From Research to Productivity:

A Systems Analysis of UK Innovation Pathways

cambridge econometrics
clarity from complexity

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Contents

Executive Summary

Successive generations of UK innovation and industrial strategy documents have emphasised the key role of quantity and quality of scientific research and researchers but also highlighted challenges associated with turning ideas into solutions for business growth and public good. The UK's track record across stages of the innovation system has historically been highly variable. The Industrial Strategy (HM Government 2024) is the most recent of many reports that call this out explicitly, highlighting a particular weakness in technology adoption.

Overcoming these challenges requires a better understanding of innovation systems and the nature of links between innovation and economic performance. We need more evidence of the UK's strengths and weaknesses across the innovation process – from research to commercialisation to adoption – in order to more effectively design and target interventions. While many studies explore aspects of these questions, there are few that examine performance across the entire process. Furthermore, we know that the UK is more competitive in researching, commercialising, and/or adopting some technologies than others. Yet we have little comparative evidence of these advantages and disadvantages, which has limited the development of explanations and mitigating strategies.

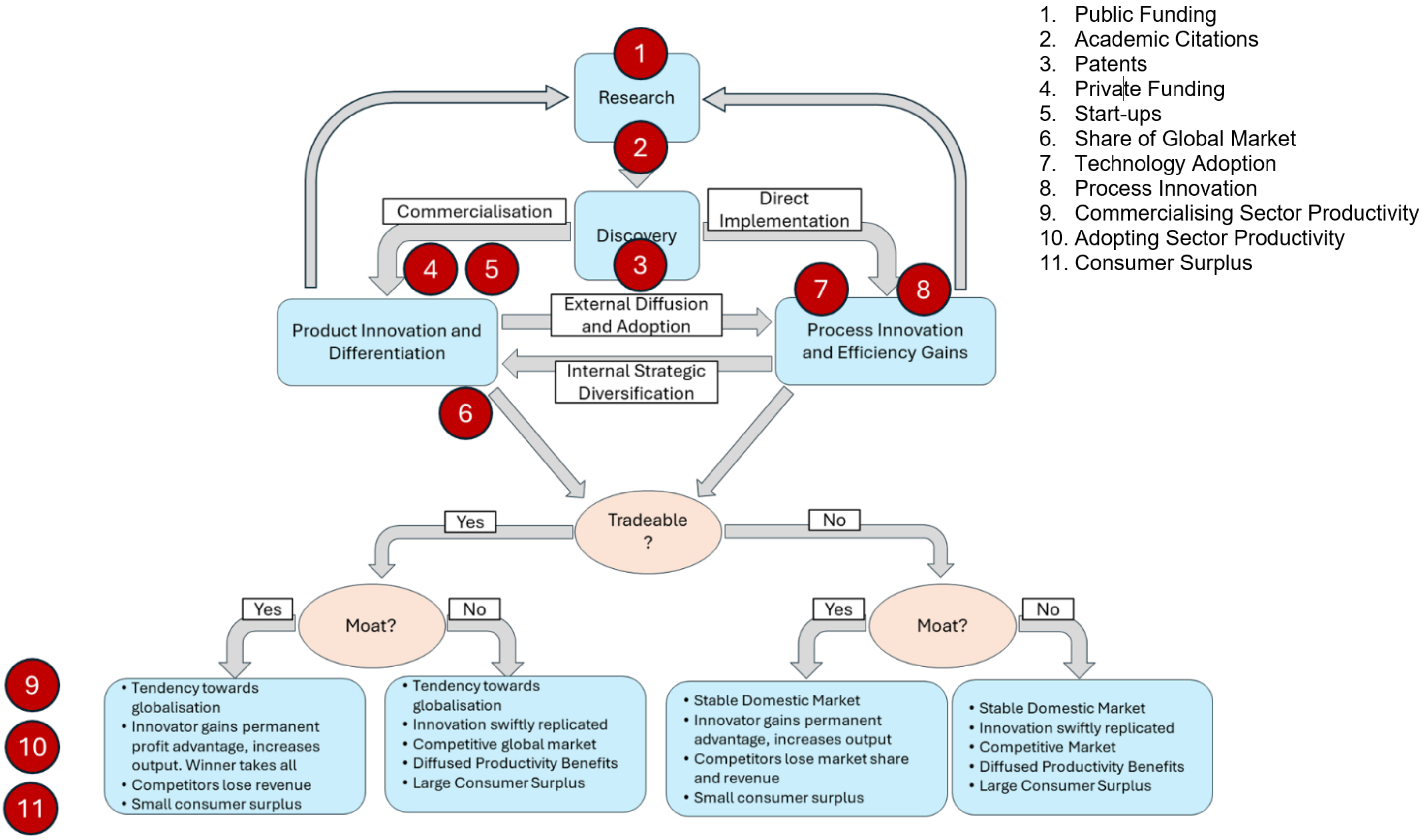
This project seeks to fill this gap by analysing UK performance across the innovation pathways of ten key technologies and disciplines, selected for a combination of variety and relevance.

Semiconductors	Quantum technologies
Artificial intelligence	Mobile technologies
mRNA vaccines	Agricultural gene editing
Offsite construction	Industrial robotics
Modern supply side economics	Innovative galleries

To do this, we developed a theoretical systems "map" that depicts, firstly, how knowledge chains (the set of steps through which ideas are developed into economically useful products) interact with specific value chains (the sequence of processes through which raw materials are turned into final products). In doing this we illustrate the different routes through which innovation activity in knowledge chains increases the efficiency and effectiveness of the value chains they feed into, ultimately leading to productivity growth and consumer surplus across the economy. Figure A visualises these system dynamics and provides a scaffolding upon which we can explore the different pathways from research to market across the different technology families.

We used a combination of qualitative and quantitative research to try to articulate and understand the current situations and underlying mechanisms at work for each of our chosen case study technologies, focusing on studying rates of research, commercialisation, implementation, and adoption to explore the effects of these patterns on economic outcomes, such as productivity and consumer surplus.

Figure A: Innovation process map with 11 collected metrics identified



Although every technology we looked at had a distinct underlying narrative, some generalisable patterns emerged. We found that distinct differences in dynamics appeared between sectors that produce goods and services that can be sold internationally (what we term “tradeable technologies”) and technologies that are primarily developed within the domestic market that they ultimately serve (“non-tradeable technologies”).

For tradeable technologies, research, commercialisation, and adoption can all occur at different rates in different places, which means that different nations can become more or less competitive at capturing value from different stages. This sets up a situation, familiar in the UK, where a nation may excel at research of a technology, for example, but not at its commercialisation. Significantly, strength or weakness in one phase of the process does not necessarily influence subsequent phases. For instance, it is possible for the UK to be strong in research, weak in commercialisation, and strong in adoption for a technology or technology family. This is currently the case for semiconductors, where UK knowledge contributes to chip design, commercialisation occurs elsewhere, but UK businesses are relatively advanced in adopting technologies that rely on semiconductors. Consequently, for tradeable technologies other countries can position themselves to better capture value of UK R&D investments at crucial stages of the innovation process. Our research demonstrates that the characteristics of the market structure of a technology can help illuminate and explain why we find different patterns of strengths and weaknesses in value capture across the innovation process for different technologies.

For instance, for tradeable technologies with high moats – that is, technologies where competition is constrained, for example because of network effects, economies of scale, or patent law – we found that a relatively larger proportion of the value generated is captured by firms in the commercialisation phase. For the UK, there is therefore significant additional value to be captured in the better commercialisation of those high-moat tradeable sectors in which the UK already has a research specialism, but is currently underperforming at commercialisation.

However, we identified multiple barriers to the commercialisation of tradeable technologies in the UK, including examples of both specific technological barriers and general economic or ecosystem barriers. Removing these barriers, both specific and general, could be a point of government intervention and would be a sensible focus of any industrial strategy. Examples here would be initiatives to support greater levels of commercialisation of the UK's leading research into genomics, including applications in both medicine and agriculture.

For tradeable technologies with lower moats, a relatively larger proportion of the value generated is captured in the adoption phase. We found that, globally, high levels of adoption in these technologies correlate with positive downstream economic outcomes. The UK has a surprisingly mixed record of adoption in these technologies compared with other developed nations.

In investigating this, we identified multiple barriers to the adoption of these lower-moat tradeable technologies in the UK, including examples of both specific technological barriers and general economic or ecosystem barriers. Again, a worthwhile focus of government intervention would be in acting to remove these barriers. For example, initiatives to tackle low levels of adoption of robotics in the manufacturing sector would have an almost immediate productivity impact in a sector in which we are falling behind globally.

However, global economic market structures are neither absolute nor immutable, and so there is still significant value to be captured from the wider commercialisation of lower-moat tradeable technologies and the wider adoption of higher-moat tradeable technologies.

The innovation systems of non-tradeable technologies exhibited different dynamics. Here we found that research, commercialisation, and adoption tend to occur along national rather than global pathways, with commercialisation and adoption much more tightly bound together, often within a single sector, often within a single firm. We see a much higher proportion of process-led innovation and direct implementation of new ideas within existing firms. Downstream barriers that disincentivise implementation and adoption therefore tend to be the limiting factors in the development and deployment of new technologies. Policy interventions that focus on encouraging technology adoption in non-tradeable sectors would likely have the secondary effect of encouraging faster domestic commercialisation of those technologies and, ultimately, incentivise more R&D activity.

For non-tradeable technologies with lower moats, the problem here is often the inherently limited incentive for the sector as a whole to invest in adoption of a technology for which they are unlikely to be able to capture the majority of the value. The result is a form of low-technology Nash equilibrium.[1] However, these technologies, if deployed, would provide substantial social benefit. This clear market failure provides a mandate for government intervention to facilitate, encourage, and even mandate adoption of desirable technologies in key domestic non-tradeable sectors. Examples here would be the acceleration of rollout of 5G and 6G technologies, and the adoption of offsite manufacturing in the construction sector.

We studied only one non-tradeable technology with a higher moat: the deployment of innovative technologies in galleries and museums. Unsurprisingly, given the incentives for

[1] A Nash equilibrium is a situation in which no individual actor is incentivised to change their strategy in isolation

value capture, we did find evidence of higher levels of commercialisation and adoption in this sector, but this deployment was uneven, and the passthrough into consumer surplus was limited. Government intervention here should probably be light touch but could perhaps encourage the further diffusion of technology across the sector, reducing the market power of early adopter firms and increasing consumer surplus for the wider public.

Table A: Suggested government interventions based on technology and market characteristics

Suggested government interventions	**Higher moat**	**Lower moat**
Tradeable	Focus on increasing export-focused commercialisation Example: Genomics	Focus on facilitating and encouraging individual firm adoption Example: Robotics
Non-tradeable	Focus on facilitating wider adoption to reduce market power of early adopters Example: Innovative galleries	Focus on increasing incentives for developing and implementing technology Example: Offsite construction

All in all, this research both reinforces and adds empirical evidence behind the mounting recognition that research, commercialisation, and adoption pathways play out differently and under different conditions across different technology families. The patterns that we identified here for tradeable versus non-tradeable and high- versus low-moat technologies provide insights into conditions that may be prevailing in industries not covered by this research. Furthermore, these findings provide insights into the most promising potential points of government intervention.

1. Introduction

1.1 Research, Innovation, and Productivity

The recent Industrial Strategy green paper and Autumn Budget lay the foundation for an agenda in which research, innovation, and productivity are expected to be core drivers for growth. This builds on previous initiatives, such as the UK Innovation Strategy (BEIS 2021b), R&D Roadmap (HM Government 2020), and Science and Technology Framework (DSIT 2023 and 2025) that link growth to the development of a world-class research and innovation system.

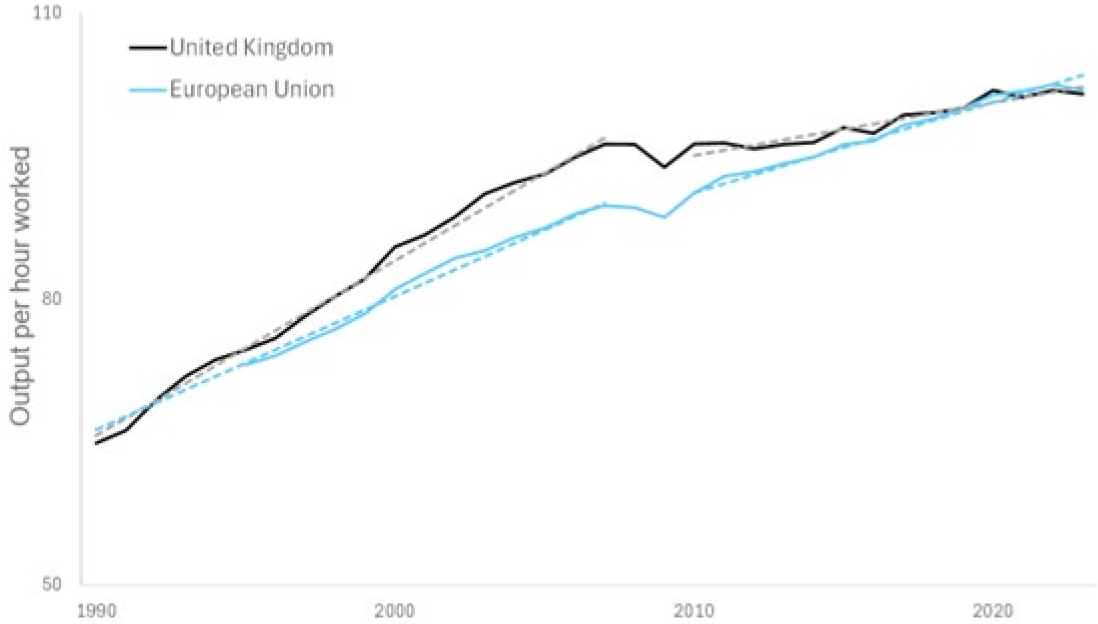
These strategies all emphasise the key role of quantity and quality of scientific research and researchers, but also the crucial importance of a strong capability to turn ideas into solutions for business growth and public good. To accomplish this, it is vital to understand performance across the broader innovation system and identify where research, development, and innovation (RD&I) levers can be most effectively employed to increase value and impact. Indeed, successive strategies have called out the UK's track record across stages of the innovation journey as being highly variable. The Innovation Strategy described the trajectory of tech-based innovation to market as one that is "long, complex, and often non-linear" and notes that the UK "excels at certain stages of this process but is weaker at others", arguing that "we should pursue these signals of weakness and address the underlying issues" (BEIS 2021b, p. 94). The Industrial Strategy reflects on the UK's many strengths, for instance in emerging technologies, but notes weakness in the "adoption of both established and novel technologies, ideas, and processes" (HM Government 2024, p. 10).

One key justification for government funding and engaging in RD&I is that it can lead to improvements in economic productivity. Economists have long studied the relationship between innovation and productivity (see, e.g., Crowley & McCann 2018; Kijek & Kijek 2019; Audretsch & Belitski 2020; Ortega-Argiles & McCann 2021; van Ark et al. 2021). The UK was one of the first countries to see productivity rise at the start of the industrial era, contributing to the nation's economic successes and improved living standards over the past few hundred years. Rapid improvement in GDP per capita did not occur until the innovations of the industrial age, such as machine-enhanced manufacturing, led to greater productivity of the workforce (BEIS 2021b). The continued adoption of new technologies, both domestic and imported, delivered widespread growth across the UK's economy over the 20th century (Jones 2023).

Consequently, the UK, as with international comparators, has long prioritised funding and supporting domestic RD&I activities through government-funded research grants. The private sector also contributes to funding RD&I activities, as it allows firms to capture value from research by converting insights and ideas into products and improvements that can be commercialised and implemented for profit. There is evidence that public and private sector investments in R&D are complementary, as public investments in the science base enhance private sector productivity (both directly and by increasing the absorption capacity for applied research) and also serve to facilitate additional private sector R&D investment, which then leads to increased innovation and economic growth (Haskel, Hughes & Bascavusoglu-Moreau 2014). Indeed, innovation was found to be responsible for two-thirds of the UK's private-sector labour productivity growth between 2000 and 2007 (Nesta 2013), thus highlighting innovation's importance in driving the creation of new products, services, and processes that enhance efficiency and competitiveness.

Yet productivity growth in the UK has declined in recent years. Since 2008, when the global financial crisis occurred, growth in output per hour worked (a traditional indicator of labour productivity) in the UK has markedly declined (figure 1.1.1). The annual growth rate of output per hour worked was 2.68% between 1990 and 2008 but just 0.58% between 2009 and 2023. In the EU, by contrast, pre-2009[2] productivity growth was 1.73% p.a., and from 2009-2023 it was 1.08%.[3]

Figure 1.1.1: Output per hour worked, UK and EU (index 2019=100)

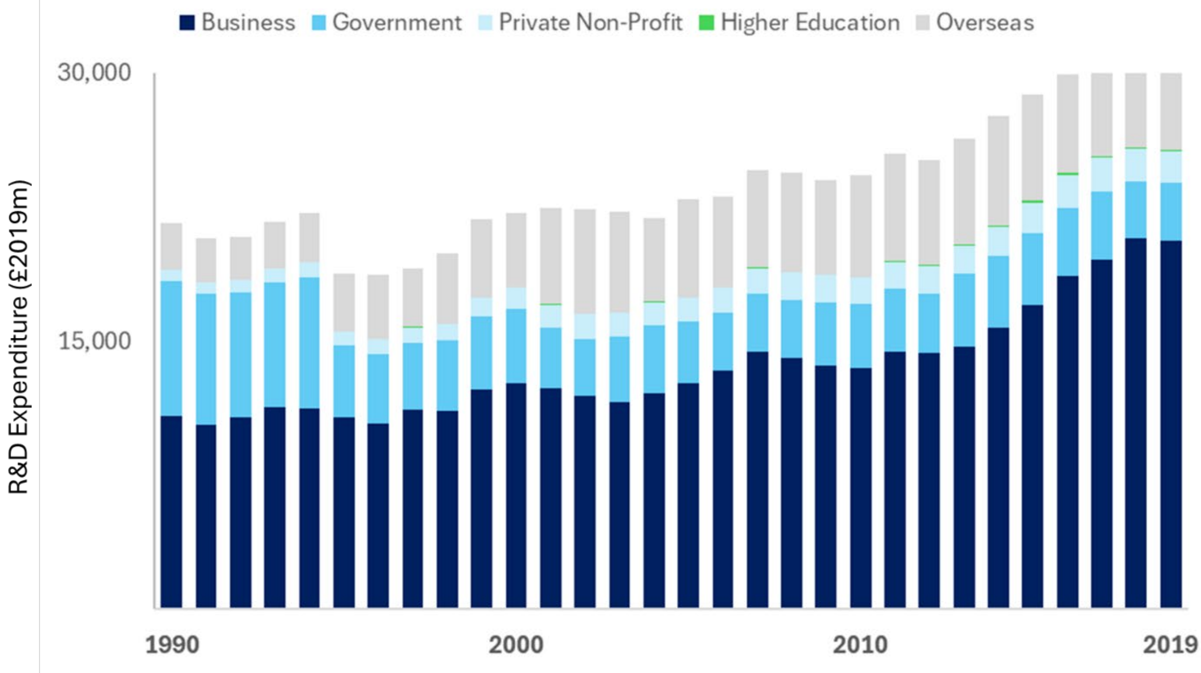


Source: Office of National Statistics (LZVB)
Note: The dashed lines show trend values for pre-2008 and post-2009.

This period of slow productivity growth persists despite the fact that investments in R&D have continued to grow in real terms over the same period. Figure 1.1.2 shows the real gross domestic expenditure on R&D by category of funder, including business, government, private non-profit, higher education, and overseas. Total R&D expenditure has grown since the 1990s, driven by business spending while government spending has fallen. Government’s share of total R&D expenditure fell from 35% in 1990 to 10% in 2019. In real terms, government R&D expenditure has decreased by 57% over the period 1990–2019.

