CSTI Policy Discussion Note

Innovating the Research & Innovation 'Toolkit'

Unlocking private sector investment in emerging tech R&D

In the context of the UK government's '*Innovation Strategy*', this briefing note explores the following issues:

- Why a competitive **innovation 'toolkit'** (of research tools, engineering development tools and testbeds) can be critical to capitalising on strengths in disruptive **emerging technology** domains
- Why there is key role for government in supporting the R&D for such 'infrastructural' technologies (and why the **UK may be underinvesting** by comparison with other leading innovation economies)
- Why public sector investment in enabling 'tool' technologies and demonstration facilities may **unlock private sector investment** in product/process development R&D (**raising UK R&D£ as a %GDP**)

In particular, this note highlights policy attention to supporting 'infrastructural' R&D tools for emerging technology innovation in the United States.

Dr Eoin O'Sullivan, University of Cambridge (May 2021)

Introduction

The UK is a world-leading "*science superpower*", but it falls behind other leading innovation economies in national expenditure on R&D. UK-based firms contribute less to overall national R&D expenditure and, in particular, spend less on '*experimental development*'[1] (product/process) R&D than businesses in other major industrial economies, such as the US, Japan, and Korea.

The UK has the potential to be a leader in a range of new emerging technology areas from quantum information science to synthetic biology. There are, however, significant innovation challenges in making the transition from promising applied science domains into engineered technology domains, which underpin significant value capture for the economy. In particular, one critical challenge is that the process of developing and scaling-up disruptive emerging technologies (especially those based on radically new science and/or with high levels of system complexity) requires the development of new of research and engineering 'tools'.

Emerging technology domains like quantum technology and synthetic biology, for example, require new R&D 'toolboxes' of enhanced measurement, characterisation and test tools; new modelling/simulation tools; new process engineering/fabrication tools; new systems integration tools; and new demonstration and testbed facilities. Critically, many of these tools need significant levels of R&D innovation effort in their own right. The 'infrastructural' nature of these technologies, however, results in significant market failures inhibiting private sector investment in the 'R&D of R&D tools'. Being at the leading edge of innovating the 'toolbox' for an emerging technology domain has the potential to catalyse private sector investment in disruptive product/process R&D, and offer significant national competitive advantage in associated emerging industries.

Without a competitive emerging technology innovation 'toolbox', however, there is a danger that the UK "*science superpower*" just becomes a science lab for the rest of the world. International tech companies may be attracted by the UK science base to carry out basic and applied scientific research, but then go elsewhere to carry out product/process development R&D. Investing in innovation of world-leading 'R&D toolkits' has the potential to enhance the UK's comparative advantage in key disruptive technology domains. And open up opportunities to translate UK scientific strengths into the technology leadership required to drive competitiveness and growth in important emerging S&T-based industries.

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[1] *"Experimental development is systematic effort, based on existing knowledge from research or practical experience, directed toward creating novel or improved materials, products, devices, processes, systems, or services*". Source: OECD *Frascati Manual 2015: Guidelines for Collecting and Reporting Data on Research and Experimental Development* p. 29.

The importance of innovating the innovation toolkit (especially for disruptive science-based technologies)

A competitive national research & innovation system requires more than excellent basic research and early-stage generic 'platform' technology R&D. It also requires a competitive 'toolkit' of enabling R&D technologies and innovation tools and testbeds to support the process of emerging technology innovation itself.

The US economist, Gregory Tassey - a leading thinker on the economic evaluation of technology R&D - calls these '***infrastructural technologies***' (or 'infra-technologies'). As with many other types of infrastructure which support enterprise and industrial innovation, 'infra-technologies' can be all too easily overlooked or neglected. Infra-technologies are a less visible, but potentially critical, source of competitive advantage and productivity in key emerging technology-based sectors.

Discussion of the importance and impact of **R&D "infratechnologies" should not be conflated with "research infrastructure"** used in the sense of large-scale facilities containing major scientific equipment (e.g. synchrotron science facilities, high performance computing facilities, etc).

