evaluation.) The Green Book notes that, "in government appraisal, costs and benefits are discounted using the social time preference rate of 3.5%" (see page 7, paragraph 2.18).

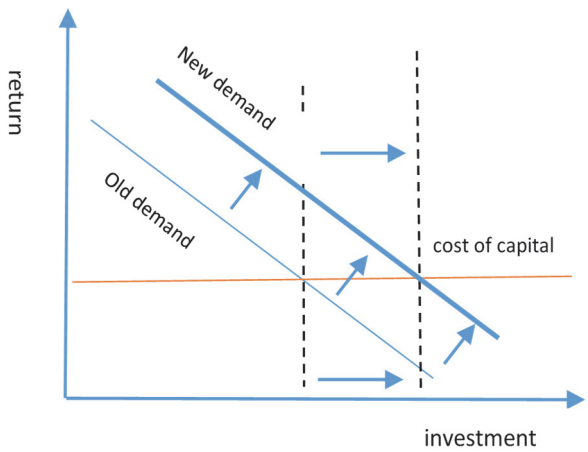
demand curve. (See RHS figure represents the demand and supply of funding for investment. The vertical axis can be thought of as both the rate of return on the marginal project and the interest rate.)

This model is helpful when thinking about how various factors will affect the level of investment. Nonetheless, it represents a simplification of more complex reality. The primary element missing from this model is the highly uncertain nature of returns from R&D. The sketch graph leads one to imagine that the portfolio only contains projects with a positive return. In reality, many projects will have a negative return, but a few will have huge positive returns. This means that, the returns on successful projects are large but there's a large chance of making a loss. (The average return across the whole portfolio of potential projects could well be negative.)

Ideally, businesses would fund many projects to achieve the average return; but R&D projects are so expensive that most businesses can't afford to play the averages. Rather, they must pick a handful of projects and hope one of them pays off. This means that risk averse investors will add a risk premium to the conventional cost-of-capital (interest rate) when setting the hurdle rate for an R&D project.[28] Consequently, the cost of capital for drug discovery (biotechnology) is around 10%[29] as opposed to 5% in less risky sectors.

The demand curve will move upwards if something (e.g. an intervention) causes the cost of potential projects to decrease; or if something causes the benefits to increase. Thus, to move the investment demand curve upwards requires one of three things to happen:

- Reduce the costs of R&D
- Increase the benefit from R&D
- Provide better information about returns on each project in the portfolio.



Assuming the interest rate remains the same, the demand curve will intersect the cost-of-capital to the right of its previous crossing point; which implies that the intervention or event tends to increase in the level of investment. This classic investment demand model (see above) can be used to think about the impact that it can have upon the level of private investment in R&D.

28 The return demanded by an investor consists of two components: the interest rate that can be obtained through the investment in risk-free assets, and a risk premium derived from the uncertainty surrounding the investment. This risk premium is a fundamental element of investor behaviour. For instance, the long-term return on the stock market has traditionally been around 13%, while the return on Treasury Bonds is much lower, around 5%. This shows the disparity of risk perceived by investors. Risk depends not only on how uncertain the investment is, but also the time it takes until the investment materializes, since at longer durations there is a greater chance of negative events impacting the investment. This is shown by the typical upward sloping shape of the *yield curve* (this curve shows yields across different contract lengths for a similar asset.

29 http://people.stern.nyu.edu/adamodar/New_Home_Page/datafile/wacc.htm

6. REDUCE THE COSTS OF R&D

NPL estimates that measurement activities, such as, testing and calibration, make up 14.3% of the R&D activity in terms of time spent by researchers and technicians on its sub-activities.

This estimate is based on data from the last census (NOMIS) and the Annual Population Survey (APS). This data allows one to look at the distribution of SOCs (Standard Occupation Codes) among the employees of a given industry.

NPL's analysis of these datasets found that:

- 14.3% of employees in the research and development sector are calibrators, testers, or analysers.
- A further 5% of employees take measurements as part of their role.

Since around 20% of R&D activity is connected to taking measurements, the availability of knowledge and devices that makes measurement more efficient or more accurate is vital to reducing the cost of R&D.

National measurement institutes perform publicly funded R&D and publish many hundreds of articles in peer-reviewed journals each year. This research activity makes scientific knowledge, technical data, and software freely available to innovators. The diffusion of infra-technologies lowers the cost of applied R&D and experimental development; and these articles help to replenish the stock of infra-technologies used by the wider research base. Occasionally these advances enable a whole new area of quantitative experimental science.