2 We use 1995 as the start date for the EU trend, as that is the first year the source reports data for it.
3 For further context, the US (not shown in the chart) had pre-crisis growth of 2.25% and post-crisis growth of 1.29%.

Figure 1.1.2: Gross domestic expenditure on R&D by category of funder, 1990–2019 (£2019m)[4]



Source: Office of National Statistics (GERD)

If the UK is spending more than ever on funding R&D, why then has productivity declined so dramatically?

One explanation is that the UK economy, like all Western advanced economies, has undergone great transformation from being manufacturing-based to being services-based.[5] Fisher (2024) argues that productivity growth slowdowns are a common challenge in such transformations. Services sectors may not be able to benefit from RD&I as much as manufacturing sectors (Haskel, Hughes & Bascavusoglu-Moreau 2014). This suggests that the concepts of investment and productivity may require reframing; a quantitative concept of productivity, such as output per hours worked, may be less applicable to services, where quality is more significant (Fisher 2024).

Another trend observed in the literature is the diminishing marginal returns from investment in innovation (Haskel, Hughes & Bascavusoglu-Moreau 2014). For example, Bloom et al. (2017) find that the required number of researchers to achieve technological advancement in line with Moore's Law[6] is now much higher than in the 1970s. New discoveries are less straightforward than those in the past and now require more effort, resources, and time. The digital technologies of the current era have also been shown to be less impactful on productivity as past innovations – these technologies experience longer delays before commercial adoption (Coyle 2023). While R&D spending may have grown since the 1990s, it may not be growing fast enough to produce sufficient advancements to maintain the

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[4] When reporting values in real (ie inflation-adjusted) terms, its usual to specify a year as a reference point. "£2019" is a short-hand term for the real terms value as it was in 2019

[5] Of course, the UK's productivity slowdown has been more pronounced than that of other post-industrial economies. The reasons for this are discussed in the "productivity puzzle" literature and relate to many specific UK factors, with importance given to infrastructure and the investment climate – but the deindustrialisation story is still relevant.

[6] Moore's Law is the observation that the number of transistors in an integrated circuit doubles about every two years.

productivity growth of the past (Jones 2023). Furthermore, when compared with other countries, the UK's business investment in R&D has not kept pace (BEIS 2021b).

Historically, measurement of innovation relies on R&D metrics, despite innovation being more than just R&D. There has been more investment in intangible assets – which includes investment in workers' skills – than in tangible assets, and these intangible assets are more prevalent in services (Goodridge, Haskel & Wallis 2014). Innovation in the service sectors is often people-focused, and businesses in these sectors may invest outside the scope of what is recorded as R&D spending. These investments are not being fully captured, understood, or valued (British Academy 2023). Thus, the full scope of investment into the RD&I system in the UK cannot be totally understood with official statistics and existing conceptions of productivity.

Another explanation is skills shortages and mismatches. Higher skill levels lead to better utilisation of advanced technologies and more efficient work processes. Despite increasing investment in skills and education, the skills developed in the UK are not necessarily the skills needed in the UK economy (Rincón Aznar et al. 2015). Slowdowns in labour productivity and productivity growth have been shown to be largest in more intangible, knowledge, technology, and digital-intensive industries, such as software and telecommunications. This slowdown in these types of industries almost entirely explains the economy-wide productivity slowdown (Goodridge & Haskel 2022). Furthermore, the UK is at risk of being a net exporter of talent, exacerbating existing workforce skill gaps in key areas (BEIS 2021).

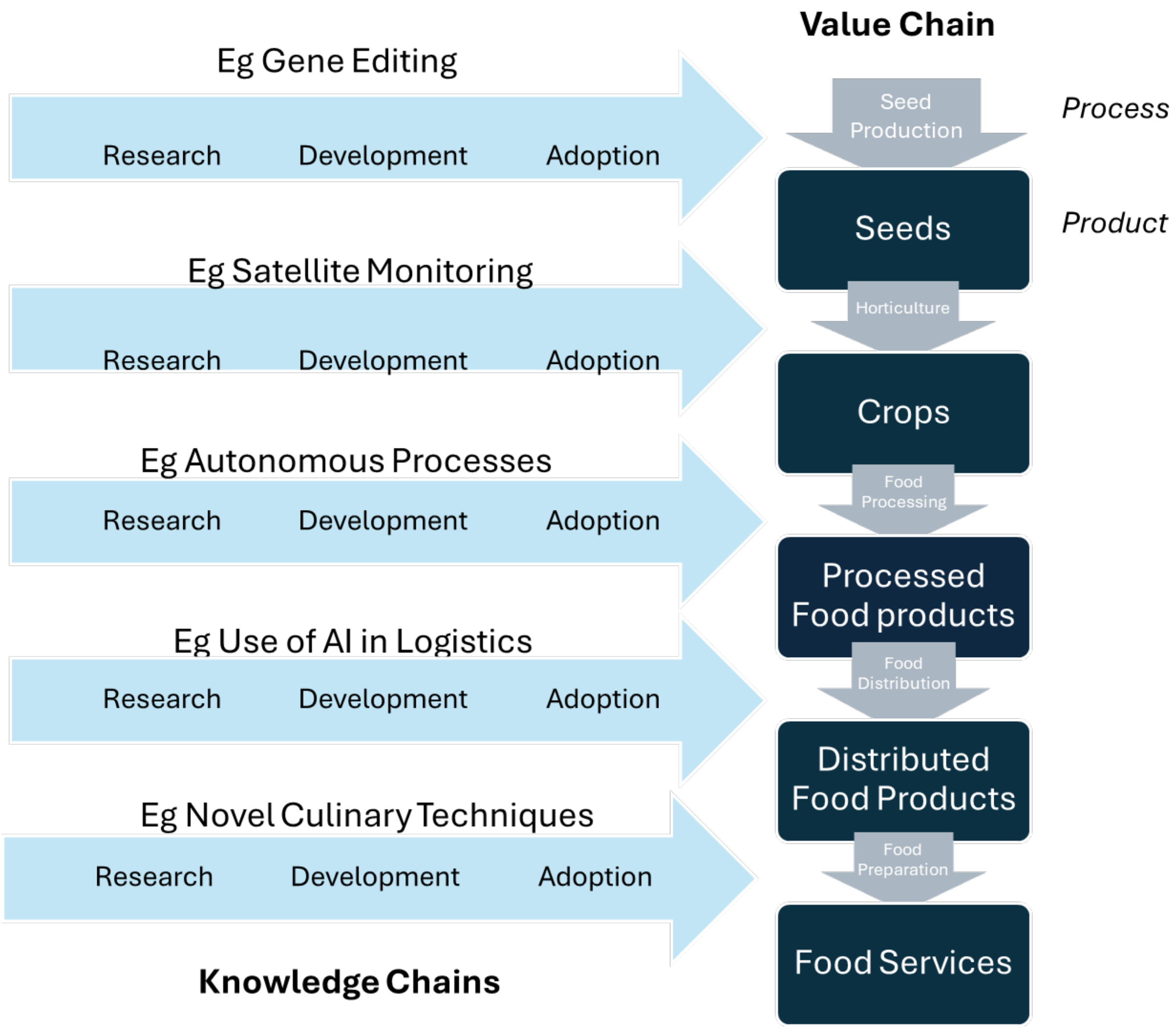
The UK also faces challenges in taking advantage of existing innovations. For example, the country has low rates of technology adoption by firms, leading to underutilised knowledge (BEIS 2021). This is particularly true in regions that lag behind London, with its many technology-focused firms, and other innovative areas of the country. Jones (2023) advocates for a greater focus on translation and diffusion of innovations to enhance productivity gains from R&D investments, as well as rebuilding innovation ecosystems in lagging regions. Barriers to technology adoption include inadequate infrastructure, skill gaps, and organisational inertia (Coyle 2023). From the perspective of value creation, including through improving economic productivity, the translation of ideas into products or practical applications is more important than the ideas themselves.

1.2 Research Framework and Hypotheses

We are interested in understanding the strengths and weaknesses of different sectors in the research–discovery–commercialisation–adoption chain to point the way to how and where RD&I levers can increase value and impact. Our approach to this challenge is by exploring ten technology case studies in more detail and developing accompanying data dashboards to draw out where sectors are building on global knowledge versus developing technologies locally, or where data signals weaknesses in parts of the innovation life cycle. To conceptualise these questions, we first develop and explore a conceptual framework of the nature of knowledge chains, their relationship to value chains (which they are related to but distinct from), and the importance of their distribution across national boundaries.

Knowledge Chains vs Value Chains

Critical to the research framework is the distinction between knowledge chains and value chains. Whereas value chains track the progress of tangible or intangible inputs as they move through a series of processes before ultimately becoming a final product that is either consumed or installed as fixed capital, knowledge chains instead track the process through which high-level *ideas* are developed into commercially useful products or processes, typically over a much longer period of time. We've provided a simplified depiction of how a variety of knowledge chains feed into a single value chain in figure 1.2.1. Here we show the well-known “farm-to-fork” value chain, as crops are grown from seeds, processed, distributed, and ultimately constructed into a meal for a paying customer. We identify five stages to this process – although arguably this could be more finely sliced, or include additional initial stages. However, the salient point is that each of these five stages is the result of its own knowledge chain – the knowledge of how to carry out that process in the most efficient and effective way. For each knowledge chain, we’ve given an example of a recent or current innovation that is changing the processes that the value chain utilises. It is worth also considering that even if these knowledge chains are not directly linked, they are effectively interlinked because they all service the same value chain: for example, if satellite monitoring advances affect horticultural processes, then this may shift the balance of demand for different types of seed, to which the seed production process knowledge chain



will have to respond.

Figure 1.2.1: Interaction of various horizontal knowledge chains feeding into the processes that make up the vertical “farm-to-fork” value chain

Some knowledge chains will be value chain specific: the example above includes knowledge chains involved in generating useful innovations in seed production, horticulture, and cooking. Innovations here may spill over to a small number of other value chains, for example the use of satellites in geo-monitoring has applications outside agriculture. However, some knowledge chains produce innovations of such widespread applicability that they impact the majority of value chains; one of the most obvious examples of this is the use of semiconductor chips and the electronic devices they enable. Technologies that have the potential to be utilised in a wide number of value chains are generally referred to as general purpose technologies (GPTs). The invention and diffusion of a new general purpose technology can cause fundamental paradigm shifts in the way the entire global economy functions.

Domestic vs International Value and Knowledge Chains

Both value chains and knowledge chains may – in both theory and practice – vary from being entirely internally domestic to highly globally integrated, with both ideas and intermediate goods crossing into and out of the UK multiple times. There are very many possible combinations within this, between which dynamics are likely to subtly shift. For example, we could conceive of an entirely *domestic* value chain, processing UK resources for UK consumers, but in which each process stage is the result of a *global* knowledge chain, or an export-focused value chain that leverages *domestic* knowledge chains to maintain a *global* competitive advantage.

The way we treat this question below is to consider whether the ultimate output of the value chain is *tradeable* or *non-tradeable*, as this dictates the spatial nature of the incentives for product and process innovation that flow “up” the value chain and its contributary knowledge chains and the economic actors most likely to respond to this. Tradeable here simply means that the product can be easily transmitted across administrative and geographical boundaries. Tradeable products have increasingly tended towards a globally integrated supply chain and market since the earliest beginnings of globalisation, whereas non-tradeable products tend to be transmitted primarily through independent national, regional, or local market structures. For these independent, non-tradeable product markets, it is more likely that the value created and value captured within a single nation will approximately match. For tradeable products, it is much more likely that value created in one location will be captured elsewhere. The UK is both beneficiary and benefactor of these spatial dislocations of value creation and capture.

Systems Map

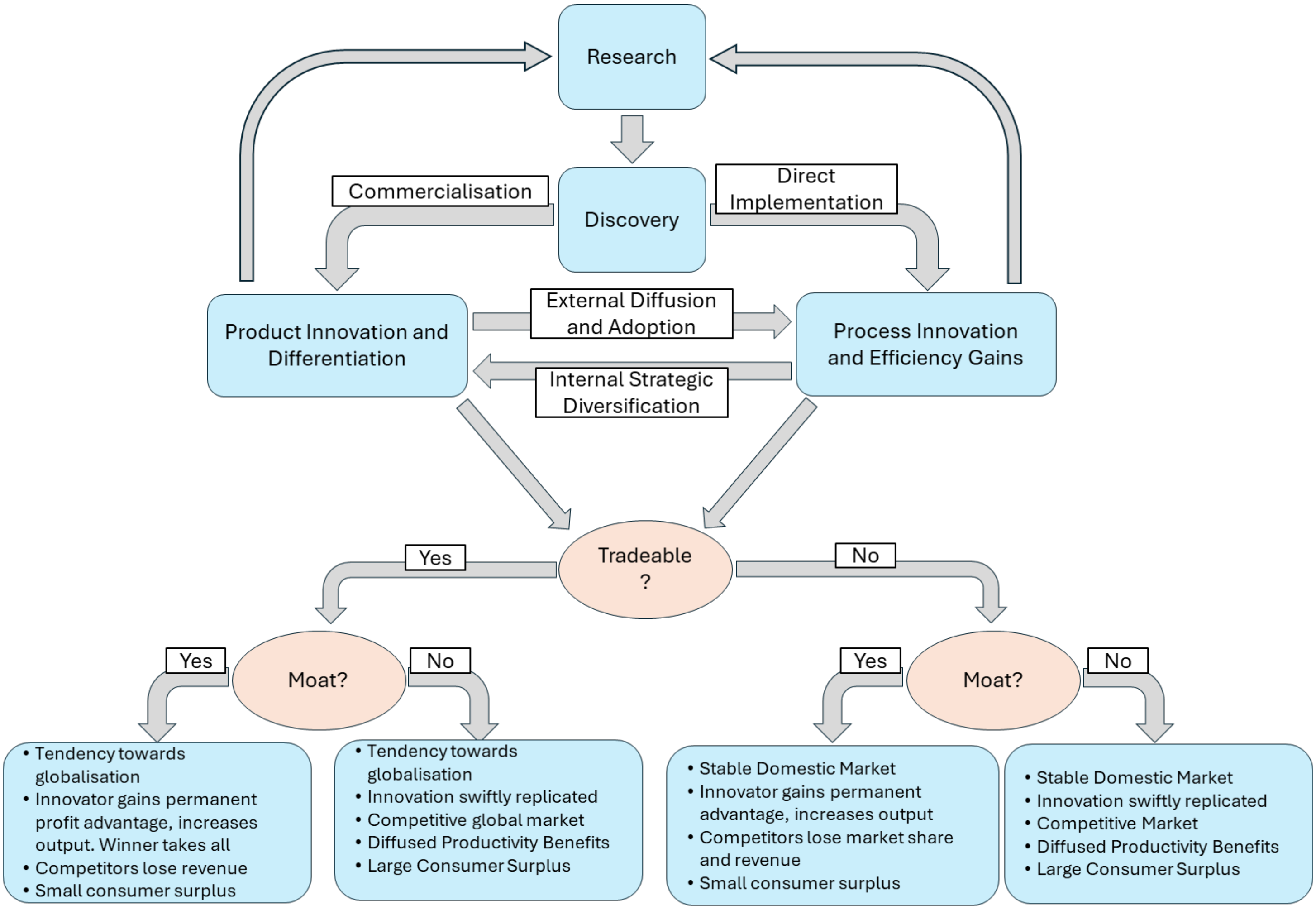
This study builds on previous collaborative work between Cambridge Econometrics and the Innovation & Research Caucus to develop an RD&I systems map as a lens through which to understand the innovation process (Brown & Nelles 2020). The systems map used in that study depicted an innovation “process” – with stages moving between research, implementation, and adoption – as being embedded within a wider innovation network of institutions, workers, entrepreneurs, and industries. For this study, we’ve suppressed those wider links for the sake of visual clarity, but have instead added a form of decision tree onto the bottom of the innovation map in order to provide a framework for thinking about how and why innovation gains manifest as measured productivity growth and as consumer surplus, and in which places. Figure 1.2.2 shows the updated innovation process map. The map should *not* be read from top to bottom as a linear process, but rather as a series of interconnected relationships forming loops and cycles. Whereas the “supply” of new ideas starts at the top of the map, winds its way through various cycles of product and process innovation, and ultimately ends up as value captured by either firms or consumers, it’s equally important to consider the role of “demand” originating at the bottom of the map, providing incentives for product and process innovation in the central layer, and ultimately stimulating research activity at the top of the map.

Over time, that research can lead to discovery, or the production of new knowledge or ideas. Depending on the nature of the ideas generated, these can either be commercialised and sold in the market, as product innovation,[7] or directly implemented by the innovating firm, as process innovation.[8] Firms choose to do this for rational, strategic reasons: product innovation results in product diversification and the possibility of greater market share, higher prices, and profit margins through monopolistic competition effects, whereas process innovation is usually intended to improve efficiency and cost-savings, whether in the reduction of capital equipment usage, labour hours, or input materials.

However, the two types of innovation are strongly connected to the other, albeit in different ways. Product innovation in one part of the knowledge chain will often directly stimulate process innovation further down the chain, as firms adopting new products and technologies often then put these to use to improve methods and workflows: in essence, product innovation stimulates process innovation through an *inter-firm* innovation spillover mechanism. Process innovation within a firm also opens up a wider range of viable production possibilities, which are then used to generate new products: here process innovation stimulates further product innovation, but this time as an *intra-firm* spillover effect. Innovations of both types often diffuse across sectors through competition, legitimisation, and mimicry effects. At this stage, crucially, the implementation of these new products and/or processes creates new research questions, opportunities, and challenges that stimulate further research at the start of the process map. In the long run, the technologies being researched are strongly dictated by the technologies already in use and adjacent possibilities for which there is evidence of further potential demand. Thus, causality in the overall process flows both from top to bottom and from bottom to top.

[7] Product innovation is here defined as the creation and development of new or improved products, services, or processes by a company or organisation.
[8] Process innovation is here defined as the process of development and implementation of new or improved processes, methods, or systems within an organisation to enhance efficiency, effectiveness, and value creation.

Figure 1.2.2: Innovation process map



Source: Adapted from Brown & Nelles 2020

The systems map also considers the extent to which the value created through the research and innovation process may be captured as profits, wages, and consumer surplus, and where this might occur. The impact on productivity depends on whether the company that developed the product is able to create protective "moats" around the product, such as high capital costs of replication, strong network and customer lock-in effects, tacit knowledge such as trade secrets, or high legal barriers such as patents or trademarks. The presence of defensible moats tends to lead to higher prices (*ceteris paribus*), with productivity growth manifesting almost entirely in the firm(s) responsible for the product innovation, while the lack of moat means that product innovations are more easily copied and more cheaply adopted, with the result being productivity growth impacts both across and along supply chains. Depending on market structure and strength of competition effects, these productivity impacts may be short lived, as the value of new products is simply passed through to consumers as higher consumer surplus impacts.[9]

On the process innovation side, firms that successfully instigate process improvements do so with the intent of becoming more efficient, but whether this ultimately manifests as a productivity impact depends on other firms' ability to replicate the process innovation, and on

[9] Note that this would still show up as an overall growth in productivity due to the way inflation estimates take account of improved quality; however, this would be quite a diffuse effect and hard to attribute to a specific innovation.

the price competitiveness of the market. With perfectly replicable process improvements and perfectly competitive markets, any additional margin gained through process innovation is likely to be rapidly worn away and instead passed on to consumers through lower prices. In reality, of course, very few markets work this efficiently.

Finally, the implications of process innovation for labour demand are dependent on both the elasticity of demand and the presence of coinciding product innovation: in more demand-elastic markets, or where product innovation is also being utilised as a market differentiator, firms that are able to lead on process innovation tend to be rewarded with increased market size and productivity growth. In less demand-elastic markets, or where process innovation is not coupled with product innovation, efficiency gains often simply lead to similar levels of output but at lower costs and with reduced input and labour demand, which is often considered to have negative economic and social externalities.