R&D 'infra-technologies' are the tools used in technology development, demonstration and scale-up, including: measurement, characterisation and testing tools; modelling and simulation tools; databases and data analytics tools; process models, technical standards and standardised reference materials. Infra-technologies can catalyse disruptive innovation, **increase innovation efficiency, decrease development costs, and enhance productivity**. They may also have the potential to **unlock private sector investment** in product / process development R&D, especially in key emerging technology domains.

> **Definition: Infra-technologies**
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> " *Infratechnologies are a diverse set of technical tools that are necessary to efficiently conduct all phases of R&D, to control production processes, and to execute marketplace transactions for complex technology-based goods. These tools are called 'infra-technologies' because they provide a complex but essential technical infrastructure.* "
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> Source: **Gregory Tassey** (2005)

Innovating the toolkit for key (science-based) emerging technologies

The UK is a research leader in a number of high potential science-based emerging technology areas, such as quantum technologies, synthetic biology, advanced functional materials (e.g. graphene). These disruptive technology areas, based on radically new science, cannot rely on the off-the-shelf R&D tools and techniques of current materials engineering or molecular biology innovation. In order to maintain competitiveness, these fields will need to make the transition from promising applied science disciplines into real engineered technology domains (encountering a range of novel development, systems integration and manufacturability challenges along the way). In the US, government innovation strategies for key emerging technologies highlight the importance of building new technology innovation and engineering toolkits and facilities, acknowledging that these tools may need significant R&D innovation effort in their own right (e.g. US Quantum Information Science Initiative).

> Example (US *Quantum Information Science Initiative*):
> **Enabling technologies and tools for Quantum Technology innovation**
>
> " *The successful development of technologies based on QIS will enable increasingly more advanced quantum research, but* ***hinges on the availability of suitable tools, facilities, and other infrastructure items****. The QIS research and development enterprise is not yet large enough to sustain an industry focused on developing and supplying all the necessary infrastructure…*
>
> *The U.S. Government can play a critical role in fostering this field by encouraging programs that target* ***the development and fielding of supporting technologies…*** "
>
> Source: **US National Science & Technology Council** (2018)

Innovating the innovation spaces: The importance of demonstration facilities and co-innovation environments

Innovating disruptive emerging technologies not only requires a competitive innovation 'toolkit', it also requires effective demonstration and test environments for different phases of the innovation process. Translating promising applied science research knowledge into viable commercial technology-based applications involves a range of innovation activities, including: technology development, prototyping, testing, application system integration, demonstration, and manufacturing scale-up. For many emerging technologies, these activities often require specialized demonstration facilities (e.g. testbeds, living labs, and pilot lines) to provide dedicated innovation environments with the right mix of 'tools' and enabling technologies, and the skilled technicians capable of operating them.

Again, care should be taken not to overly conflate national budgets for **R&D demonstration/test infrastructure** (for technology innovation) with **'research infrastructure'** in the sense of large-scale facilities containing major equipment primarily dedicated to scientific experiment (e.g. particle accelerators, radio astronomy telescopes, etc). While there may be potential for technology developers to access some categories of major equipment for product/process innovation-related activities (e.g. high performance computing facilities for device modelling, synchrotron facilities for protein analysis), the innovation system missions, functions and commercialisation capabilities of such facilities are very different.

Emerging technology demonstration and testbeds are currently a significant focus of innovation policy discourse in the United States. In particular, different proposals to increase funding for the National Science Foundation (from the White House, Senate, and House of Representatives) have a common focus on R&D for key emerging technologies and particular attention to demonstration, testing and scale-up infrastructure. Perhaps the most ambitious of these plans is the high profile *Endless Frontiers Act* (summarized in the boxed example).