There are three mechanisms by which better research tools and techniques lower the cost of R&D projects:

1. The availability of appropriate research tools and techniques make it easier to generate reliable information on the performance of a new technology, avoiding costly 'dead ends' as early as possible. The cost of generating new knowledge is increased by needing to repeat a study multiple times due to inconsistent results or being led down 'blind alleys' by incorrect journal papers.

2. Sometimes a new tool or technique enables the measurement of things that weren't previously quantifiable and so could only be investigated with qualitative techniques (e.g. expert pattern recognition).[30] The introduction of such techniques can greatly increase the speed and reproducibility of research in certain areas of life science.

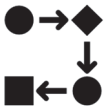
3. Without improvements in measurement science the only way to get more precise estimates is by testing more samples, running more trials, or increasing the scale of an experiment to produce a detectable effect. But this means experiments take longer to perform and R&D projects are more expensive.

30 Traditionally microbiologists in pathology labs looked for specific patterns of mould in petri dishes to identify the presence of pathogens. Now mass spectrometry makes it possible to detect large molecules that act as chemical signatures for the presence of pathogens.

7. INCREASE THE BENEFITS FROM R&D

There are essentially three ways in which infra-technologies increase the benefits from R&D:

There is the better technical performance of instruments and process control equipment.



The existence of appropriate protocols for testing safety and performance enables faster commercialisation and adoption of new technologies.

Supporting the development of clear performance-based product standards lowers non-tariff barriers and makes it easier for new entrants to displace incumbents.

These channels will now be discussed in turn.

A. BETTER TECHNICAL PERFORMANCE

Around 7% of all business R&D spending (£1.7 billion) is directed at instrumentation. NPL works closely with instrument manufactures to develop complementary calibration services. Indeed, there is a symbiotic relationship between advances in instrumentation and advances in calibration. To realise the benefits of better instrumentation you need better calibration techniques and vice versa.

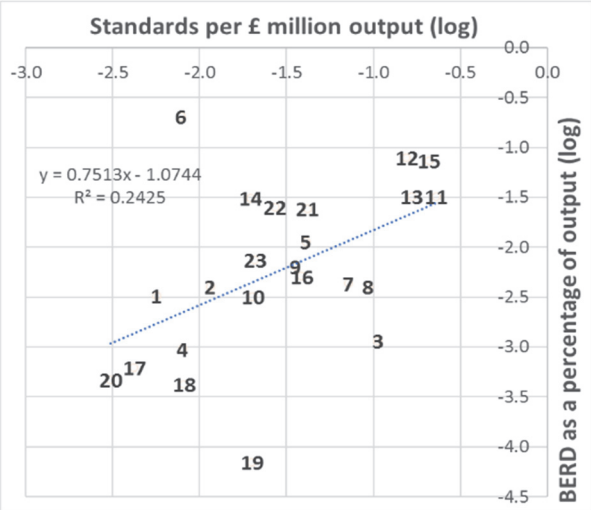
Indirect benefits exist in cases where one of the NMS laboratories generate benefits for firms that don't directly use its services and aren't even aware of its role. For example, suppose that NPL manages to extend the range of one of its calibration services, which enables the calibration labs who take traceability from them to pass on this extension of the range to their customers. Initially, only a few calibration labs might offer calibrations in this range which could allow them to charge a premium to firms who benefit from this new capability. However, as more calibration labs update the service they offer, this price premium will be eroded by competition and the full benefit of the new service will be passed on to the customers of the calibration labs.

Lastly, measurement maximises value from incremental innovation by enabling performance of existing technologies to be optimised. Measurement error limits the scope for incremental innovation through the optimisation of product characteristics. In short, the inability to fully control or reproduce these characteristics creates are gap between the theoretically optimal performance and the physically achievable performance.

B. FASTER COMMERCIALISATION

(Lambert & Temple, 2019) investigate the link between standards, business strategy and innovation using data from the UK innovation survey and the BSI standards database.

They find that, standards have a significant impact on the extensive margin of R&D expenditures.[31] Although, there is probably a symbiotic, two-way relationship between standards and investment in innovation activities. Hence, the figure, right, is meant to illustrate an association rather than a one-way casual connection.



The figure compares standardisation activity to R&D intensity across 23 sectors of the economy in 2012.[32] In the context of this analysis, R&D intensity is BERD as a percentage of a sector's output; and standardisation intensity is the number of standards generated by a sector normalised by size of that sector.[33] The figure shows that there is a strong positive correlation between R&D spending and the stock of standards. (Of course, some industries are more (or less) R&D intensive for reasons that have nothing to do with standards. Pharmaceuticals and Construction don't quite fit the trend but, even with these oddities, the correlation is still statistically significant at the 5% level.)