Hypotheses

As discussed in the introduction, there are various hypotheses as to the failure of the UK's innovation system to produce higher economic productivity and other benefits. A common view is that the most significant constraint is not in the (academic) research/knowledge creation pipeline, but in commercialisation (i.e. translation) and diffusion (i.e. adoption and absorptive capacity). This is often associated with generic challenges of business scaling, which is clearly relevant; however, a focus on scaling alone misses a much broader phenomenon: that markets for innovations are not always located in the same place, region, or country. The concept of global value chains encompasses the idea that the range of activities from product (or process, etc.) conception to end use frequently occur in different places, with a range of inputs and partners that may also not be local (Crescenzi & Harman 2023).

The narrative about how the UK has strengths in some aspects of the pathway to market (e.g., invention) but not others (e.g., commercialisation) assumes that the commercial potential of UK research capabilities ought to be realised within the UK. In some cases, a lack of UK capability or capacity at later stages in the innovation process means that ideas generated in our RD&I system never scale or diffuse at all. However, in many more cases, it is likely that ideas generated in the UK – even possibly with public support – are simply commercialised and/or adopted elsewhere. As an example, graphene, discovered in 2010 in Manchester, has since found commercial applications in other countries at higher rates than in the UK (Shapira, Gök & Salehi 2016). Conversely, it may be that for some technologies, the UK excels at adopting foreign innovations even if it does not have distinctive research strengths in those areas. This can be a good thing and is important in cases where there are not UK alternatives. The point here is that the journey from research to productivity, and the value captured from it, does not typically occur within a closed system. As such, it is important to understand strengths and capabilities at different places in the system in order to effectively drive productivity solutions.

These dynamics are important because they shift the focus from where various stages of the value chain take place globally to which stages *generate* and *capture* the most value – tangible and intangible – relative to (public) investment. The highest value phases likely differ by sector, industry, subindustry, and even technology. Similarly, UK value capture capabilities differ from those in other countries and across different sectors and technologies as well. Understanding the relationship between these capabilities is a crucial missing link that could transform RD&I investment strategy. The importance of these dynamics has been recognised, but the evidence base needs further development. For instance, the British Academy (2023, p. 6) calls for greater understanding of the "processes of discovery, creativity, incubation, and diffusion, alongside factors like knowledge exchange between actors and institutions". To go beyond simply developing measures of value – that black box so favoured by conventional economics, “investment in, gross valued added (GVA) out” – it is clear that understanding the dynamics and systemic connections is more useful than metrics of return. Innovation systems, and the diverse range of activities that occur within and across them, are an area ripe for study.

The introduction highlighted a number of hypotheses as to the causes of low translation from research activity to measurable productivity outputs in the UK. There are many hypotheses that we consider important and relevant – for example, the increased difficulty in discovering new ideas from research, or challenges in the measurement of productivity and consumer surplus – but that we are not able to investigate through this project. We identify four below that we hope the findings will be able to shed some light on:

1. (UK specific) The UK does high-quality basic research but is less successful at commercialisation of these ideas through the full spin-off to scale-up process. This is because of a combination of a small domestic market and a deficit of key generic enabling factors, including entrepreneurial know-how, access to funding and skilled workers, and the necessary government support.

   We might expect to see this through low levels of commercialisation across most sectors, backed up by specific evidence of commercialisation barriers in case study technologies. We might also see evidence of a lack of commercialisation even in technologies with high levels of research and/or adoption.

2. (UK specific) The UK economy has weaker innovation absorption capability due to a combination of low demand, low skills, low funding, knowledge domain mismatches with fundamental research specialisms, and a lack of industrial capability. This makes it difficult to either adopt new products or directly implement new ideas, whether produced in the UK or elsewhere.

   We might expect to see this through low levels of adoption and process innovation across most sectors, backed up by specific evidence of barriers to adoption in case study technologies. We might also see evidence of a lack of adoption even in technologies with high levels of research and/or commercialisation.

3. (General/UK specific) The global supply chains of tradeable technologies have high moats and oligopolistic market structures, meaning that the value of innovation is captured by a relatively small number of commercialising firms. If very few of these are in the UK, then it is likely the value is being captured elsewhere.

   We might expect to see evidence of high barriers and concentrated global markets in tradeable technologies – with the largest, most profitable firms being based outside the UK – and a cross-country correlation between higher sectoral productivity and share of largest companies.

4. (General) A long-term investment or regulatory deficit in the key sectors with the highest productivity spillovers or most widespread consumer benefits has discouraged researchers and entrepreneurs from targeting these sectors, leading to a misalignment between innovation focus and productivity- and welfare-enhancing technologies.

   We might expect to see a sectoral mismatch between technology adoption and either achieved or potential consumer surplus. This mismatch might also stretch to include commercialisation and fundamental research due to the nature of incentives.

It is important to note that these hypotheses are potentially interacting and, in some cases, mutually reinforcing. A tendency towards low levels of technology investment in a particular sector or geography reduces the incentive for entrepreneurs to commercialise products in that space. Similarly, low levels of domestic technological commercialisation create access barriers for downstream firms to adopt. It may be that the UK suffers from this problem both generally (i.e., across all sectors) and also specifically in the sectors that might provide the highest level of productivity spillovers.

2. Methodology and Data

2.1 Methodology Overview

Our approach to tackling this problem is to combine both qualitative and quantitative analysis in a series of ten technological case studies and then see what conclusions we can infer. This chapter will provide an explanation and rationale for (a) the ten technologies we have selected as case studies and (b) the quantitative metrics we have collected to try to characterise these technologies in a systematic way. We'll then give a brief overview of the data collection methods and high-level results, before diving into the individual case studies in chapter 3.

Case Study Selection

The technologies chosen included the five "critical technologies" identified by DSIT in the 2023 Science and Technology Framework: semiconductors, artificial intelligence (AI), quantum technologies, mobile technologies, and engineering biology. Engineering biology is a very broad technological category, and so we focused specifically on mRNA vaccine development as an example. These technologies were chosen as they are of demonstrable interest to the government and are likely to play a major role in future innovation plans and industrial strategies.

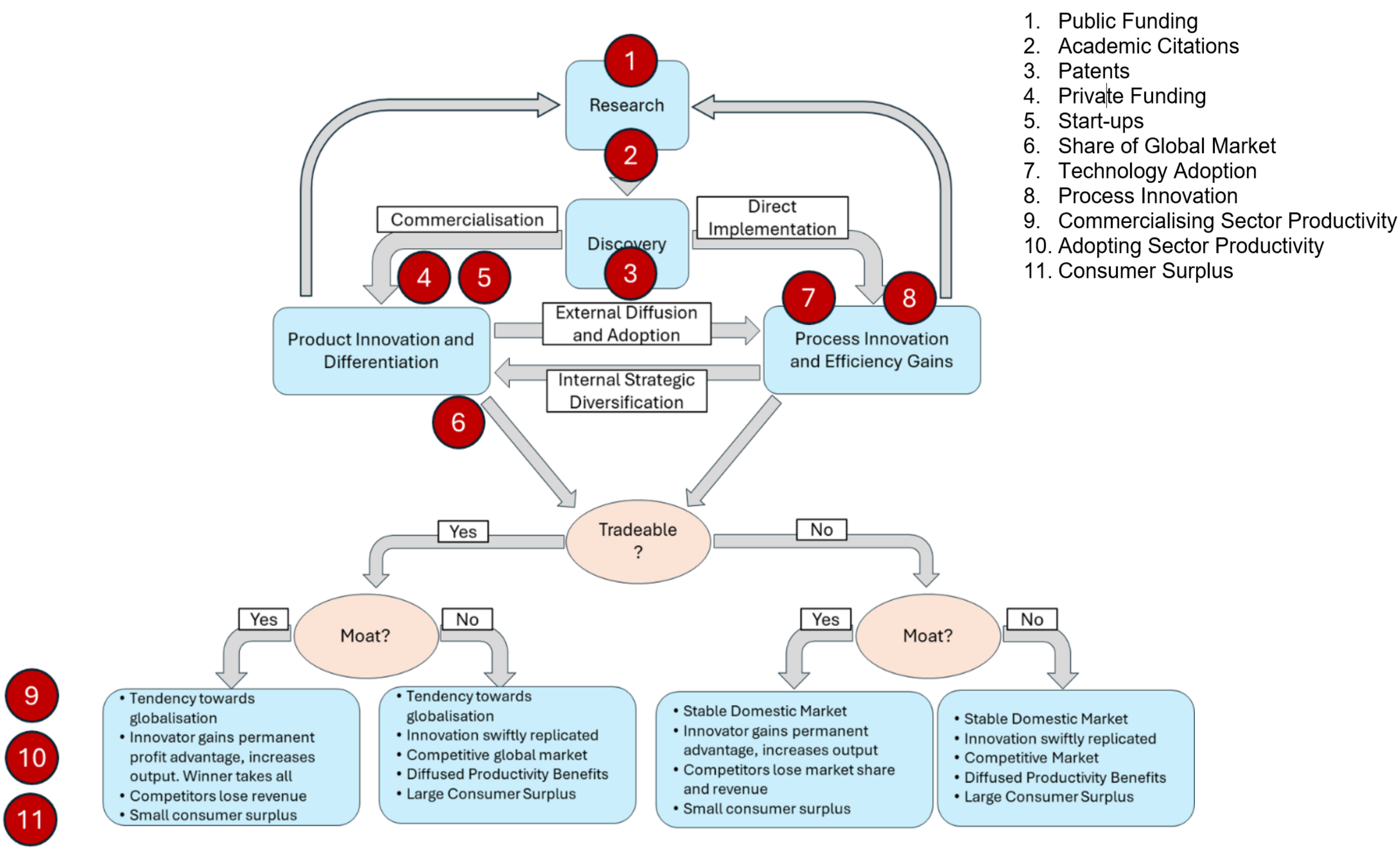
The other technologies selected were intended to complement these more fundamental technologies by exploring more sector-specific applications of innovation. These deliberately cover a wide range of different knowledge domains and include applications of technology in agriculture (gene editing), construction and manufacturing (offsite construction, industrial robotics), and cultural heritage (innovative galleries), as well as the application of theory in public administration (modern supply side economics).

Metric Selection

This section discusses the data and scoring methodologies used to characterise value creation and capture in the knowledge chains of these technologies. This is split into the three stages of the innovation cycle – research, commercialisation, and adoption – plus an "outcomes" section intended to identify the areas of value capture more broadly, for example through productivity diffusion or consumer surplus. Each of these stages have multiple indicators, which are scored using one or more datasets. These are then converted into red, amber, green (RAG) scores through a process of referencing and normalising,

We collected 11 metrics. These are annotated on the innovation process map (figure 2.1.1) in the approximate stage of the process we think they capture. In brief: we think measures of public funding (1) capture an input into the research process, whereas number of citations (2) measures an output of this. Patents data (3) allows us to identify the approximate point in the process at which actors consider their research to be directly relevant for commercialisation or implementation. The level of private (venture capital) funding (4) and the percentage of firms that are start-ups (5) give us insight into the early stages of commercialisation, whereas the UK share of total market capitalisation in that sector (6) gives us an indication as to how far this has developed. Measures of technology adoption (7) and process innovation (8) then provide us with an indication of how downstream sectors are responding (or driving) this. Finally, international comparisons for both commercialising (9) and adopting sector (10) productivity, along with an estimate of consumer surplus (11), tell us which of the four final outcome description boxes best describes the economy-wide outcomes for that technology.

Figure 2.1.1: Innovation process map annotated with location of data metrics



2.2 Research Metrics

We score the research phase with three indicators:

1. Public funding: within-UK funding of the ten technologies
2. Citations: UK relative performance on citations in leading journals
3. Patents: UK relative performance on inventing and patent filing

Funding

We use data from UK Research and Innovation (UKRI) that show successful applications for grants. This is a measure of how public money is being distributed through the collected research councils and Innovate UK grants to support different strands of research. We use a wordsearch algorithm to score grants as belonging to a technology (note that one grant may theoretically span more than one technology with this approach, which captures that some may be interdisciplinary). We score the projects relative to each other rather than to an external comparator, and the results can be interpreted as: “of our ten technologies, which are the best funded?”. We calculate the total funding for each technology as a share of the total UKRI funding in the past ten years. Summary results are shown in table 2.2.1.

Table 2.2.1: Estimated share of UKRI funding by technology

Technology	Estimated Amount of Funding (2012–2022)	Share of Total UKRI Funding (2012–2022)
Agricultural Gene Editing	£30,945,000	0.07%
AI	£78,512,000	0.17%
Industrial Robotics	£81,966,000	0.18%
Innovative Galleries	£23,400,000	0.05%
Mobile Communications	£147,541,000	0.33%
Modern Supply Side Economics	£38,393,000	0.09%
mRNA Vaccines	£241,804,000	0.54%
Offsite Construction	£50,820,000	0.11%
Quantum	£540,041,000	1.20%
Semiconductors	£35,429,000	0.08%

Citations

We use data from OECD on fractional counts of scientific publications among the world's 10% top-cited scientific publications. Fractional counting means that if a publication has three co-authors located in three different countries, each country would be credited with one-third of the publication. We proxy the ten technologies using the closest available matches.

The full results show that technologies such as quantum technologies, semiconductors, mRNA vaccines, gene editing, and offsite construction have experienced a decline in citations. In contrast, wireless technologies and AI have seen an upward trend. Summary results are shown in table 2.2.2. The UK is ranked between 2nd and 6th for all the technologies we looked at, with between 3.6% (semiconductors, ranked 6th) and 11.3% (innovative galleries, ranked 2nd) of global citations between 2012 and 2022.

Table 2.2.2: Estimated global share of UK academic citations and global rank by technology

Technology	UK Share of Global Citations 2012–2022	Global Rank
Agricultural Gene Editing	7.8%	3
AI	5.6%	4
Industrial Robotics	4.2%	6
Innovative Galleries	11.3%	2
Mobile Communications	5.0%	5
Modern Supply Side Economics	9.2%	3
mRNA Vaccines	5.0%	4
Offsite Construction	4.9%	5
Quantum	4.2%	5
Semiconductors	3.6%	6

Patents

The dataset is patent data from Espacenet. We create one dataset per technology using multiple keyword searches, and selecting all Cooperative Patent Classification (CPC) codes that align with the technology. Patents data include the applicants in whose name the patent is filed and all inventors, in both cases listing the country in which they are based. We score all countries based on location of inventors and normalise these scores. Summary results are shown in table 2.2.3. On average, the UK performs slightly less well on patents than on citations, ranking between 5th and 8th globally, with between 1.3% and 4.9% of global patents (in semiconductors and mRNA vaccines respectively). There was no category of patent activity that reasonably matched modern supply-side economics, so we left this as N/A.

Table 2.2.3: Estimated global share of UK patents and global rank by technology

Technology	UK Share of Global Patents (2012–2022)	Global Rank
Agricultural Gene Editing	3.6%	6
AI	3.2%	8
Industrial Robotics	2.2%	7

Innovative Galleries	3.2%	6
Mobile Communications	3.4%	6
Modern Supply Side Economics	N/A	N/A
mRNA Vaccines	4.9%	5
Offsite Construction	4.1%	5
Quantum	3.8%	7
Semiconductors	1.3%	8

2.3 Commercialisation

For measuring commercialisation by technology, we classify economic activities using Real-Time Industrial Classifications (RTICs) from The Data City. These are much more detailed and up-to-date classifications of economic activity than conventional Standard Industrial Classification (SIC) codes, built in partnership with sector experts and based upon web-scraped data and machine learning. We evaluate the commercialisation phase with three indicators:

1. Private funding: level of venture capital funding from Dealroom data
2. Start-up share: using The Data City data to identify average age of firms in relevant RTIC
3. Market capitalisation: share of global market cap held by UK firms

We also collect some data on broad sectoral trends using standard SIC code-based data; this is useful context, but in most cases is not targeted enough to tell us anything specific about the technology in question.

Private Sector Funding

We use Dealroom datasets of venture capital (VC) funding on RTIC classifications. Results can be seen in table 2.3.1 below. We see that over the 5-year period from 2019 to 2023 inclusive, VC investment is dominated by AI and biotech (data on mRNA vaccine technology specifically was not available). We were unable to confidently attribute data in the dealroom dataset to modern supply side economics so left this as N/A.

Table 2.3.1: Estimated technological share of UK venture capital funding 2019–2023

Technology	Share of Total UK VC Funding (Aug 2019–Aug 2023)	Total amounts (£m)
Agricultural Gene Editing	0.4%	947
AI	3.8%	8,240
Industrial Robotics	0.4%	906
Innovative Galleries	0.3%	766
Mobile Communications	1.9%	4,176
Modern Supply Side Economics	N/A	N/A
mRNA Vaccines (Biotech)	4.9%	10,701
Offsite Construction	0.0%	1
Quantum	0.5%	1,200
Semiconductors	0.4%	957

Source: Dealroom data

UK Start-Up Share

We again use RTIC data for this indicator, where we aim to map out the level of activity in each technology occurring in the UK and then identify the average age of firms in each sector. We estimate the number and average age of the firms in the ten technologies in the UK through use of keyword algorithms that filter in firms most likely to match the technologies, and manual, visual sorting to remove false positives. Note that table 2.3.2 indicates data for modern supply side economics as “N/A” since there was not data on this in The Data City dataset. Numbers of firms ranged from 42 (quantum) to 437 (AI), with average ages ranging from 8 years (quantum) to 55 years (semiconductors).

Table 2.3.2: Number and average age of UK firms by technology from The Data City database

Technology	Number of Firms	Average Age of Firms (Years)
Agricultural Gene Editing	51	20
AI	437	10
Industrial Robotics	303	15
Innovative Galleries	70	12
Mobile Communications	289	31
Modern Supply Side Economics	N/A	N/A
mRNA vaccines	61	14
Offsite construction	63	17
Quantum	42	8
Semiconductors	236	55

Share of Global Market Capitalisation

The goal of this indicator is to measure how many UK firms there are among the largest global firms producing each of the technologies. There is no single dataset that carries all this information, so we have pulled together a variety of different datasets as best as we have been able to – but this has been more comprehensive for some technologies than others.

For most technologies, we use data from CompaniesMarketCap (for the technologies for which it was available), but Yahoo and Insider Monkey for quantum technologies, and the Open Think Tank Directory for modern supply side economics. This allows us to categorise the leading think tanks in economics and classify those whose policy stance aligns with modern supply side economics. The relative sum of all a country's major listed companies compared with international comparators is what is scored. We also calculate the total market capitalisation of large firms by country for each technology and identify the UK's rank within this. In some cases, the UK does not have any large, listed firms and so is denoted as unranked. Although the UK is unranked in mRNA vaccines specifically, this doesn't reflect its broader global position in biotechnology more generally – we highlight this in the table as we think this is important context. We weren't able to score innovative galleries or offsite construction on this metric as no suitable proxy data existed.

Table 2.3.3: Estimates of UK-domiciled firms' share of total global market capitalisation and rank by

technology

Technology	Estimated Share of Total Market Capitalisation of UK-Owned Firms	UK Rank
Agricultural Gene Editing	2%	4
AI	0.04%	4
Industrial Robotics	0%	unranked
Innovative Galleries	N/A	N/A
Mobile Communications	2%	8
mRNA Vaccines	0% (Biotech 6%)	unranked (Biotech 4)
Modern Supply Side Economics	5% of registered global think tanks	4
Offsite Construction	N/A	N/A
Quantum	0%	unranked
Semiconductors	2%	6

Note: figures in this table rounded to 1 significant figure due to varying scale of values

2.4 Adoption

To evaluate the adoption phase, we use two indicators:

1. Cross-country technology adoption: various cross-country comparison indicators of technology uptake
2. Sectoral adoption and process innovation: investment in developing and acquiring technologies and in undertaking process innovation

Cross-Country Adoption

The goal is to measure how much the UK embraces the ten technologies as compared with other countries – or how well it is prepared to effectively absorb them into its economy. As with market capitalisation, there is no single dataset that contains all the information we need, and so reliability of coverage of different sectors varies substantially.