Policy attention to demonstration and development facilities
US Senate's proposed *Endless Frontiers Act*

Proposes new National Science Foundation **Technology Directorate** with 5 year **budget of US$100B**, with funding for the following:

- **Emerging Technology R&D** in critical domains (including areas reflecting UK strengths / priorities: A.I.; quantum technologies; biotechnology, genomics, synthetic biology; etc)
- **Development / prototyping** activities at 'Univ. Technology Centers'
- **Testing and demonstration** based at new testbed[2] facilities to de-risk a range of emerging technology innovation challenges
- **Technology scale-up** addressing innovation risks related to 'manufacturability' at 'regional innovation hubs'

Endless Frontier Act, S.1260. 117th Congress)

DARPA's contribution to infratechnologies, demonstrators and testbeds (and the implications for UK ARIA)

In the context of the UK Government's plans for an Advanced Research and Invention Agency (ARIA), it is worth noting the significant investments made by DARPA in testbeds and enabling technologies.

As part of DARPA's effort to develop high potential emerging technologies in pursuit of key mission goals, DARPA programmes may start strategically filling in missing capabilities in the emerging innovation system – linking competences and resources associated with scientific discovery and technology R&D, but also research and engineering tool development, and the demonstration of product 'manufacturability' and scale-up.

In this way DARPA, and other R&D mission agencies, make significant contributions to building and renewing the nation's research and innovation 'toolkit' -- building novel tools required to develop promising scientific discoveries into viable/manufacturable engineered technologies.

[2] **NSF Technology Directorate testbeds:** It is proposed that testbeds would receive at least 10% of the NSF Technology Directorate budget, and would include support for "*fabrication facilities to advance the operation, integration, and, as appropriate, manufacturing of new, innovative technologies in the key technology focus areas, which may include hardware or software*".

The role of government in supporting 'infrastructural technologies'

The case for government funding of basic research (and some early-stage 'generic' technology research) is typically made in terms of the 'public good' nature of the research knowledge created. This category of knowledge is readily accessible to the entire research community and its use by one group does not reduce its availability to others (i.e. it is 'non-excludable' and 'non-rivalrous'). By contrast, commercial applications based on novel technologies are considered pure 'private goods' and fully the preserve of private sector firms.

Infra-technologies, however, have an intermediate 'quasi-public good' nature, as they are typically derived from a mixture of public and private sector assets. The benefit to industry (and the national economy) in terms of enhanced innovation efficiency and productivity can only happen if the tools are readily accessible and their adoption is consistent (often standardised) and widespread across relevant sectors. In emerging technology domains, which require novel manufacturing or integration processes, new tools need to be developed *in advance* of the development, scale-up and differentiation of commercial products.

In this context, there are a number of sources of market failure inhibiting private sector investment in infra-technologies, including:

- **Insufficient rate of return:** Infratechnologies enhance the innovation efficiency and productivity of sectors only if their adoption is widespread across many firms and industries. In this context, infratechnologies are not fully proprietary in nature and private sector firms may not be able to earn a sufficient rate of return from their development.
- **Beyond the scope of individual firms:** The development of many infratechnologies requires expensive capital equipment and highly skilled R&D staff. In the 20th century, significant infratechnology tool development was carried out by corporate R&D laboratories[3] of major firms. Today the scale of relevant R&D expertise within individual firms is generally insufficient to develop novel R&D tools.
- **Distributed benefits:** The distributed impact of infratechnologies along the innovation cycle of emerging technologies (e.g. supporting platform technology research, product R&D, integration engineering, manufacturing scale-up) mean that it is especially challenging to anticipate and quantify the potential economic benefits, thus further inhibiting investment by individual private sector firms.
- **Lack of visibility:** By contrast with technologies which are embedded within commercial products or services, breakthroughs in 'infratechnology' innovation (and their potential application across the extended innovation cycle) mean they are less visible to corporate strategists and private investors.