The relationship between R&D and standards can be explained as follows: R&D creates inventions that must be commercialised and brought to market as innovations. A key driver in accelerating this process is giving potential customers or regulators (public or private) confidence that a new technology works as well as its owner claims it does. This is easier to do when there are established methods for testing the performance of a product or process.[34]

Robust measurement and accepted protocols provide a source of reliable and trusted data for potential customers. Measurement plays a vital role in the process by which a new process or new product is accepted by the market. Codified measurement knowledge, in the shape of good practice guides, helps innovators to agree protocols for testing and validation with customers or regulators. (The existence of these standards can be especially important ahead of the development of formal standards and or regulations.)

It follows that the confidence created by the technical infrastructure (protocols and standards) brings better products and processes to market sooner. And, since money 'now' is worth more than money in the future, speeding up commercialisation, increases the value of an

31 This means that potential projects are brought in to existence and firms become R&D active.

32 ID numbers for the 23 sectors: 1 - Mining and oil, gas extraction. 2 - Food and beverages, tobacco. 3 - Textiles, clothing, leather. 4 - Wood, paper, printing, recording. 5 - Chemicals inc. petroleum ref exc. pharma. **6 - Pharmaceuticals.** 7 - Rubber and plastic 8 Non-metallic mineral products. 9 - Basic metals. 10 - Metal products. 11 - Manufacture of computers, electronic and optical products. 12 - Manufacture of electrical equipment. 13 - Manufacture of machinery and equipment n.e.c. 14 - Manufacture of motor vehicles, trailers and semi-trailers. 15 - Manufacture of other transport equipment. 16 - Other manufacturing, repair. 17 - Electricity, gas, water. 18 - Sewerage, Waste and Waste management. **19 - Building and construction.** 20 - Transport and distribution. 21 - Telecommunications. 22 - Computing and IT services. 23 - Scientific and technical services.

33 These standards are generated by businesses with the support of the British Standards Institute.

34 This is discussed in (Hawkins, 2017).

innovation. (Shifting the revenue curve to the left raises the present value of the income generated by sales of a new product or cost savings from a more efficient process.)

C. LOWERING NON-TARIFF BARRIERS

Lastly, NPL represents the UK within the international network of measurement institutes, and its scientists sit on international committees, many leading to standards and regulatory requirements.

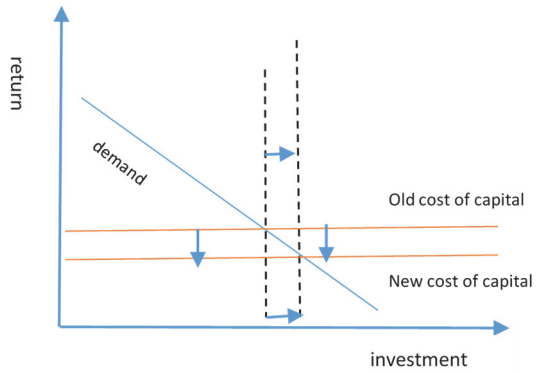
NPL works in partnership with other NMIs (National Measurement Institutes) in developing the test methods and standards for emerging areas. This helps to ensure that UK companies are not put at a disadvantage by allowing standards based on technology favoured by a foreign incumbent.[35] Better measurement protocols allow less prescriptive, performance-based, product standards, that make it easier for novel products to reach the market. This input to the development of standards increases the sales of new products by making it easier to enter foreign markets.

35 Over many years NPL's scientist have helped to create a system of standards and protocols that enabled regulators to move away from requiring that the materials used for aerospace components have the same properties as steel. NPL has worked with other research institutes to support the UK Composites Association in its aim of promoting the adoption of novel new materials in highly regulated sectors. Specifically, there has been a drive to change aviation standards used by the European Aviation Safety Association (EASA). Moving from standards based on equivalence to steel to performance-based standards has opened the market to manufacturers making parts using lighter composite materials.

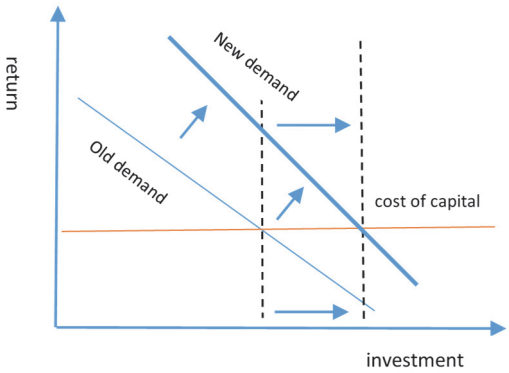
8. BETTER ALLOCATION FOR R&D RESOURCES

The stylised models discussed in an earlier section implicitly assumed that companies can form reliable expectations about the likely return on R&D projects. But, in reality, there is significant uncertainty around R&D investments. (In extreme cases, investment decisions may be badly hampered by technological uncertainty.) Therefore, increasing the reproducibility of research provides investors with better information, which increases investment for the following reasons:

- Less technological uncertainty reduces the risk premium and so lowers the hurdle rate. This allows projects with lower expected returns to be funded. (See RHS figure.)