We use a variety of datasets including regulation, importing, plans to adopt, and anecdotal evidence. The result is less of an objective, quantitative ranking as done for patents, for example, and is more of a case-by-case approach. In summary:

- **Agricultural gene editing**: We used the Global Gene Editing Regulation Tracker Index compiled by the Genetic Literacy Project
- **AI**: the IMF's AI Preparedness Index which assesses the level of AI preparedness across 174 countries
- **Industrial robotics**: multiple sources to allow us to compare two time periods, including International Federation of Robotics (IFR) data, Forbes' summary of historical IFR data (McCarthy 2018), and various reports to fill in gaps between the two
- **Innovative galleries**: We found a mixture of sources, some that discussed absolute rates of implementation of immersive and interactive exhibitions in various nations, and some that provided limited cross-country comparison.
- **Mobile communications**: GSMA Intelligence 5G Connectivity index, which measures the performance of 39 countries against the key outcomes for 5G infrastructure and services
- **Modern supply side economics**: As a key recommendation of modern supply side economics is for the public sector to invest in public goods and infrastructure, we proxy it by collecting data on public investment into gross fixed capital formation as a share of GDP, since this indicates to some degree the willingness of government to invest in capital to spur supply side growth.
- **mRNA Vaccines**: We used national rates of immunisation from the OECD as a proxy for deployment of vaccines.
- **Offsite construction:** We found multiple sources that estimated shares of construction activity using offsite construction methods in developed nations. The most comprehensive and up to date was a November 2024 article in Building Matters (Pages Ruiz 2024).
- **Quantum:** The technology is too nascent for it to be adopted, so we do not attempt to score its adoption.
- **Semiconductors**: the OECD's cross-country datasets on household access and persons employed using a computer at work, which run to 2023, as a proxy for the adoption of semiconductors
-

Table 2.4.1: Evidence as to level of UK adoption relative to other nations by technology

Technology	Level of Adoption
Agricultural Gene Editing	The UK is one of the 6 territories where legislation towards gene editing is under consideration and with likely approval.
AI	The UK has a score of 0.73 (out of 1) in the AI Preparedness Index made by the IMF, resulting in the 14th position below leading nations.
Industrial Robotics	The UK has 101 industrial robots per capita, substantially below the global average of 151 and well below the leading nations.
Innovative Galleries	20% of the top 30 immersive galleries are in the UK (behind only the US), and 68% of UK museums report using interactive displays and visual projections in the 2021 Museum Innovation Barometer.

Mobile Communications	The UK ranks 23rd (out of 25 countries) on the GSMA Intelligence 5G Connectivity Index with a score of 44.18.
Modern Supply Side Economics	The share of GDP dedicated to gross fixed capital formation in the UK has been 2.7% during 2021-2024, positioning it in the 29th position out of 38 OECD countries.
mRNA Vaccines	The UK has an immunisation rate of 91%, the 11th lowest rate of OECD countries. mRNA COVID-19 vaccines were deployed, but made up a lower share of all COVID-19 vaccines than in other developed nations
Offsite Construction	According to industry surveys, UK adoption rates are around 16%, below the European average and well below global leader Sweden at 85%, but ahead of the US at 5%.
Quantum	N/A – quantum technologies are not ready for full-scale adoption.
Semiconductors	80% of people had a personal computer or used one at work in 2023 in the UK. Within the OECD, the UK ranks 19th for personal adoption and 8th for business adoption of computers.

Sectoral Adoption of Specific Technologies, and Process Innovation

In order to augment our evidence as to the levels of adoption of specific technologies in the UK, for each case study technology, we chose to use SIC codes to identify the relevant sectors that would adopt the technologies in order to undertake process innovation, and then create a combined indicator. This involves two steps:

1. Identify paired combinations of adopting sectors and investment assets that best proxy our technology and collect data on trends in this investment combination.
2. Look to see if this correlates to an increase in self-reported process innovation in those same adopting sectors.

Investment in assets is measuring using ONS data on gross fixed capital formation. We measure growth rates against other technologies and the broader economy, but with a difference: for adopting sectors, we use a weighted average of one or more sectors rather than the single sector used in the commercialising sector analysis. Some of our technologies can be better captured by this approach than others. Data for some sectors is not available in the source, so these are marked as N/A in the table below. Combining these datasets into a single metric allows us to glean some useful information without being overly reliant on a single proxy or source. The results are shown in table 2.4.2.

Table 2.4.2: Evidence as to sectoral adoption levels and process innovation by technology

Technology	Paired Sector and Technology	Investment (in £ in 2022)	Percentage of Businesses That Self-Reported Process Innovation
Agricultural Gene Editing	Agriculture, forestry, and fishing investing in cultivated assets	£1,332m	N/A
AI	Information and communications, professional scientific and technical activities investing in software	£7,162m	45.5% of businesses in the publishing, computer programming, and information service sectors
Industrial Robotics	Manufacturing investing in machinery and equipment	£2,996m	40.3% of businesses in the manufacturing sector
Innovative Galleries	Cultural sector investing in hardware	£67m	N/A
Mobile Communications	Information and communications investing in telecoms	£4,090m	39.6% of businesses in the telecommunications sector
Modern Supply Side Economics	Public administration and defence investing in intellectual property products	£7,439m	N/A
mRNA Vaccines	Human health activities investing in intellectual property products	£2,597m	N/A
Offsite Construction	Construction investing in machinery and equipment	£3,124m	23.8% of businesses in the construction sector
Quantum	N/A – quantum is not yet ready for large-scale adoption	N/A	N/A
Semiconductors	Manufacturing, information and communications investing in hardware	£1,219m	42.9% of businesses in the manufacture of computer, electrical, and optical equipment

2.5 Outcomes

Finally, to measure wider economic outcomes, we collected three indicators, intended to give us a broad overall understanding of where the value of innovation was ultimately being captured:

1. A cross-country comparison of commercialising sector productivity
2. A cross-country comparison of adopting sector productivity
3. An estimate of UK consumer surplus by technology

Commercialising Sector Productivity

The goal is to measure the productivity of the sectors commercialising the technologies. This tells us how much of the value of the technology is being captured by the sectors commercialising and selling the products embedding the technologies themselves. We identify the main commercialising sectors and use OECD data on GVA and employment (hours worked) to calculate productivity as GVA per hour for each of these sectors, and do so for every country that has both employment and GVA data for that sector. The results are shown in table 2.5.1. The only standout UK sectoral productivities are in pharmaceuticals, where the UK ranks 2nd globally, and scientific R&D, where it ranks 5th.

Table 2.5.1: UK productivity ($GVA per hour worked) on the commercialising sectors of each technology

Technology	Proxy Sector	UK Relative Performance (all figures $GVA per hour worked)	UK Rank
Agricultural Gene Editing	Agriculture, forestry, and fishing	31 compared with an OECD average of 26	15th among OECD countries
AI	Computer programming, consultancy, and information service activities	65 compared with an OECD average of 90	18th among OECD countries
Industrial Robotics	Manufacturing of machinery and equipment	80 compared with an OECD average of 88	10th among OECD countries
Innovative Galleries	Arts, entertainment, and recreation	37 compared with an OECD average of 48	19th among OECD countries

Mobile Communications	Telecoms	124 compared with an OECD average of 171	20th among OECD countries
Modern Supply Side Economics	Professional, scientific, technical	53 compared with an OECD average of 65	20th among OECD countries
mRNA Vaccines	Pharmaceuticals	273 compared with an OECD average of 213	2nd among OECD countries
Offsite Construction	Construction	45 compared with an OECD average of 47	15th among OECD countries
Quantum	Scientific R&D	118 compared with an OECD average of 99	5th among OECD countries
Semiconductors	Manufacture of computers, electrics, or electronics	105 compared with an OECD average of 111	10th among OECD countries

Adopting Sector Productivity

The goal is to measure the current productivity levels in the sectors that would use the technologies. We use OECD data on GVA and employment (hours worked) to calculate productivity as GVA per hour for each of these sectors, and do so for every country that has both employment and GVA data for that sector. We define sectors more broadly in some cases, since a wider range of industries typically adopts technologies than develops them. The results are shown in table 2.5.2 below.

Table 2.5.2: Productivity ($GVA per hour worked) in sectors adopting each technology

Technology	Proxy Sector	UK Relative Performance (all figures $GVA per hour worked)	UK Rank
Agricultural Gene Editing	Agriculture, forestry, and fishing	31 compared with an OECD average of 26	15th among OECD countries
AI	Computer programming, consultancy, and	65 compared with an OECD average of 89	18th among OECD countries

	information service activities		
Industrial Robotics	Manufacturing	69 compared with an OECD average of 81	16th among OECD countries
Innovative Galleries	Arts, entertainment, and recreation	37 compared with an OECD average of 48	19th among OECD countries
Mobile Communications	Telecoms	124 compared with an OECD average of 171	lowest among OECD countries
Modern Supply Side Economics	All	59 compared with OECD average of 67	19th among OECD countries
mRNA Vaccines	Human health	47 compared with an OECD average of 53	17th among of OECD countries
Offsite Construction	Construction	45 compared with an OECD average of 47	6th lowest among OECD countries
Quantum	N/A	N/A	N/A
Semiconductors	Information and communications	78 compared with an OECD average of 109	18th among OECD countries

Consumer Surplus

We measure the degree to which consumer products that are linked to the technologies have experienced price reductions. This measures the degree to which the process improvements of innovation lead to consumer surplus, as outlined in the systems map (figure 1.2.2). We use data on consumption by product (in chained volume measures, to capture real consumption) and ONS data on the UK Consumer Price Index (CPI). Since we are interested in measuring real changes in affordability, we scale price changes to changes in incomes (again using ONS data). We take 2008 as a base year to capture long-term impacts. We score amber for price changes within +/− 10%, green for > 10%, and red for < 10%. A small version of the results can be seen in table 2.5.3 below.

Some caveats should be noted. We were only confidently able to score six of the ten technologies. These are consumer products, and many of the technologies are fairly distant from the retail end of the supply chain. Proxies are not exact. Several technologies did not match sufficiently closely with any of the 52 products. Quantum is not yet commercial, so is not scored. The CPI controls for quality improvements, so price changes do not capture these. Price dynamics may therefore understate how much surplus consumers gain if there have been notable quality improvements (e.g., in smartphones) or deteriorations.

Table 2.5.3: Consumer surplus – price changes relative to income, 2008–2022

Technology	Proxy Consumption Product	Relative Price Change 2008–2022	Relative Quantity Change 2008–2022
Agricultural Gene Editing	Food	−2%	17%
AI	N/A	N/A	N/A
Industrial Robotics	Manufactured Goods	−6%	12%
Innovative Galleries	Cultural Services	13%	1%
Mobile Communications	Telecoms	1%	412%
Modern Supply Side Economics	N/A	N/A	N/A
mRNA Vaccines	N/A	N/A	N/A
Offsite Construction	Housing	−11%	24%
Quantum	N/A	N/A	N/A
Semiconductors	Audiovisual Equipment	−60%	74%

2.6 Data Summary Tables

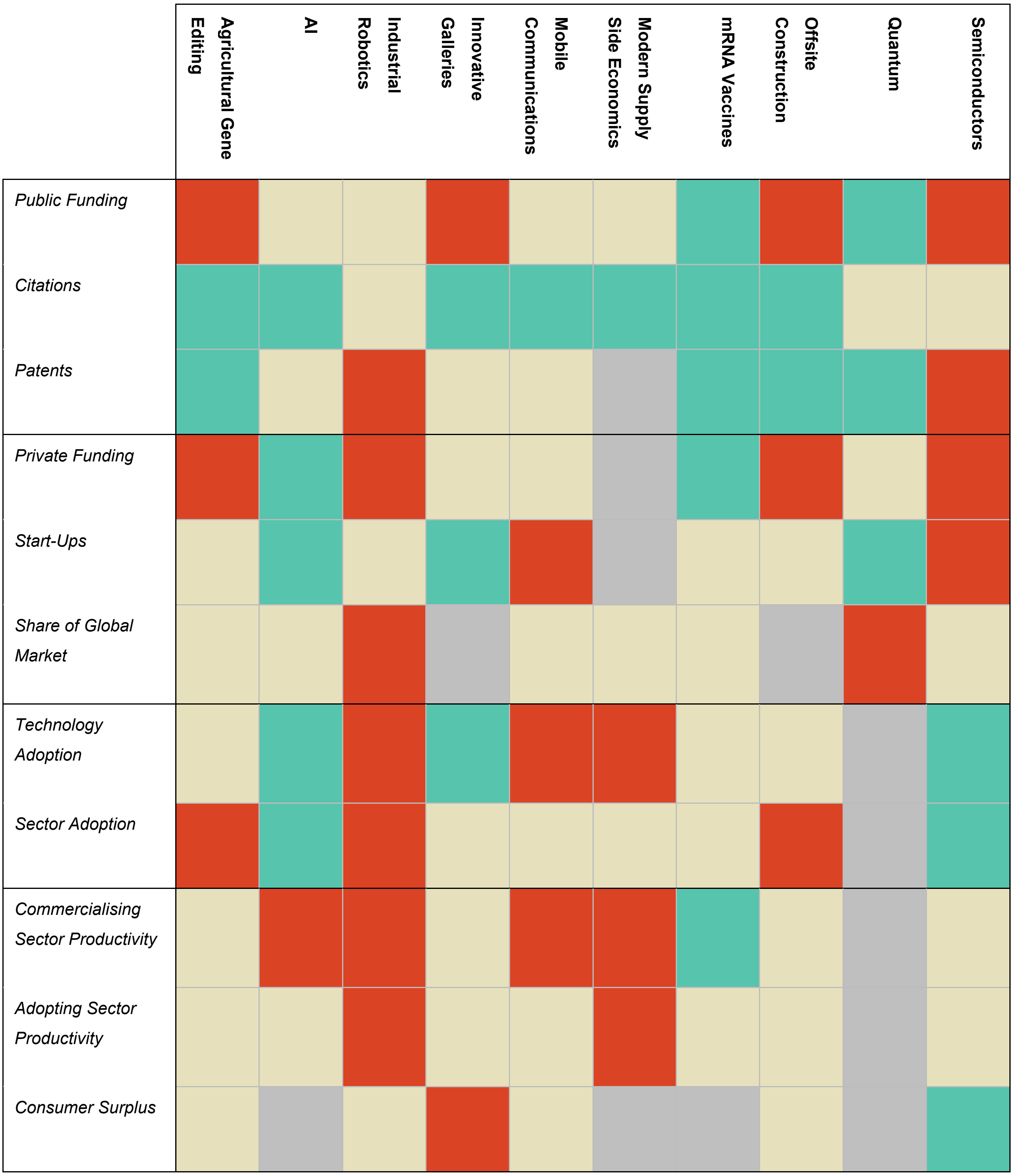
Below are shown two summary tables. Table 2.6.1 shows an overview of the data collected for each metric, the method of identification of individual technologies, and the means of comparison. Where global data were available, a cross-country comparison was performed; where these were not available, technologies were compared against each other.

Table 2.6.1: Summary of data gathered and used for RAG assessments

Metric	Dataset Source(s) Used	Means of Identifying Technology	Means of Comparison
Research			
Public Funding	UKRI Funding Data	Keywords	Relative
Citations	OECD	Keywords	Cross-country
Patents	Espacenet	Keywords	Cross-country
Commercialisation			
Private Funding	Dealroom	RTICs	Relative
Start-ups	The Data City	RTICs and Keywords	Relative
Global Market Cap	Various Sources	Investment Categories	Cross-country
Adoption			
Technology Adoption	Various Sources	External Definitions	Cross-country
Sector Adoption	ONS, UK Innovation Survey	Proxied by SIC code and GFC Category	Relative
Outcomes			
Commercialising Sector Productivity	OECD	Proxied by SIC code	Cross-country
Adopting Sector Productivity	OECD	Proxied by SIC code	Cross-country
Consumer Surplus	ONS	Proxied by Product	Relative

Table 2.6.2 shows a summary for the findings for each metric for each of the ten technologies. This is inherently a partially subjective exercise, although we have attempted to apply a consistent systematic comparison method between technologies as far as this was possible.

Table 2.6.2: Summary of RAG scores by metric by technology



3. Case Studies

This section presents short summaries of the ten case studies into the knowledge chains underlying the development and diffusion of different technologies and the UK's role within this.

3.1 Semiconductors

The term "semiconductor" refers to a category of elements and compounds with electrical conductivity that falls between that of an insulator (e.g., glass) and that of a conductor (e.g., copper). The ability of semiconductors to control and amplify electrical currents puts them at the heart of modern electronics. Generations of research into semiconductor physics had made it possible for microchips to become ever smaller, faster, and more efficient (Barclays 2023).

Semiconductors originated with Michael Faraday's experiments with silver sulphide in the 1830s (Pearson & Brattain 2007). In the 19th and 20th centuries the development of semiconductor devices was made possible by discoveries in radio waves, electrical conduction in metals, and quantum mechanics, among others (Pearson & Brattain 1955). Semiconductor research evolved with the development of the transistor, which eventually led to the development of the integrated circuit and the microprocessor, fundamental components for modern electronic devices and computers (Orton 2009).

The semiconductor industry has experienced significant growth in production volume over multiple decades, with over a trillion semiconductor chips manufactured globally each year in diverse forms. Figure 3.1.1 shows the semiconductor knowledge chain: fundamental physics research at universities is complemented by a substantial industrial semiconductor research base. This knowledge then flows into product design and fabrication. The semiconductor knowledge chain feeds into almost every global value chain, with semiconductor chips being used directly as components in a wide range of electronic devices, and semiconductor chip–based devices themselves being used as processing steps in almost every possible value chain, from mining to legal services.