At the other end of the 'public good' spectrum, the investment processes and criteria of public sector research & innovation agencies may lead to underinvestment in basic and applied research underpinning R&D tools:

- **Market size (*versus* market impact) criteria:** Applied technology innovation agencies whose investment criteria include the size of the potential markets, may end up prioritising technologies with the potential to underpin large consumer mass-market products/services (over the smaller specialists markets for R&D tools). Such prioritisation neglects the contribution of infratechnologies to unlocking the larger market potential of novel product technologies. And neglects the potential competitive advantage from having the most advanced R&I toolkit relevant to key emerging technology domains.
- **Scientific novelty (versus scientific progress) prioritisation:** Science and engineering research councils, which use competitive merit review processes to prioritise research project investments, may end up prioritising the core scientific research underpinning emerging technology area. In particular, panels of peer reviewers may favour investments in novel science or engineering projects over less glamorous infratechnology research projects (even if advances enabling tools and technologies have the potential to unlock progress in the key emerging S&T domains of interest).

[3] Many of the great corporate R&D labs of the 20th century made major contributions to infratechnology R&D. For example, AT&T's Bell Labs developed measurement tools, simulation technologies, etc relevant to the telecoms and ICT sectors.

How does UK strategic attention to 'infratechnology' R&D compare?

By comparison with other leading innovation economies - notably the United States – 'infratechnology' R&D tools and related enabling technologies feature less prominently within UK strategies (and budgets) for major emerging technology initiatives and national laboratories / R&I institutes. Similarly, funding of infratechnology innovation appears to make up a smaller component of targeted technology R&D project solicitations by research and innovation agencies.

Benchmarking UK investment in research & innovation infrastructural tools and facilities and exploring the implications for private sector investment in product/process R&D should be a critical part of UK innovation strategy analysis and planning. It is currently very difficult to quantify and compare international levels of governmental investment in infratechnology R&D:

- Infratechnology R&D is not formally categorised (or systematically counted) within national statistics.
- Investment is often buried within the budgets of broader R&D programmes or initiatives
- Infratechnology R&D is carried out by a range of different R&D actors (mission agencies, national labs, RTOs, etc) many of which do not have direct comparators in the UK

Nevertheless, 'infratechnology' R&D appears to be significantly more visible within flagship R&D initiatives of leading innovation economies such as the United States, for example.

- **Flagship emerging technology initiatives:** Federal R&D investment in new research tools, novel enabling technologies and advanced instrumentation is a highly visible element of the strategies (and budgets) of many high profile / high budget emerging technology programmes, for example: the **National Nanotechnology Initiative**, the **National Quantum Initiative** and the **BRAIN Initiative**. The **Materials Genome Initiative** - which is focused on developing the tools and enabling technologies to accelerate advanced materials innovation - had a budget of US$250M over its first 5 years.

- **Small Business Innovation Research (SBIR):** Projects to develop novel infratechnologies and novel manufacturing/engineering tools and techniques make up a significant fraction of the Small Business Innovation Research investments of Federal agencies. Several formal reviews of Federal agency SBIR programmes highlight the scale and importance of SBIR's contribution to national research and innovation tools and innovation infrastructure.

- **R&D procurement solicitations / targeted programmes:** Infratechnologies are frequent targets of the R&D procurement solicitations of US mission agencies, e.g. US Department of Defense (including DARPA) as well as National Institutes for Health. Infratechnology-related solicitations (addressing the need for "research tools" or "enabling technologies") make up a significant fraction of funding opportunities on the databases of Federal Mission agencies (e.g. grants.nih.gov).

  Research tools and enabling technologies also appear in the targeted programme calls of National Science Foundation, e.g. calls related to "AI-Powered Tools" (in maths/physical sciences), tool development for cell biology ("Tools4Cells"), and computational tools for studying microbiomes.

- **National Laboratories and R&D Institutes:** The US' system of national laboratories and Federal research institutes carry out significant levels of infratechnology R&D (in support their mission-driven technology R&D programmes or applied R&D projects with industry). For example, US Department of Energy Labs, such as Sandia have significant efforts in developing and applying innovative characterization and diagnostic techniques, as well as advanced computational methods to materials engineering challenges. Tool development features heavily in the strategic plans of many National Labs (e.g. LBNL, 2019; SNL, 2016).