- Better information increases the slope of the demand curve, increasing investment in R&D, assuming the hurdle rate is above the average return for all potential projects in the portfolio, which could well be negative.



The second of these bullet points deserves some explanation: When the returns on projects in the portfolio are very uncertain, the expected return on any one project (based on available data) won't differ much from the average return across the whole portfolio. Consequently, the demand curve will have a gentle slope, but as better information becomes available the slope of the demand curve will rise. (The line will pivot about the average return, because the average return across the portfolio can't change[36].) The RHS figure shows how investment rises as the demand curve pivots clockwise about the average return for the whole portfolio of potential projects.

Essentially, high quality, trusted data provides reliable information about the performance of new technologies by supporting research reproducibility. This makes innovation decisions more effective – enabling investors to target those areas with the highest potential. Thus, better information on the likely returns improves allocative efficiency of R&D resources. This is particularly important in the medical and life sciences given the iterative (trial and error) nature of the research. (In the physical sciences it's easier to use mathematical models to predict behaviour but areas like medicine require extensive clinical trials.)

36 Remember that the average return for the full portfolio of potential projects could be negative.

9. CONCLUSION

A. THE CENTRAL ARGUMENT

The argument made in this paper can be summarised as follows:

- Firstly, raising the returns from R&D should increase private investment in R&D towards the 2.4% target by expanding the set of privately profitable R&D projects.
- Secondly, investment in infra-technologies increases the return on private R&D activity, through making one of its essential sub-activities - taking measurements - more reliable and productive.
- Lastly, extensive externalities drive a wedge between the private and social returns meaning that businesses will not invest adequately in infra-technologies despite the benefits they generate. Therefore, public funding is required to remedy the inevitable underinvestment in infra-technologies and this will raise private R&D spending by fundamentally increasing the productivity of R&D itself.

B. NPL'S VISION FOR THE FUTURE

NPL's vision is to be an exemplary national laboratory for the UK, delivering extraordinary impact from excellent science and engineering.

NPL can support BEIS's aspirations in many more areas and are contributing to a recent study entitled 'Review of Government Science'. This review suggests that: *The Government should make greater use of Public Laboratories as leaders in directed R&D programmes, and in supporting innovation through intermediate technology readiness levels.*

NPL and its sister labs (LGC and NEL) are responsible for both maintaining and developing the nation's existing measurement infrastructure. Traditionally, the focus of these labs has been on providing an infrastructure for the physical sciences and engineering. As discussed there are issues with the reproducibility of research in the life sciences that can only be addressed by extending and adapting metrology to this complex domain. However, just maintaining and improving the existing infrastructure consumes most of the labs' public funding. That is, the current level of public funding does not allow NPL and its sister labs to create whole new sets of infra-technologies without neglecting existing areas of metrology.

Areas that need additional support include:

- Medicine and life sciences
- Quantum technologies
- Climate science
- Data and digital technologies

C. ONE EXAMPLE: REPRODUCIBILITY IN THE LIFE SCIENCES

The life sciences are one area where new infra-technologies are needed to address the issue of research reproducibility.

Reproducibility is a central methodological criterion of science. If an empirical observation cannot be reproduced, it will not belong to the established body of scientific knowledge. Nevertheless, the reproducibility of an empirical result is only necessary, not sufficient for its

acceptance by the scientific community. An additional condition is the consistent incorporation and interpretation of reproduced results in a theoretical framework.

Many large-scale physical structures or biological systems either do not permit, or at the very least, make it hard to actively control the circumstances around any empirical set up. In such situations we tend to observe what has been generally referred as 'emergence'. This phenomenon occurs when an entity is observed to have properties that its constituent parts do not have on their own. These properties only show when the parts interact in a wider whole.