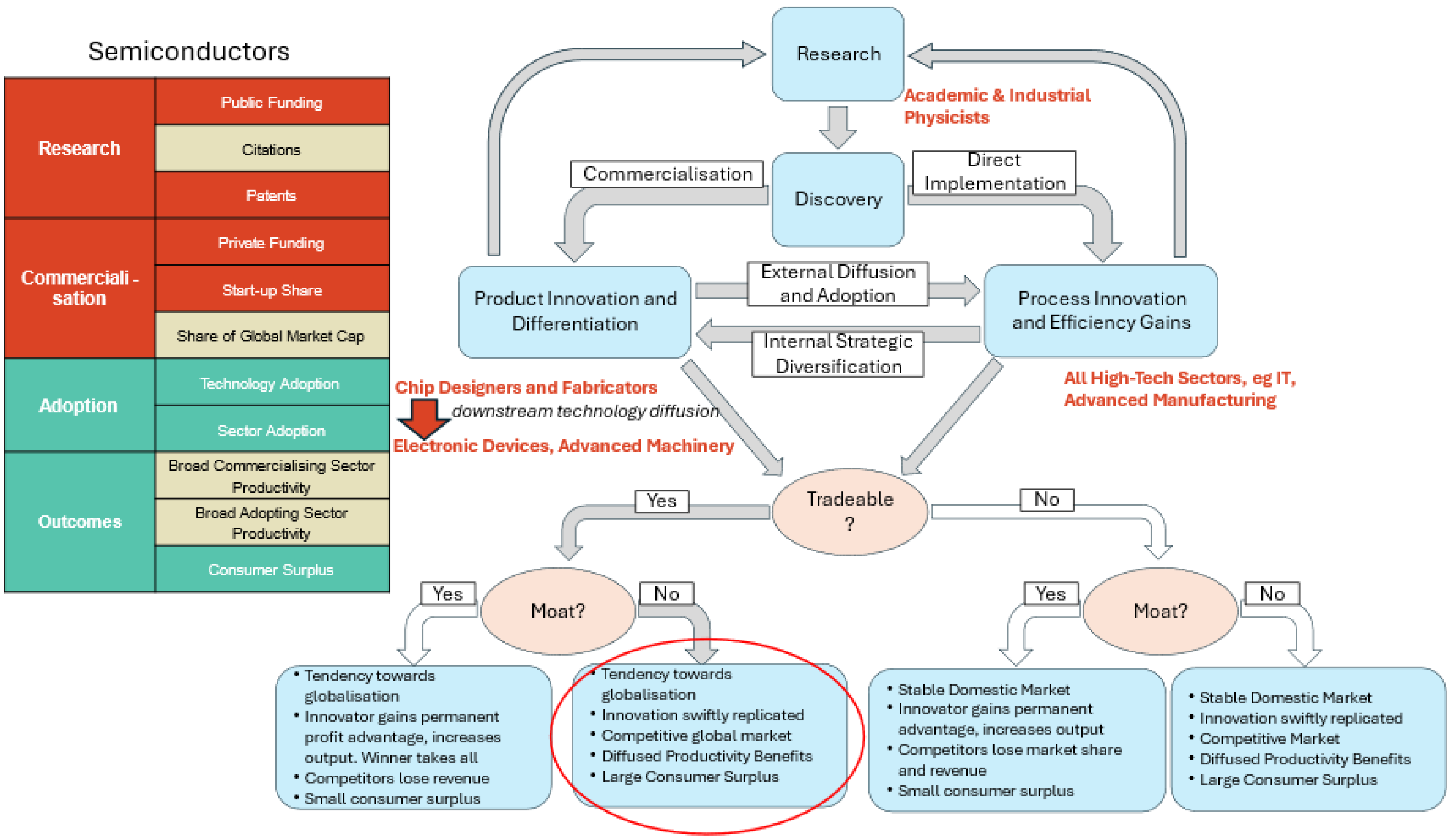
Semiconductors underpin almost all modern technology and have had an unparalleled role in productivity growth and consumer surplus since the IT revolution. As both computing power and storage have become more affordable, this has led to substantial diffusion of the benefits of the technology to both consumers and corporations. Semiconductors are a technology where productivity benefits have accrued to both the innovators and the manufacturers that produce either the chips or devices based on the chips, as well as the sectors that adopt the technology (which is effectively the entire economy), while providing substantial levels of direct consumer surplus: semiconductor devices were the category that scored highest overall on our consumer surplus indicator.

The UK both contributed to this development (through its initial research into semiconductor physics and applications) and has benefited from it (through its adoption of digital technologies). However, the location and ownership of the majority of profitable multinational semiconductor designers, manufacturers, and distributors indicates that the UK has not captured as much of the value generated. Reasons for this are both specific to semiconductors (the decision not to develop and protect cutting-edge domestic fabrication facilities many decades ago proved ill advised, but is now irreversible) and general (like many other tradeable sectors, the semiconductor industry inevitably tends towards global concentration and amalgamation, and UK firms, with their small domestic market, tend to be the ones amalgamated, rather than the ones doing the amalgamating). Currently, the UK semiconductor industry is relatively niche, consisting of ARM (a large chip designer) and smaller firms.

There are no current major barriers to adoption of semiconductor chips in the UK, although these are almost entirely imported, as despite having the technological capabilities, the UK did not attempt to develop its own fabrication industry during the 1980s and 1990s. The majority of the world's chips and most of the most valuable semiconductor companies are in Taiwan, South Korea, Japan, and the US (DSIT 2023c).

Figure 3.1.1 shows the semiconductors knowledge chain. We characterise this industry as a competitive, globally integrated market with high levels of downstream productivity diffusion and consumer surplus. It may seem surprising to describe the extremely valuable global semiconductor industry, which does have dominant firms such as NVIDIA and TSMC, as one "without" moats – but it is also an industry with high levels of productivity benefit diffusion to other sectors and famously rapid reductions in costs to the consumer for both storage and speed. Clearly semiconductors are such a valuable technology that there is room for both consumer surplus *and* high levels of profitability.

Figure 3.1.1: Semiconductors knowledge chain and RAG chart



Our data analysis shows that the UK has historically contributed to fundamental semiconductor research. However, recent performance on patents and citations has weakened. The UK produces 3.4% of citations (ranking 6th globally) and 1.4% of patents (8th). Data also show relatively low levels of public funding fuelling the research community. This can be partly explained by the fact that this is a mature industry with strong private sector R&D. Given the importance of corporate R&D, and secrecy around designs that may be limiting academic dissemination, it is likely that our indicators are not capturing the full extent of research being conducted in the UK.

Although there is a vibrant commercial ecosystem around semiconductor devices in the UK, this does not translate to representation on the global stage, with only ARM holdings among the top ten global semiconductor firms. ARM's presence in the UK market is largely responsible for the UK's comparatively robust market capitalisation. Low venture capital (VC) figures and high average age of start-ups suggest that the domestic semiconductor industry is not particularly dynamic, which is partly explained by its relative maturity and higher barriers to entry.

However, this has not prevented the UK from taking advantage of the global semiconductor industry to adopt the technology and downstream devices enthusiastically, which has most measurably manifested in UK residents' consumer surplus and their plethora of mobile phones and other technological devices.

While broadly our adoption of this technology could be seen as the UK being a beneficiary of a successful global industry, there is the question of an opportunity missed with the UK's inability to leverage past researchinto a more competitive position further upstream. The question is whether we can build on that position in developing the next generation of semiconductor devices, much of the underlying physics of which are currently being developed by UK researchers.

According to the National Semiconductors Strategy, in 2022 the global semiconductor industry generated US$601.7 billion in revenue (DSIT 2023c). Despite the industry's cyclical nature, market analysts predict an annual growth rate of 6% to 8% through 2030. This expansion will be driven by diverse applications, including in the automotive sector, where the demand for electric vehicles is on the rise (DSIT 2023c).

In May 2023, the government launched the UK Semiconductors Strategy, which aims to position the country as a world leader in future semiconductor downstream applications – such as AI, high-performance computing, quantum, and cyber – by focusing on UK strengths (DSIT 2023c). The strategy announced investments of up £200 million between 2023 and 2025 and up to £1 billion in the next decade. Rather than expanding silicon manufacturing capabilities, it seeks to enhance existing strengths in chip design, advanced packaging, and compound semiconductors, an alternative formulation of semiconductor device which has different physical properties from silicon-based devices and provides a wider range of functions, many of which will become increasingly useful in future decades. Beyond the Semiconductor Strategy, the UK boasts an extensive network of initiatives that drive growth and foster innovation, such as the Compound Semiconductor Applications Catapult, UK Space Facility, and the National Epitaxy Facility. These programmes elevate the existing network of research and IP that forms the backbone of the UK's semiconductor ecosystem.

A sensible strategy for enhancing future value capture in this knowledge chain would be to focus on building capacity to lead the global commercialisation of new innovations in the niche (but potentially transformational) subfields of semiconductor physics in which the UK is already a leading player, for example next-generation compound semiconductors, or the utilisation of advanced packaging methods. If the UK invests in this wisely, for example by undertaking the establishment of the Semiconductor Infrastructure Initiative in full, some of the mistakes of the past may be avoided this time round.

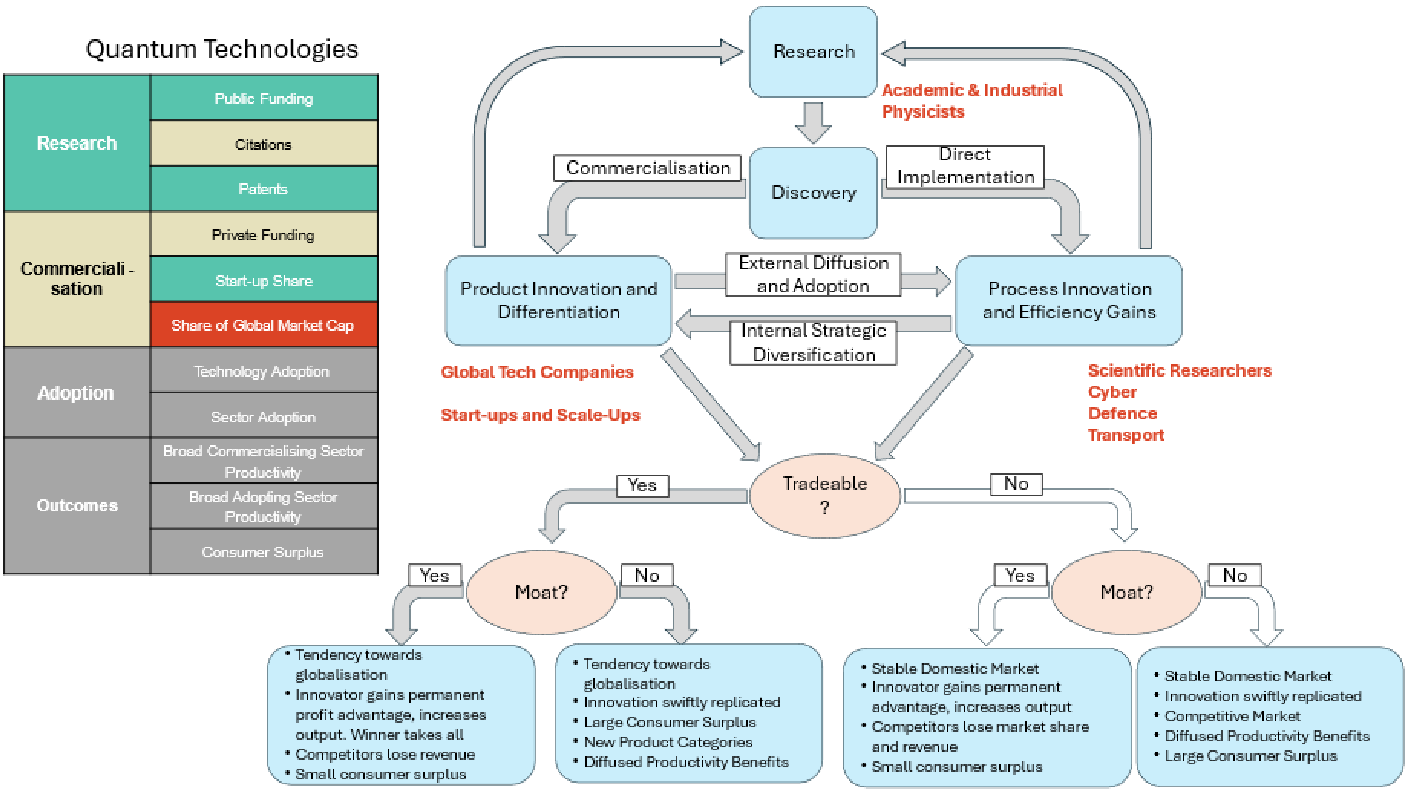
3.2 Quantum Technologies

The first generation of quantum technologies originated with discoveries by Max Planck (black body radiation, 1901) and Albert Einstein (photoelectric effect, 1905) that led to the development of quantum theory in the formulation of matrix mechanics by Heisenberg, Born, and Jordan in 1926 and Schrödinger's wave mechanics (Scheidsteger et al. 2021). This theoretical foundation led to the development of solid-state physics and the emergence of first-generation technologies that exploited quantum behaviours such as spin and quantum tunnelling for applications in lasers, transistors, nuclear power plants, and solar cells; and superconducting magnets in nuclear magnetic resonance (NMR) devices and particle accelerators. Discoveries in the 1970s and 1980s enabled the preparation and control of single quantum particles, such as atoms, electrons, and photons, allowing them to interact on an individual basis. A second quantum revolution in the 1990s combined physics, engineering, and computer science using long-known quantum features – especially superposition and entanglement of single quantum states – for a whole range of next-generation applications.

The current generation of quantum research is producing an emerging class of devices that control and manipulate superposition and entanglement of quantum states of light or matter and have fundamental performance advantages over existing machines (Wang et al. 2020). Quantum technologies are typically classified as related to computing, sensing, or communication. This most recent generation of quantum technologies is likely to have significant impacts on a wide variety of industries in the near future. For instance, research in quantum computing, communication, and sensing will speed up and expand the capabilities of innovators in scientific research, cybersecurity, defence, transport, and other areas. The commercialisation of quantum technologies is underway, as we can see from the emergence of start-ups and scale-ups in this space as well as rapid expansion of interest and engagement from global tech companies. Of all the technologies we studied, we found that UK quantum computing firms had the lowest mean age, at just eight years on average.

Figure 3.2.1 shows the quantum knowledge chain. As the technology is still in the commercialisation stage, no scores are yet given for adoption and downstream impacts. However, this isn't a distant science-fiction technology: we expect to see more widespread adoption and diffusion of many of these devices within the next few years.

Figure 3.2.1: Quantum technologies knowledge chain and RAG chart



The UK ranked fourth (after the US, China, and Germany) in publications on second-generation quantum technologies 2000–2018 (Scheidsteger et al. 2021). In 2014, the UK National Quantum Technologies Programme established four National Hubs in Quantum Science and Technologies in Communications (University of York), Sensors and Timing (University of Birmingham), Enhanced Imaging (University of Glasgow), and Computing (University of Oxford). These research groups have claimed many world firsts, such as the first industrial demonstrations of a quantum gravimeter (capable of sensing underground objects), the first chip-to-chip quantum key distribution (QKD) encrypted transmission, and achieving world record performance in ion trap quantum computing (DSIT 2023b). The Imperial College London Centre for Cold Matter is working on a quantum compass, with support from UKRI's Technology Missions Fund and the UK National Quantum Technologies Programme, which will enable more precise geolocation than is possible with current global navigation satellite system (GNSS) technologies (McKie 2024). Researchers at the University of Manchester, in partnership with the University of Melbourne (Australia), have recently created material that has been described as a critical "brick" needed to construct a silicon-based quantum computer (University of Manchester 2024). This enhanced, ultra-pure form of silicon will enable the production of high-performance qubit devices – a fundamental component required to pave the way towards scalable quantum computers.

Large-scale quantum computing is still in development and used largely in research, but some applications are starting to proliferate, particularly in parallel with machine learning and cryptography. Quantum sensing is currently being used in advanced medical imaging, environmental monitoring, and navigation. Magnetic resonance imaging, superconducting quantum interference devices, and medical lasers have long relied on first-generation quantum technologies and are in widespread use. However, advances based on next-generation technologies are increasingly being developed for clinical applications, for instance quantum sensor–based brain imaging (Boto et al. 2018) and nuclear magnetic resonance at the scale of individual proteins and cells (Glenn et al. 2018). Quantum technologies are currently integrated into communication systems and processes. QKD is one of the most mature and commercially available quantum communication technologies. QKD uses quantum mechanics principles to generate and distribute secure cryptographic keys between parties, ensuring secure communication. Quantum random number generators (QRNG) are devices that generate truly random numbers based on quantum processes. UK firms are active in developing commercial applications in all these areas. However, this cluster has yet to generate a champion, and little is known currently about adoption intentions.

Quantum computing will likely have the broadest impact by making complex calculations and operations faster and more secure. Recent commentary by The Productivity Institute compared the productivity potential of quantum technologies – particularly computing – with the digital revolution of the 1970s and 1980s (Velu 2024). It anticipates that early adoption will be characterised by high integration costs and low short-term rewards as businesses initially adopt quantum computers to solve existing problems, where improvements are likely to be incremental. The full potential of quantum computing may take longer to realise, as the mechanics that underpin the technology operate on counterintuitive principles, often unfamiliar to engineers and business managers. Finally, quantum computers can work against progress as quantum cryptography leaves conventional computer systems vulnerable to hacking. As with semiconductor devices, the UK physics community has been a global leader in developing quantum entanglement applications and now has a small but vibrant commercial start-up community and a scientific R&D community with the knowledge capability to be early adopters of quantum computers – a clear opportunity for the government to push demand and supply simultaneously.

Quantum computing will almost certainly become a globally integrated market, but it is unclear as yet whether this will be a highly competitive market with widespread adoption and rapidly falling prices, or whether leading innovators are able to maintain global market power for extended periods. In either eventuality, the government's quantum strategy needs to consider the dual opportunities of both commercialising the technology as it emerges and ensuring early adoption in addition to supporting catalytic research.

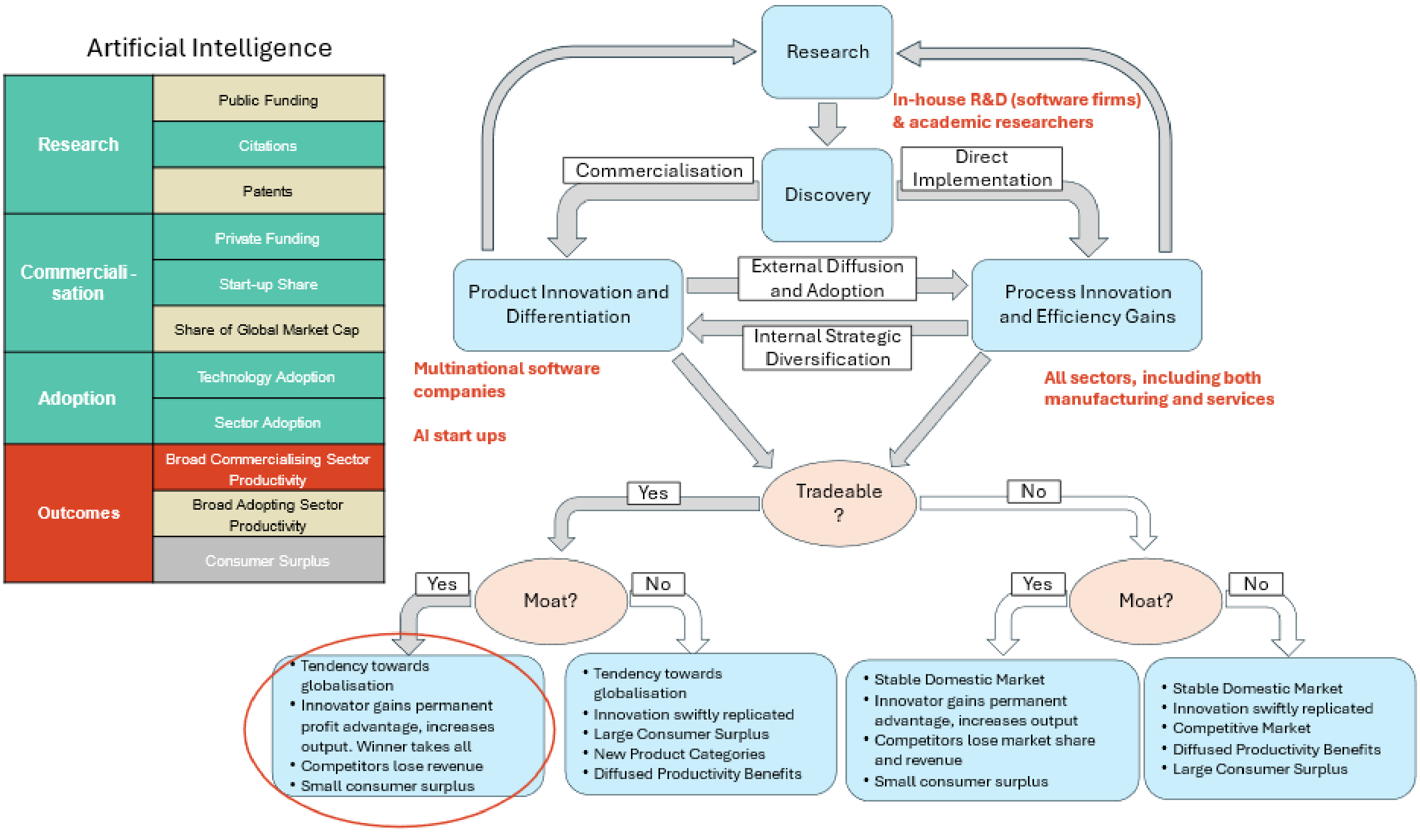
3.3 Artificial Intelligence

Artificial intelligence (AI) is an umbrella term for a set of technologies that "enable computers to do things that are thought to require intelligence when done by people, such as understanding language, driving cars, answering questions, or generating text" (Heaven 2024). More formally, an AI system is a "machine-based system that for explicit or implicit objectives, infers, from the input it receives, how to generate outputs such as predictions, content, recommendations, or decisions that can influence physical or virtual environments" (OECD 2024).