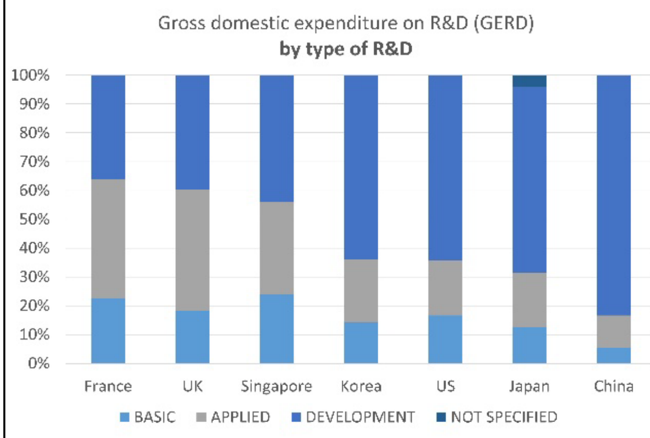
  Similarly, prestigious research institutes, such as the **Janelia Research Campus** (neurobiology), have **'tool building'** – e.g. molecular tools and imaging technologies; computational / modelling tools – as a **core element of their research mission**.

Why investment in enabling R&D tools may catalyse private sector R&D in product/process development

A competitive national innovation system requires competitive innovation 'toolkit' of R&D tools, engineering development tools, and related enabling technologies and demonstration facilities. In particular, the process of technology development and scale-up of disruptive technologies (especially those based on radically new science and/or with high levels of system complexity) is likely to need new innovation and engineering tools, which often require significant R&D in their own right.

If the necessary 'toolkit' is not developed, then promising advances in applied science may fail to get translated into engineered technologies and scaled-up into commercially viable products and emerging industries. Similarly, if a particular national innovation system does not have a competitive 'infratechnology' toolkit and/or does not have the capacity to co-innovate the required research and engineering tools, then it is unlikely to be an attractive location for corporate product/process development R&D activities.

This is potentially important in the context of the **UK Government's ambitions to raise the level of gross expenditure on R&D to 2.4% of GDP**.



SOURCE: OECD Research & Development Statistics (Expenditure)
Data extracted on 20 May 2021 09:25 UTC (GMT) from OECD.Stat

It has been rightly observed that the UK-based business contributes comparatively less to total R&D expenditure (<55%) than other leading economies, e.g. Germany (66%) and Japan (79.1%). What is highlighted less frequently is the fact that it is the R&D category related to product/process *development* (what the OECD labels '*experimental development*'[4]) where the UK falls behind other major economies, such as the US, Japan, and Korea.

This raises important questions about whether the UK's advanced intratechnology capabilities and level of UK public sector investment in 'infratechnologies' R&D.

The UK may be a world-leading "*science superpower*" (and the UK science base may attract significant levels of corporate *science* R&D), but without a competitive 'toolkit' of engineering innovation tools and enabling technologies, will it be able to attract and retain significant levels of 'experimental development' R&D?

Without expanding the levels of industrial 'experimental development' R&D, can the UK reach its ambitions for higher national expenditure on R&D (%GDP)? Could further government investment in 'public good' infratechnology R&D actually unlock or catalyse untapped corporate R&D investments in product/process development R&D?

Is there a danger that the UK just becomes the global 'science lab' for the world? A place where international tech companies come to do the more basic and applied scientific research, but then go elsewhere to carry out 'experimental development' R&D?

Is there a danger that a world-leading 'science superpower' without a world-leading 'innovation toolkit' will not be able to compete in translating 'basic'/ 'applied' science research into 'development' R&D? And will, therefore, miss out on opportunities to translate its science strengths into the technology leadership required to drive industrial competitiveness, productivity and growth?

[4] *"Experimental development is systematic effort, based on existing knowledge from research or practical experience, directed toward creating novel or improved materials, products, devices, processes, systems, or services*". Source: OECD *Frascati Manual 2015: Guidelines for Collecting and Reporting Data on Research and Experimental Development* p. 29.