New improved infra-technologies are essential to properly describe and measure emergent properties of complex systems. Hence, public interventions that promote the development of new infra-technologies, reduce uncertainty in the empirical analysis of complex systems which entails better reproducibility.[37]

For further information contact

Dr Robin Hart

Strategy Director, NPL

robin.hart@npl.co.uk

Dr Mike King

Chief Economist, NPL

mike.king@npl.co.uk

Eugenio Renedo

Economist

eugenio.renedo@npl.co.uk

37 Note that 20 years ago, something similar was done for chemistry through the Valid Analytical Measurement (VAM) programme; having a fundamental effect on the field of analytical chemistry.

REFERENCES

Bloom, N., Griffith, R. & Van Reenen, J., 2002. Do R&D tax credits work? Evidence from a panel of countries 1979-1997. *Journal of Public Economics,* pp. 1-31.

Bloom, N., Jones, C. I., Van Reenen, J. & Michael, W., 2017. *Are ideas getting harder to find?,* Cambridge, Massachusetts, US: National Bureau of Economic Research.

Carreyrou, J., 2018. *Bad Blood: Secrets and Lies in a Silicon Valley Start-up.* New York: Knopf Doubleday Publishing Group.

Department of Trade and Industry, 2005. *The Empirical Economics of Standards,* London: s.n.

Freedman, L. P., Cockburn, I. M. & Simcoe, T. S., 2015. The economics of reproducibility in preclinical research. *PLoS biology,* 13(6), p. e1002165.

Guellec, D. & Van Pottelsberghe, B., 2003. The impact of public R&D expenditure on business R&D. *Economics of innovation and new technology,* pp. 225-243.

Hall, B. H., Mairesse, J. & Mohnen, P., 2010. Measuring the Returns to R&D. In: *Handbook of the Economics of Innovation.* s.l.:Elsvier, pp. 1033-1082.

Hawkins, R., 2017. Standards, systems of innovation and policy. In: *Handbook of Innovation and Standards.* Cheltenham: Edward Elgar.

HM Treasury, 2018. *The Green Book: Central Government Guidance on Appraisal and Evaluation.* s.l.:s.n.

King, M., Lambert, R. & Temple, P., 2017. Measurement, standards and productivity spillovers. In: *Handbook of Innovation and Standards.* Cheltenham: Edward Elgar, p. 162.

Lambert, R. & Temple, P., 2019. *Standard Setting Organisations, Information Flows and Business Strategies: An Empirical Investigation,* Guildford: School of Economics, University of Surrey.

Shane, S. A., 2004. Academic entrepreneurship: University spinoffs and wealth creation. s.l.:Edward Elgar Publishing.

Tassey, G., 2004. Underinvestment in public good technologies. *The Journal of Technology Transfer,* 3(1-2), pp. 89-113.

ANNEX: USER COST OF R&D

This annex provides an explanation of how to derive the use cost of R&D. What follows is based on the Hall-Jorgensen formula for the real user cost of fixed capital.

If 'MRPK' is the marginal revenue product of capital, then the post-tax income is MRPK*(1 - T), where 'T' is the corporation tax rate (T = 18%). If 'P' is the price of a unit of capital, then the post-tax cost of unit of capital for a profit-making company is given by:

$$\text{Post-Tax Cost of a Unit of Capital} = P*(1 – T)*(r + \delta) – P*(1 – T)*\delta.$$

The first term accounts for the interest foregone from not depositing the money in the bank along with the decrease in the value of the machine due to depreciation; and the second term is needed because depreciation is deductible as a cost and so reduces the tax bill. However, if S is the subsidy rate, then the post-tax cost of a unit of capital becomes:

$$\text{Post-Tax Cost of Unit of Capital with Subsidy} = P*(1 – T)*(1 – S)*(r + \delta) – P*(1 – T)*\delta.$$

That is, the firm gets to claim a credit from the government that is proportional to its investment and so it only pays a fraction of the price of a new unit of capital.

In equilibrium, the post-tax cost of unit of capital must equal the post-tax return on a unit of capital, which implies that $P*(1 – T)*(1 – S)*(r + \delta) – P*(1 – T)*\delta = MRPK*(1 - T)$. It can be seen that this simplifies nicely to $P*(1 – S)*(r + \delta) – P*\delta = MRPK$, because they pay tax on the credit. Hence, the pre-tax return on a unit of capital becomes:

$$\text{Pre-Tax Return on a Unit of Capital} = MRPK/P = (1 – S)*(r + \delta) – \delta$$

Lastly, the B-index is define by the $u + \delta = (\text{B-index})*(r + \delta)$, where 'u' denote the user-cost of capital. And, in equilibrium, this user-cost of capital is necessarily equal to the pre-tax return on a unit of capital. Therefore, in this instance, we must have B-index = 1 – S, where 'S' is the subsidy rate.