AI is often described as a potential "general purpose technology" or "GPT" (unrelated to Chat-GPT). These are technologies that are a key input into other innovations – akin to the steam engine, electricity, computing, and the internet. Some key differences between AI and previous general purpose technologies include characteristics of autonomy and self-improvement. Also, while outputs that AI permits are generally cognitive (as with computing and the internet), the potential for AI systems to invent/innovate by producing new tools, hypotheses, and research in response to human queries is a differentiator of another order (Calvino et al. 2023; Ludwig & Mullainathan 2024; Babina et al. 2024). As AI systems and capabilities have evolved, the definition of what constitutes AI continues to expand, and the AI landscape has become more nuanced, to the point where the term captures many very different types of systems, applications, and levels of functionality.

Figure 3.3.1 shows the AI knowledge chain. We have characterised the AI industry as a globally integrated market, albeit one in which large software firms currently maintain a dominant position. While the UK has substantial research capability and a vibrant (and now long-standing) start-up community, it doesn't hold a large share of global market capitalisation (it ranks 4th globally but far behind competitors). The most prominent UK AI firm, London and Cambridge–based DeepMind, was bought out by Alphabet (Google) in 2014, only four years after formation. Although the UK shows high levels of adoption of the technology, as yet this hasn't translated into measurable benefits.

Figure 3.3.1: Artificial intelligence knowledge chain and RAG chart



The UK has a strong research base in AI and related computer science, along with strengths in mathematics, computer science, and data systems that enable AI sector-specific applications, as well as in AI ethics. These have applications across a variety of sectors. AI for digital twins aims to optimise high-value manufacturing systems (DTHIVE) and multiphase flow systems. Digital twins are live digital couplings between virtual duplicates of real-world systems and the physical "twin". They have applications from green energy to healthcare, smart cities, and more efficient manufacturing. The UK has also developed wider expertise in healthcare applications of AI. Research in this area includes projects to use smart algorithms to reduce burdens on healthcare providers and increase efficiency of treatment decisions, health safety monitoring, and diagnosis. Several projects focus on the intersection between sectors – for instance, combining healthcare and robotics. A recent UKRI investment of £100 million resourced nine AI Hubs around the country that are consolidating and supporting research expertise and increasing potential for translation and application.

The UK ranks 4th globally in terms of academic citations, indicative of a strong research base. However, it performs less well on levels of public funding and patenting. Because AI is still an emerging industry, data on public funding may be lagging behind programme development. Indeed, several new funding initiatives were announced in late 2024. Lower relative patent rates, however, are more difficult to explain in the context of a global boom in AI patent filings. That said, data on commercialisation indicates that the UK has a vibrant, and young, start-up industry, which has been attracting relatively high levels of VC investment, indicating a high level of confidence in commercial activity that may yet generate world-leading AI businesses.

Machine learning is being applied in a wide range of industries in the UK – most notably, financial services, healthcare, transportation and logistics, and data analysis. In financial services, innovative companies are developing AI-based tools that are being used in companies around the world. Banks and financial institutions across the UK are also adopting AI internally with most major banks now claiming that they use or are rolling out AI-based tools. The Lloyds Bank Annual Financial Institutions Sentiment Survey (Lloyds Bank 2024) revealed that two-thirds of financial institutions reported that they are already investing in AI – double the amount among those surveyed in 2023. Many reported that they viewed AI as an opportunity (81%) and are convening dedicated teams to explore its uses, while a significant amount are also looking to establish partnerships with established AI firms (39%) or already have such partnerships in place (15%).

UK companies are using machine learning to develop innovative healthcare applications. While the use and potential transformative impact of AI on healthcare have been widely acknowledged and embraced across the health infrastructure and policy landscape, proponents also recognise that application of these technologies must proceed with caution and within a carefully considered regulatory context (NHS 2023).

Transport and logistics sectors are also benefiting from AI-based tools, and UK companies are actively innovating in this area. While UK companies continue to develop AI-based tools for the industry, there is some evidence that there are gaps in adoption across the transport and logistics sector. The On the Move survey found that only half of logistics firms in the UK are currently using basic data analytics, and only 19% were incorporating AI into their operations. Cost was cited as the top barrier to implementation, followed closely by concerns about potential disruption to existing services (12%) and lack of required skills and expertise (11%) to implement AI solutions (HERE Technologies 2024).

Reports about the potential productivity impacts of AI vary dramatically in their conclusions. Research by the OECD found that AI use among businesses was associated with substantially higher labour productivity (Calvino & Fontanelli 2023). PwC (2024) found that AI-exposed sectors (e.g., financial services, information technology, and professional services) experienced a fivefold increase in the rate of productivity growth. Research indicates that workers are not only more productive with AI tools, but that they report improved job enjoyment and positive mental health impacts (Milanez 2023). Filippucci et al. (2024) stress that, because AI is a method of invention, its productivity impacts are intensified to the degree that it enables research, innovation, and discovery. As such, they postulate that broader impacts of AI may be being underestimated.

As with other digital technologies, the rate at which productivity growth will increase will depend not just on developments in AI technology, but also on the rate at which other technologies and other business processes are adapted to take advantage of it (Coyle & Jones 2024). At present, conservative calculations forecast less than 1% cumulative productivity growth over the next ten years (Acemoglu 2024), where growth not only takes time but is mediated by factors such as labour reallocation and unexpected negative consequences. Productivity growth might also be boosted indirectly through knowledge diffusion and spillovers, resulting in an increase in multifactor productivity (MFP) (Corrado et al. 2022). As a method of invention, AI has the potential to push out the productivity frontier.

It is important to note that the AI sector is broad and made up of a diverse set of technologies with different profiles and potential. Research on machine and deep learning, for instance, has yielded successful and proven applications but has had a considerably lower profile than the most recent boom in generative AI. Large language models (LLMs), by contrast, still have a long way to go to demonstrate genuine widespread application and productivity impact but are more directly accessible to non-expert users and, consequently, are in a hype cycle. There is a risk that public investment prioritises these less proven, and perhaps ultimately less productive, types of AI because of their higher profile. For all the justified high expectations, the data suggest that AI has produced very little in the way of productivity impact or consumer surplus in the UK thus far. One potential reason for this may be that some of the strongest international benefits come from the integration of AI with other autonomous technologies, such as robotics and drones, and, as we shall see below, the UK has a very poor record at investment in and adoption of these potentially AI-complementary technologies.

3.4 Mobile Technologies

Mobile communication technology has evolved significantly from 1G to 5G (the current industry standard), with each generation bringing major improvements in speed, capacity, capabilities, and security. Increasing demand, however, has revealed limitations in existing technology. In addition to capacity issues, as connected technologies have matured, existing networks are falling short of evolving technical requirements. For instance, next-generation virtual augmented reality (VAR) needs a data rate and ultra-low latency not available on the 5G system (Banafaa et al. 2023). Increased connection density will also require enhanced energy efficiency.

6G networks are not yet a reality, and so current applications of this technology are limited. Ericsson estimates that the first 6G networks are likely to appear in 2030. Adoption of 6G technologies is likely to be constrained by infrastructure limitations. The UK currently lags in the deployment of 5G technology. Rollout of this technology is mostly managed by private companies – currently EE (owned by BT), Three, Vodafone, and O2 (a joint venture with Virgin Media) – that decide when and where to locate network infrastructure. Most of the 5G network is “not standalone”, meaning that it has been deployed on top of existing 4G technology. As a result, the advent of next-generation mobile network technology does not necessarily provide additional coverage (Clark 2023). The government published a new UK Wireless Infrastructure Strategy in April 2023 that acknowledges that significant investment will be required to meet the UK’s ambition for all populated parts of the UK to have standalone 5G by 2030, but this goal is expected to be privately funded as there were no new funding sources dedicated for 5G deployment (Clark 2024). Whereas the UK was a global leader and early adopter in the rollout of previous generations of mobile networks, it has become a laggard in the rollout of 5G technologies. Recent estimates suggest that UK mobile users have access to 5G only 8%–10% of the time and the UK ranks last in major economy 5G connectivity (O’Halloran 2024). It also came 21st out of 25 countries on measures of mobile download speeds, significantly slower than top performers.

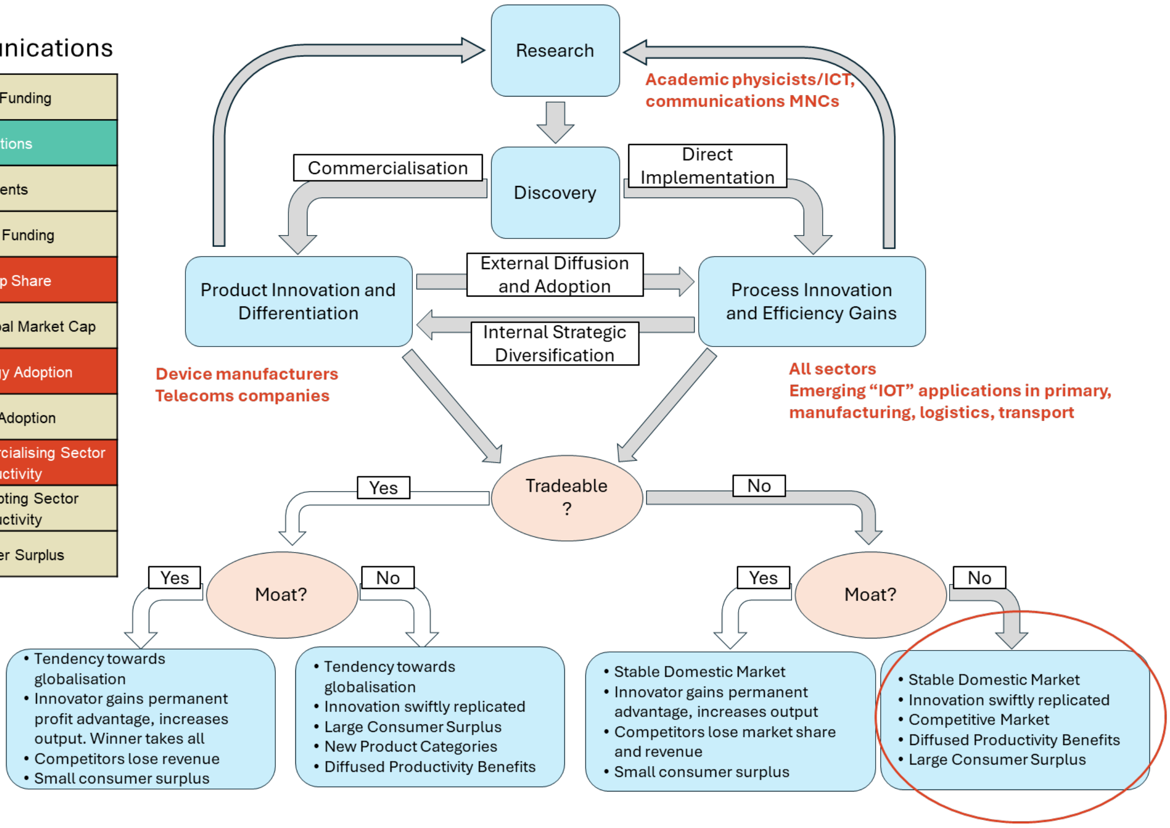
The rollout of 5G networks offers some clues about how commercialisation and adoption occur in the sector. Access to 5G networks enabled the development of 5G-enabled mobile phones and devices. An estimated 62% of phones worldwide currently have 5G capabilities. Other technologies include wearables and a wide variety of sensors and connected devices that make up the Internet of Things (IoT).

Figure 3.4.1 shows the mobile technology knowledge chain. Although many of the leading firms are multinational, the global telecoms market is split into independent domestic markets, making it a competitive, non-tradeable service sector. This is an interesting example of a single global knowledge chain serving multiple separate domestic markets, each at its own stage of technological development.

Figure 3.4.1: Next-generation mobile technologies knowledge chain and RAG chart

Mobile Communications

Research	Public Funding
	Citations
	Patents
Commerciali-sation	Private Funding
	Start-up Share
	Share of Global Market Cap
Adoption	Technology Adoption
	Sector Adoption
Outcomes	Broad Commercialising Sector Productivity
	Broad Adopting Sector Productivity
	Consumer Surplus



The UK government has earmarked 6G as one of its five critical priority technologies, aiming to position the UK as a leader in global telecoms research. The investment in research hubs and collaborations with industry partners is part of a broader strategy to enhance the UK's competitiveness in the telecom sector and develop a robust intellectual property portfolio for 6G technologies. The Future Telecommunications Challenge competition projects reveal several areas of research focus, such as optimising energy efficiency and latency; upgrading cellular infrastructure (access and capacity); optical networks and photonics; and storage and network traffic management. With few exceptions, funded projects are being led by communications technology companies (UKRI 2024). These projects focus on solving crucial technical problems and exploring efficiency gains in specific applications. Future Telecom Research Hubs, involving researchers from a consortium of UK universities, are tackling more ambitious and large-scale projects focused on network and infrastructure integration, resilience, and security.

Large telecoms are also very active in driving 6G research in the UK. In 2022, Ericsson announced a multimillion-pound investment in a 6G research unit to be located in the UK. In the same year, Samsung established a 6G research group at its R&D facility in Staines-upon-Thames (Samsung 2022). The UK ranks 5th globally on academic citations in the area of mobile technologies. This demonstrates the strength of the UK research base and is a strong indicator that UK innovations are being adopted in other markets.

Based on current projections, 6G is expected to contribute up to US$1 trillion to global GDP by 2035 (Khan et al. 2020). While the specific impacts for 6G are currently speculative, research on 5G and productivity illustrates the areas where next-generation communication technologies will likely have an impact. In a study of five sectors – healthcare, smart utilities, consumer and media, industrial manufacturing, and financial services – PwC (2021) estimates that adoption of 5G technologies will add US$1.3 trillion to global GDP by 2030.

A survey of network executives conducted by Deloitte (Littmann et al. 2020) revealed that organisations are adopting advanced wireless to unlock competitive advantage and create new avenues for innovation in their operations and offerings rather than focusing on traditional network metrics such as reliability and coverage. Among the surveyed executives, 57% reported that their company's current networking infrastructure may be preventing them from addressing the innovative use cases they would like to target. Furthermore, 87% thought that their company would be able to generate a significant competitive advantage by leveraging advanced wireless technologies. Expectations of long-term impact from adopting innovative communications technologies are high – 86% of the executives surveyed believe that advanced wireless would transform their organisations within three years, and 79% thought the same about the effect of these technologies on their industry. While 6G promises significant productivity gains, it may also lead to job displacement in some sectors due to increased automation and optimisation. Adapting to and leveraging 6G technology will be crucial for businesses and workers to realise its full productivity potential.

There are also concerns about the UK's ability to take advantage of 6G technologies as they become available. The UK government is aiming for nationwide standalone 5G coverage in all populated areas by 2030, as part of its Wireless Infrastructure Strategy, but it is notably lagging behind this target, which suggests that the UK will also struggle to deploy 6G networks when they are available. This could have significant productivity implications, particularly if network performance and access continue to lag behind other developed and developing economies. There should be considerable urgency within government to first understand the causes behind current issues, which stem primarily from a lack of incentives to the private sector firms responsible for the build-out of enabling infrastructure, and to develop a plan to avoid these problems being repeated.

3.5 mRNA Vaccines

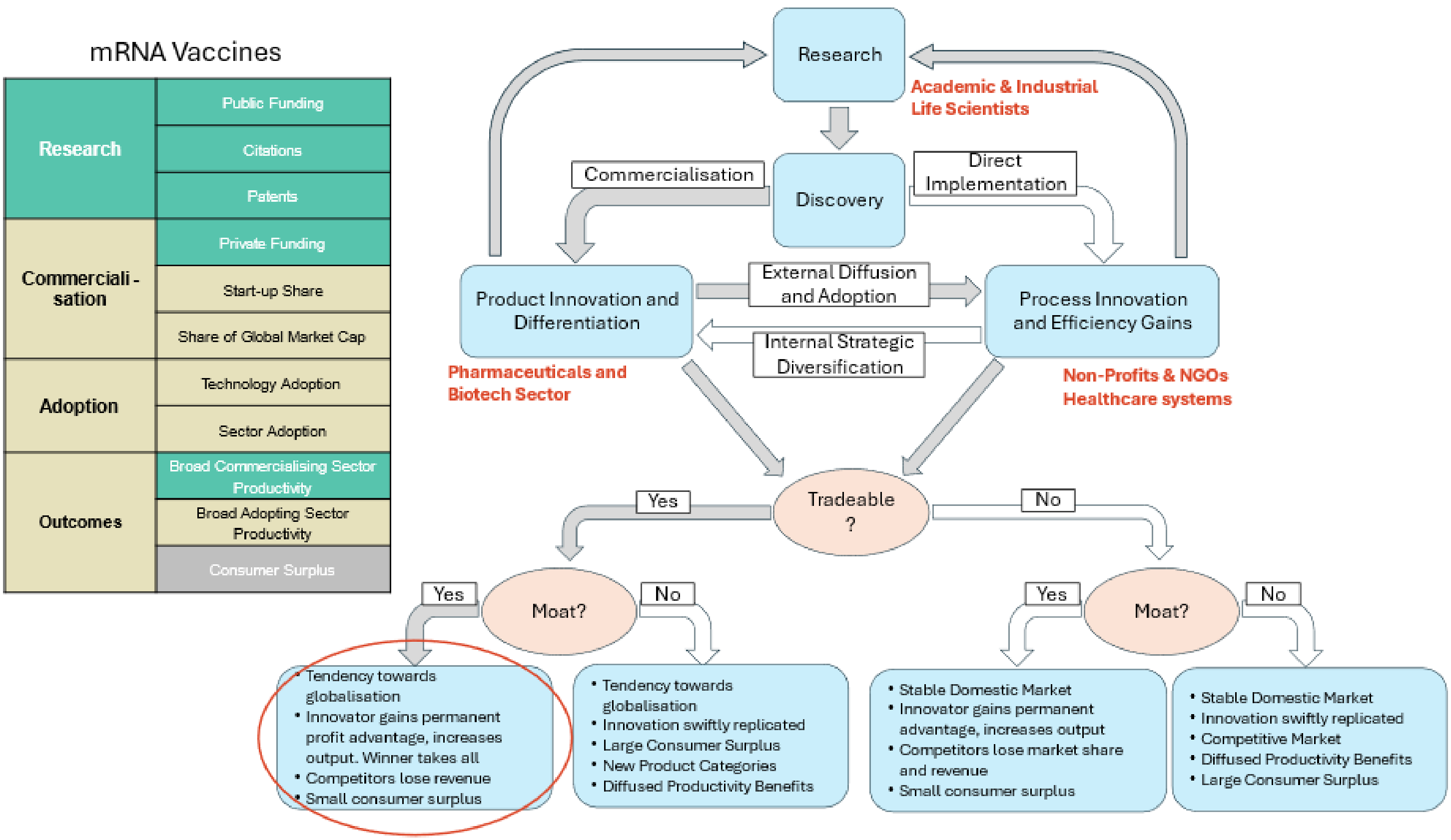
Messenger RNA (mRNA) is a type of single-stranded ribonucleic acid that is transcribed from a strand of DNA, which carries the coding information for protein synthesis to be further transcribed and processed into functional proteins (Qin et al. 2022). When used in vaccines, mRNA delivers the instructions to the "protein factories" of our cells for making a harmless piece of protein identical to one found in a particular virus or bacterium (UKHSA 2024b). Once the instructions have been decoded and the protein assembled, our immune system recognises it as a foreign body and starts to produce antibodies that can attack the protein if it encounters it again in the form of the "real" virus.

mRNA has been extensively explored since 1989 as a potential therapeutic agent for various diseases, but only recently has it become mature enough for use against SARS-CoV-2. mRNA vaccines have demonstrated many specific advantages that conventional vaccines do not have. The most significant advances using mRNA approaches will be the development of new vaccines and therapies that will predominantly be commercialised by large pharmaceutical firms. UK firms are at the forefront of research, discovery, and development and are likely to remain globally competitive.