References

- de Pablo, J. J., Jackson, N. E., Webb, M. A., Chen, L. Q., Moore, J. E., Morgan, D., ... & Zhao, J. C. (2019). *New frontiers for the materials genome initiative. Computational Materials*, 5(1), pp. 1-23.
- Gallaher, Michael, Jeffrey Petrusa, Alan O'Conner, and Stephanie Houghton (2007a). Economic Assessment of the Technical Infrastructure Needs of the Biopharmaceutical Industry. NIST.
- Gallaher, M.P., *et al.* (2007b). Economic Impact of Measurement in the Semiconductor Industry. Planning Report 07-2, prepared for RTI International for NIST
- JRC (2021). Janelia Research Campus website: https://www.janelia.org/about-us
- Jorgenson, L. A., *et al.* (2015). *The BRAIN Initiative: developing technology to catalyse neuroscience discovery*. Philosophical Transactions of the Royal Society B: Biological Sciences, 370(1668).
- LBNL (2019). *Biosciences 10-Year Scientific Strategic Plan 2019 Revision.* Lawrence Berkeley National Laboratory, US Department of Energy,
- Link, A.N., Oliver, Z.T., O'Connor, A.C. (2016). *Economic Analysis of Technology Infrastructure Needs for Advanced Manufacturing: Advanced Robotics and Automation*. NIST GCR 16-005, NIST.
- Link, A. N., & Scott, J. T. (2019). *The theory and practice of public-sector R & D economic impact analysis*. In The Social Value of New Technology. Edward Elgar Publishing.
- NASEM (2020). *A quadrennial review of the national nanotechnology initiative: nanoscience, applications, and commercialization*. National Academies of Sciences, Engineering, and Medicine.
- NASEM (2015a). *SBIR/STTR at the National Institutes of Health*. National Academies of Sciences, Engineering, and Medicine. National Academies Press.
- NASEM (2015b). *SBIR at the National Science Found*ation. National Academies of Sciences, Engineering, and Medicine. National Academies Press.
- NASEM (2020). *Review of the SBIR and STTR Programs at the Department of Energy*. National Academies of Sciences, Engineering, and Medicine. National Academies Press.
- NIH (2021). *NIH Grants Guide: Funding Opportunities / Solicitations ("Tools")* https://grants.nih.gov/funding/SearchGuide/index.html?query=tools
- NQCO (2020). *Quantum Frontiers: Report on Community Input to the Nation's Strategy for Quantum Information Science*. National Quantum Coordination Office. White House.
- NSF (2018). *SBIR / STTR Solicitation Topics & Subtopics.* US National Science Foundation
- *NSF (2021a). Dear Colleague Letter: Advancing Discovery with AI-Powered Tools (ADAPT) in the Mathematical and Physical Sciences.* Research grant proposal solicitation, NSF
- *NSF (2021b). Dear Colleague Letter: Tool Development for Cell Biology (Tools4Cells).* Research grant proposal solicitation, US National Science Foundation
- NSTC (2018). *National Strategic Overview for Quantum Information Science.* US National Science & Technology Council, Subcommittee on Quantum Information Science.
- Ruegg, R., O'Connor, A. C., & Loomis, R. J. (2014). Evaluating Realized Impacts of DOE/EERE R&D Programs. Standard Impact Evaluation Method (No. DOE/EE-1117). Lawrence Berkeley National Lab.
- SNL (2016). *Sandia National Laboratories: FY16–FY20 Strategic Plan.* US Department of Energy.
- Scott, T., Walsh, A., Anderson, B., O'Connor, A., & Tassey, G. (2018). Economic analysis of national needs for technology infrastructure to support the materials genome initiative. NIST.
- Tassey, G. (2004). *Underinvestment in public good technologies*. J. Tech. Transfer, 30(1-2), pp. 89-113.
- Tassey, G. (2017). *A technology-based growth policy*. ISSUES in Science and Technology, 33(2), 80.