Research infrastructure and output in the UK is relatively strong. UK researchers generate 5% of global citations in this field and nearly 5% of patents. With the aim of ensuring that the UK has early access to effective vaccines, the UK Health Security Agency (UKHSA) created the Vaccine Development and Evaluation Centre (VDEC). This centre targets the deadliest pathogens with pandemic potential, to help find, develop, and evaluate new vaccines and treatments where none exist, or improve those that do (UKHSA 2024b). On the other hand, as part of a ten-year strategic partnership with the UKHSA, Moderna are building a new mRNA research, development, and manufacturing facility at Harwell, and has committed to substantial funding to UK-based R&D activities, with the potential to develop vaccines targeting a range of infectious diseases (UKHSA 2024a).

Figure 3.5.1 shows the mRNA vaccines knowledge chain. The mRNA vaccines knowledge chains mirrors the pattern of the pharmaceutical sector more broadly, which is one of a combined private/public research effort leading into primarily private sector commercialisation, and then public sector–led adoption.

Figure 3.5.1: mRNA vaccines knowledge chain and RAG chart



The success of COVID-19 mRNA vaccines has awoken a new interest in these technologies to address other diseases. Currently, a team led by UCL, King's College London, and Moderna has created an effective therapy for a rare genetic liver disease, known as argininosuccinic aciduria, in a study in mice, demonstrating the technology's potential therapeutic use in people (UCL 2024). Moderna is developing mRNA vaccines for various diseases, including RSV (respiratory syncytial virus), HIV, Zika, Epstein–Barr virus, and more. Similarly, BioNTech is working on vaccines for tuberculosis, malaria, HIV, shingles, and flu. Both companies are also focusing on cancer treatments (Hamzelou 2023).

Additionally, numerous laboratories are testing more thermostable formulations of mRNA vaccines, which currently require storage at freezing or ultra-cold temperatures. Researchers are also investigating second-generation vaccines that will need only a single shot, and "universal" coronavirus vaccines capable of protecting against future emerging strains. Furthermore, the development of mRNA vaccines targeting a broad range of diseases in one shot is underway; this approach could significantly simplify current vaccination schedules (Gupta 2021).

The technology behind mRNA vaccines allows for faster development and production compared with traditional vaccines, because they do not need "dedicated cell culture–based and/or fermentation-based production of weakened or killed versions of pathogens, inactivated toxins, or partial subunits of the pathogen" (Moderna Therapeutics 2017). In addition, there are productivity impacts related to the adoption of the vaccines, such as preventing severe illness, which helps reduce the number of sick days taken by employees, and reducing the burden of COVID-19, which contributes to a more efficient healthcare system (Odihi et al.2020).

More broadly, the benefits of vaccination to human health are much wider and more important than the narrow lens of a productivity impact. However, a healthy workforce is a prerequisite of a productive economy. Although it is hard to directly identify the productivity benefits of vaccination, we know that vaccines are estimated to prevent almost six million deaths per year (Rodrigues & Plotkin 2020). Studies suggest that every dollar invested in immunisation programmes in 94 low- and middle-income countries over the next decade will return more than US$52 by lowering treatment costs, boosting productivity, and reducing long-term disability (WHO 2021). If mRNA vaccines were able to prevent the spread of diseases such as those mentioned above, they would have a substantial long-term economic impact on the most directly affected nations.

The immediate role for the UK is likely to be less one of adoption (as the UK is not one of those nations directly impacted by the diseases mRNA vaccines are most likely to be deployed against) and more one of development and commercialisation, whether this is through partnership with a handful of major multinational corporations such as Moderna, or by supporting the growth of the wider spin-out, start-up, and scale-up community.

3.6 Agricultural Gene Editing

The study of the role of genetics in plant breeding emerged in the early to mid-19th century with the work of Gregor Johann Mendel in what is now the Czech Republic (Stenseth, Andersson & Hoekstra 2022). Scientific breeding replaced trial and error approaches (empirical breeding) and prompted the development of ever more sophisticated techniques to understand gene complexes and polygenes, such as biometrical, or mathematically informed, genetics. By the 1960s, scientific approaches to plant breeding were partly responsible for the Green Revolution, which increased crop yields and supported important socioeconomic advances worldwide (FAO 2022).

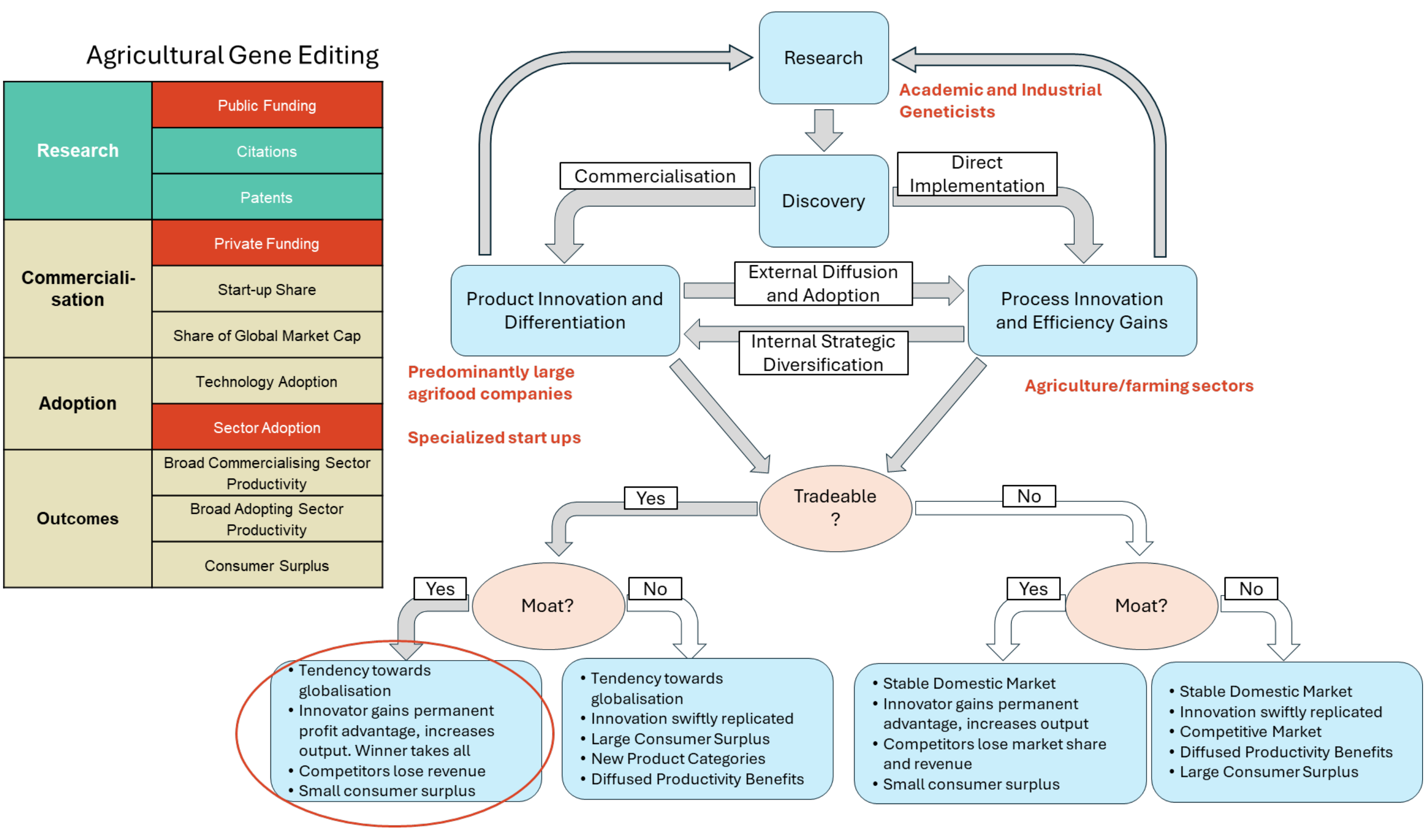
Developments in the understanding of genetic processes at the molecular level supplied plant and animal breeders with a range of new tools. Selection was no longer limited to selecting among phenotypes, based on how the material looked or behaved, but could happen at the genotype level, by examining which gene sequences were present or absent. Gene editing currently permitted in the UK (precision breeding) involves changing DNA in a targeted way, without adding new genetic sequences or genes (Genetic Technology (Precision Breeding) Act 2023). With this technology, specific genes can be removed, switched off, or "edited" with precise changes at a specific location in the genome. This enables similar but more efficient outcomes as traditional breeding, which can reduce the time it takes to bring new crop innovations to market (POST 2022).

The governance of research into and use of new genomic techniques in plant breeding remains contentious in the UK. In 2018, the European Court of Justice ruled that organisms obtained through directed mutagenesis would fall under the scope of existing legislation (2001/18/EC). The UK incorporated this stance into domestic legislation covering the definition and use of genetically modified (GM) crops. The UK's decision to leave the EU coincided with emerging debates about the suitability of regulations and the potential to introduce exclusions in cases where modifications could have been achieved naturally or through conventional breeding (Menary & Fuller 2024). In 2021, the UK initiated a period of stakeholder consultation and study, which culminated in the passage of the Genetic Technology (Precision Breeding) Act 2023 (Defra 2023), which officially exempted precision-bred organisms and products from more restrictive regulations on GM organisms. Among other things, this reduced barriers to research and commercialisation.

The restrictive regulatory environment that existed until 2023 dampened but did not completely stifle the development of UK-based research in agricultural gene editing – although observers note that countries with more permissive legislation retain a competitive advantage in research, commercialisation, and adoption of products developed using these techniques. The UK's recent legislative changes and the ascendence of engineering biology as a "critical technology" in current innovation policy are creating new opportunities to innovate across the knowledge chain. Most research being conducted in the UK has the potential to be applied in the UK but will likely be adopted first and at greater scale by companies based in other markets, such as the US.

Figure 3.6.1 shows the agricultural gene editing knowledge chain. This globally integrated industry is dominated by a small number of major multinational corporations. Due to historically stringent regulations, the UK's role has been limited to high-level research activity as many advances are patented and commercialised in more permissive jurisdictions elsewhere. This is reflected in data that show that, while the UK generates 7.3% of citations (3rd globally), it has only 3.6% of patents (6th globally).

Figure 3.6.1: Agricultural gene editing knowledge chain and RAG chart



The UK's leading plant scientists and expertise in commercial crop breeding mean it is well positioned to realise benefits. However, discoveries made by UK scientists have to date been more effectively commercialised outside the UK (Jones 2023). For instance, the first genetically modified plant approved in the US under its new framework – the "purple tomato" developed using genes from the snapdragon plant – was developed by UK researchers at the John Innes Centre, Norwich (John Innes Centre 2022). Genes for late blight resistance in potatoes, identified by the Sainsbury Laboratory, have been commercialised in the US by Simplot and could reduce fungicide spraying of potato crops if authorised in the UK. Camelina sativa oilseeds, first developed by Rothamsted Research to be enriched with long chain omega-3 fatty acids, are currently being prepared for commercial release in the US in collaboration with Yield10 Bioscience (Rothamsted Research 2024).

GM crops are now being grown in over 27 countries with more than 90% of corn, upland cotton, and soybeans grown in the US characterised as having GM traits (Economic Research Service US Department of Agriculture 2023). Recent regulatory changes have created new opportunities for research commercialisation, but these are still in the early stages and high barriers remain to bringing crops to market. The Genetic Technology (Precision Breeding) Act left GM crops under a regulatory regime inherited from the EU, which requires extensive scientific and safety trials. Satisfying these requirements is so expensive that only the largest companies can achieve regulatory approval. While research happens in both private and publicly funded labs, successful commercialisation is most likely to happen in partnership with large (often multinational) agrifood companies.

Gene editing is seen as an important tool in ensuring the resilience of the food supply to climate change, increasing yields, and improving nutritional content, all of which have direct productivity and consumer surplus benefits. Only a small proportion of agrifood businesses can directly modify their own crops; however, once a successful modification is developed, the new seed can in theory be distributed across the entire industry. Careful regulation is required here.

There are two main opportunities for greater value capture in the UK: firstly, greater adoption of existing and emerging gene editing techniques and gene-edited crops and animals to ensure reduced emissions, greater climate resilience, greater yields on small agricultural footprints, and improved domestic food security; and, secondly, better commercialisation of research being done in the UK, to capture more value of what is a growing global market. This will most likely be done in partnership with one of the major agrifood multinational corporations that dominate this field.

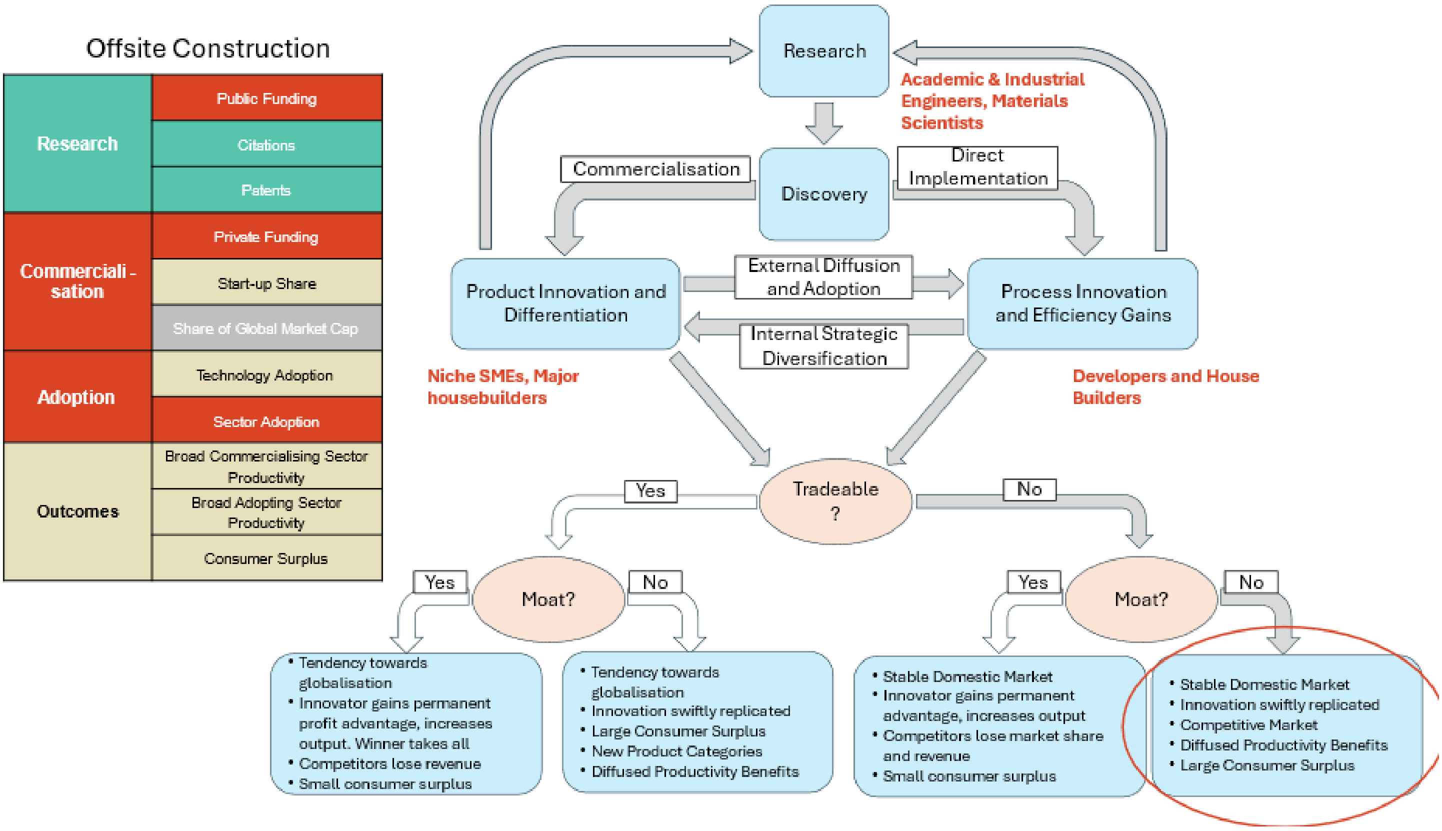
3.7 Offsite Construction

Offsite construction methods, also known as modular or prefabricated construction, involve the manufacturing of building components in a controlled factory environment before transporting them to the construction site for assembly. The concept dates back centuries, with early examples found in medieval Europe. During World War I, the urgent need for rapid construction drove the development of temporary prefabricated housing for soldiers and munitions workers. In response, the UK government commissioned the production of thousands of prefabricated homes, often called “homes for heroes”. These homes were manufactured in factories and swiftly assembled on site, providing essential housing for war workers and returning veterans (Offsite Guide n.dThis .). Following World War II, the government sponsored large-scale prefabricated housing programmes, such as the “Prefab Houses” or “Airey Houses”. These dwellings were manufactured off site and transported to their final locations for assembly (Offsite Guide n.d.).

Modular housing offers several benefits: faster construction times, higher-quality fabrication, safer working conditions, improved material efficiency, reduced waste, and less disruption for residents. Additionally, it requires fewer labour resources and minimises onsite reworking (Maslova, Holmes & Burgess 2021). The non-tradeable nature of the construction sector, and the way in which different domestic markets operate largely independently, has meant that different nations have developed their own offsite construction methods largely independent of one another. This has two implications: firstly, a wide variety in the extent to which these technologies are implemented and adopted across different national markets; and, secondly, a tendency towards *process* rather than *product* innovation. Offsite construction technologies tend to be developed and implemented in house by existing construction firms, rather than commercialised and sold as products to the industry by a separate group of (potentially global) upstream innovators.

Figure 3.7.1 shows the offsite construction knowledge chain. We characterise offsite construction as a competitive non-tradeable sector with high replicability. Research and patenting activity is relatively strong despite weaker public investment. However other barriers to adoption need to be addressed in order to maximise industry productivity and consumer surplus.

Figure 3.7.1: Offsite construction knowledge chain and RAG chart



A report by Glenigan (2020) identified a gradual rise in the proportion of projects utilising modern methods of construction (which includes offsite construction). Their research identifies that around 9% of UK new-build projects starting in 2017 employed modern methods of construction (MMC) in some way, which rose to 16% in 2023. In addition, the report argues that the take-up of offsite construction has been especially strong for new-build projects: it was utilised in 7% of new-build projects that started during the first nine months of 2023 (Wilen 2024). A report by the Cambridge Centre for Housing & Planning Research (Maslova et al. 2021) highlights the significant shortfall in home-building rates, which meet only half of the 300,000 homes needed annually, and considers MMC, including offsite manufacturing and building information modelling (BIM), as key solutions. However, the report also acknowledges risks and challenges, including the industry's slow adoption of these innovations. Barriers such as financial constraints, regulatory hurdles, and a lack of skilled workforce are significant obstacles (Maslova, Holmes & Burgess 2021).

The 2023 NBS Digital Construction Survey (quoted in Wilen 2024) found that 57% of respondents had been part of a project that involved an element of offsite construction. Respondents argued that the most common type of offsite construction was for subassemblies and accessories, which includes roof trusses, staircases, door sets, precast concrete beams, and prefabricated dormers. The other forms of offsite construction involve more substantial parts of a building or asset. These include flat-packed panels, such as structural insulated panels (e.g., insulation between timber panels). Panellised systems can be timber framed or steel framed. These systems can include services such as electrical sockets and water feed pipes. Over half of the survey respondents (52%) told NBS that they were involved in projects using panellised systems.

The Royal Academy of Engineering (2018) also notes that offsite modular construction (OMC) goes against many conventions in the UK construction industry, including introducing different and unfamiliar risk profiles and balances of liabilities between design, manufacturing, and construction. Fragmentation in the industry also reduces potential for learning lessons in this space, making it slow to change. The shift to OMC also requires a high level of collaboration in what is traditionally a competitive and low-margin industry. The report also notes that regulatory hurdles exist around procurement and payment, local procurement codes, and transport limits. Reskilling is also needed.

The productivity impact on the construction industry of more widespread adoption of OMC techniques would be substantial. In a competitive market, much of the benefit would be captured by consumers through a reduction in the cost of new-build houses, rather than driving up the productivity of the construction sector. It is likely that in reality the outcome would be a mixture of both.

The Royal Academy of Engineering (2018) identifies that the benefits of greater use of offsite manufacturing would be lower construction costs and new-build prices, improved productivity in the construction sector, reduced emissions, improved sectoral health and safety, and the greater and faster provision of new housing. Barriers to adoption that must be overcome are identified as being around sectoral coordination and procurement – including reskilling workforces, piecemeal procurement, valuation procedures, planning regulations, and the capital-intensive nature of offsite methods in the face of the cyclical nature of the housing market.

As a major component of household consumption, even small improvements to housing costs would carry substantial consumer surplus benefits. However, the reasons for slow adoption of OMC methods appear to be institutional, rather than technological. High fixed capital costs and high transport costs combined with a cyclical housing market and geographically dispersed development opportunities leave OMC firms vulnerable to an economic downturn. Indeed, the last few years have seen prominent examples of OMC projects and firms going bankrupt. This could be addressed by the government through a combination of countercyclical procurement (to de-risk capital investment by ensuring stability of demand) and land assembly and long-term planning intervention (to ensure the benefits of OMC methods are not simply lost to transport costs). The proposed new towns programme could be a viable opportunity to explore the large-scale application of OMC technologies – it would make a lot of economic sense if the first step in any major multiyear new town or urban extension construction project was the construction of an “onsite offsite” modular construction facility.

3.8 Industrial Robotics

A robot is a reprogrammable, multifunctional manipulator designed to move materials, parts, tools, or specialised devices through various programmed motions to perform a variety of tasks. Robots have a variety of uses in substituting and complementing physical human labour across a wide range of industries, from the primary sector, through manufacturing, to transport and logistics.

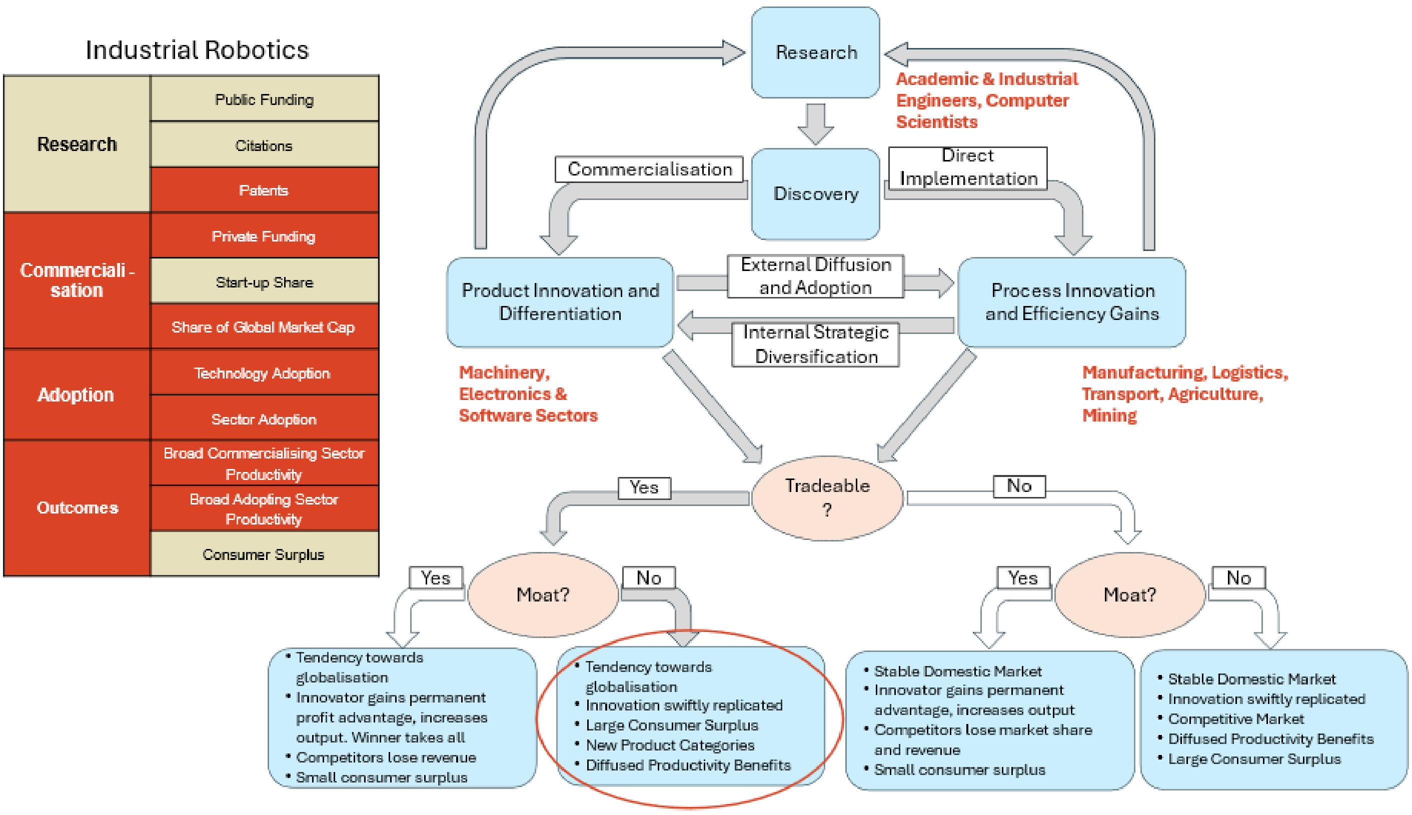
The first industrial robots were introduced in the 1950s and became widespread from the 1980s onwards. During the late 1960s and early 1970s, the focus of industrial robotics shifted away from heavy lifting to materials handling and precision work. By the late 1970s, the capabilities of robots expanded even further to include tasks such as material transferring, painting, and arc welding (Misiti 2020). Since the early 2000s, developments in industrial robotics have largely been driven by advancements in software. Emerging fields, such as machine learning and AI, are now pushing forward the frontier of what robots can do – giving them the ability to learn, improve, and make decisions without direction or guidance from humans. Collaborative robots ("cobots") are a new type of robot designed to safely operate in close proximity or direct contact with humans. They utilise advanced technology, including force-limited joints and computer vision to detect the presence of humans in their environment. Cobots are often much smaller and lighter than traditional industrial robots, easily moveable, and trainable to perform specific tasks (Misiti 2020). Other emerging types of robots currently being developed, commercialised, and adopted across the world include autonomous mobile robots, for example observation drones and delivery bots, and robots with finer motor controls able to carry out more precise tasks in "hard to automate" industries, for example textile assembly and fruit picking.

Industrial robotics are designed specifically for application in production systems. As such, a robust robotics sector produces modular, customisable, and/or bespoke units for specific industrial applications. Some manufacturing firms also have in-house robotics R&D departments and develop machinery to spec for their own production processes.

Reports claim industrial robotics is transforming multiple industries by boosting efficiency, precision, and safety. In automobile assembly, robots manage tasks like spot welding, painting, and material handling. In electronics manufacturing, they perform precision soldering, microchip fabrication, and product testing. Robots also streamline packaging by boxing products and organising pallets. In the pharmaceutical sector, they ensure accurate dispensing, sorting, and packaging of medications. Food and beverage processing benefits from robotic sorting, packing, and inspection. Furthermore, logistics, inspection, machining, cleaning, casting, and finishing tasks are increasingly optimised by robotic solutions. (Standard Bots 2024).

Figure 3.8.1 shows the industrial robotics knowledge chain. We characterise the global robotics market as a competitive, globally integrated market that provides widespread productivity and consumer surplus benefits.

Figure 3.8.1: Industrial robotics knowledge chain and RAG chart



The adoption of technologies like industrial robots, combined with AI, has proven to enhance productivity at both individual firm and broader economic levels. These technologies enable more precise work, reduce production costs, and improve operational efficiency. Robots outperform humans in speed and accuracy, while AI helps predict production issues and enhances computational capabilities. For instance, firms in Indonesia that employ industrial robots report 49% higher productivity than non-automating counterparts. Globally, adopting robots and AI leads to increased output, higher productivity, and greater export shares with diverse, high-quality products (Ing 2023).

However, UK manufacturing *severely* lags in global adoption of industrial robotics systems. The UK has one of the lowest robot densities among major industrialised nations. This is something of a mystery. The UK has approximately 101 robots per 10,000 employees, which is below the world average of 126 (International Federation of Robotics 2023). More recent data suggests the UK has fallen further to 98 robots per 10,000 workers (Industrial Compliance 2024). A report by The Economist notes that some industries in the UK have been more active at adopting this technology. The automotive industry in Britain has 734 robots for every 10,000 employees while Jaguar Land Rover's Solihull plant has over 615 high-tech robots (The Economist 2024). Automation is also being used extensively in logistics. But other industries continue to exhibit significantly lower adoption rates. MakeUK (2023) notes that most manufacturing firms spend less than 6% of their turnover on automation.

Lower levels of adoption might be attributable to a focus on short-term payback rather than longer-term total cost of ownership (TCO); a fear of or reluctance to change; outdated perceptions of engineering as a career that have resulted in skills shortages; a lack of government incentives; and/or cyclical demand and reliance on cheap manual labour (Industrial Compliance 2024). MakeUK (2023) notes that firms often lack the time and expertise needed to integrate or update robotics systems, as well as access to finance and skills that would permit smooth and timely adoption. The Economist (2024) additionally cites small average firm size as a significant barrier to adoption given the high fixed costs of machinery. It notes that firms have failed to take advantage of incentive schemes in large numbers suggesting that barriers to adoption may be multifaceted. However, it also predicts that adoption may rise as costs continue to fall.

A UK government report (DSIT 2021) suggested that robotics and autonomous systems (RAS) have the potential to bring about significant economic impacts: the annual global economic impact of advanced robotics is estimated to lie between US$1.7 trillion and $4.5 trillion per annum by 2025 (McKinsey, 2013). According to more recent estimates, boosting robot installations 30% above the baseline could add an extra $4.9 trillion per year to the global economy by 2030 (Oxford Economics 2019). While estimates of future impacts are naturally surrounded by significant uncertainty, these figures highlight the magnitude of the potential RAS opportunity (BEIS 2021). A study by Copenhagen Business School has estimated that Japan-like levels of automation would boost Britain’s productivity by over a fifth (Kroman et al.2019).

The UK government recognises the importance of RAS in driving economic growth and innovation. In recent years, there has been a concerted effort to create a supportive policy and regulatory environment for the adoption of industrial robotics. To support the adoption of robotics, the UK government has introduced several initiatives and funding programmes. For instance, the Industrial Strategy Challenge Fund (ISCF) provides funding for projects that aim to develop and deploy innovative robotic technologies (UKRI & BEIS 2021). In addition, the Regulatory Horizons Council (2023) has suggested policies to increase the adoption of robotics in the agriculture and horticulture sector. Aerospace automation specialist Loop Technology has signed a deal for seven Fanuc industrial robots, including four of the largest ever ordered in the UK, as part of a new aerospace project looking to solve composite manufacturing challenges (Weaver 2024). UKRI’s Made Smarter Innovation (MSI) Challenge, delivered by Innovate UK, the Engineering and Physical Sciences Research Council, and the Economic and Social Research Council, has awarded grants to 11 late-stage robotics and automation projects. The projects have a focus on developing solutions to improve productivity, sustainability, and resilience within the factory production area (UKRI 2024).

The UK’s low level of adoption of the general purpose technology of robotics and resulting poor productivity outcomes are extremely unfortunate. The nature of the tradeable goods that high-adopting international firms produce means that UK residents still benefit from robot deployment elsewhere in the world through consumer surplus. However, UK firms in a variety of sectors, from agriculture to transport, logistics to manufacturing, are missing out on one of the significant technological drivers of efficiency and productivity improvements, both now and for a considerable distance into the future. Urgent action must be taken to increase the domestic adoption rate.

3.9 Modern Supply Side Economics

Modern supply side economics (MSSE) is a new term for a set of economic policy ideas with a much longer pedigree, exploring the optimum level and nature of strategic government intervention into the supply side of the economy – ensuring that the right factors, including physical and human capital, shared resources, ideas, and regulations, are in place to enable greater and greater efficiency and productivity over time. These ideas include industrial strategy, infrastructure provision, market making, and smart regulation, as well as inclusive and sustainable growth policies.

Historically, these ideas around strategic government intervention might be contrasted with traditional Keynesianism, with which they are complementary, but which focuses less on directly intervening in the supply side of the economy, and instead on the government's role in growing and stabilising economic demand from year to year. *Modern* supply side economics also contrasts with *neoclassical* supply side economics, which also focuses on the supply side, but instead of promoting strategic intervention, advocates for reducing the size of the state through deregulation and low taxation.

While neoclassical supply side economics relies on creating the incentives and removing impediments for the market to increase productive capacity, the modern supply-side supports government action to increase long-run economic output (per capita) by expanding labour supply, human capital, public infrastructure, research, and development in a sustainable environment. (US Treasury 2022)

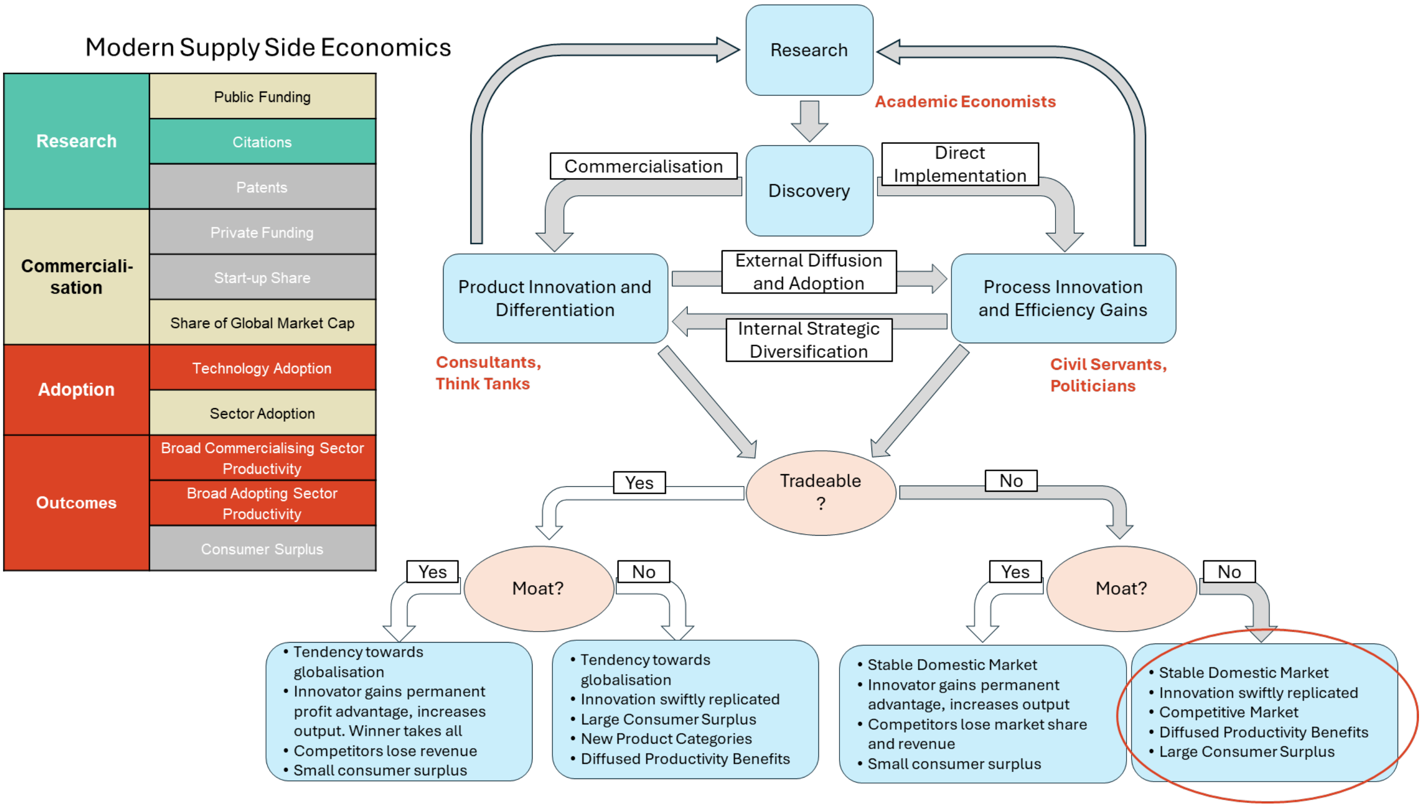
These three broad sets of ideas have been debated for many decades, with different national governments taking different approaches at different points in their history. The ideas underpinning MSSE have been applied by many countries over the centuries, including in the early years of US independence under Hamilton, as well as the New Deal years under Roosevelt, and most recently with "Bidenomics". Successful examples of government interventionalist industrial strategy can also be seen in the rapid industrialisation and economic growth of East Asian economies, particularly South Korea and Taiwan, during the latter half of the 20th century. These countries implemented policies that protected and nurtured key industries, invested heavily in education and infrastructure, and coordinated efforts between public and private sectors. These strategies helped them transform from low-income to high-income economies within a few decades.

Within the UK, policies aligned with MSSE were most prominently applied during the period after World War II, between 1945 and 1971, and more recently by New Labour between 1997 and 2005 – then-chancellor Gordon Brown famously referred to the conceptually adjacent idea of endogenous growth theory. However, they have not been adopted with any consistency by any government of the past decade, and diffusion and promotion of these ideas among the economic consultancy and think tank community remains inconsistent. After the elections of 2024 and subsequent change in government, there is potentially a policy window for MSSE ideas to be more thoroughly reintroduced to policy making in the UK.

The new Chancellor of the Exchequer, Rachel Reeves, has expressed her interest in tailoring a modern supply side approach to Britain. In this sense, the Labour party has prepared the Green Prosperity Plan, which "will see the state make public investments in industries that are vital to Britain's future success, paving the way for significant further private investment. To make sure this delivers for British workers, as well as British businesses, policies that encourage investment will include minimum standards to ensure that well-paid and secure jobs are created as a result" (Wolf 2023).

Figure 3.9.1 shows the MSSE knowledge chain. The UK is a leading research hub for progressive economic policy ideas; however, these are not implemented consistently by government – this inconsistency may be partially behind the disappointing policy outcomes the country has experienced.

Figure 3.9.1: Modern supply side economics knowledge chain and RAG chart



Ideas for economic policy approaches tend to originate within academia, before being picked up directly by politicians and civil servants. Much academic work is focused on disseminating and communicating robust evidence, findings, and policy ideas to the policy community, both directly to the civil service and indirectly via the wider discourse community. UK academic fora, for example the Industrial Strategy Council, The Productivity Institute, and previously the Productivity Insights Network, have done valuable work exploring the evidence-based case for implementing a variety of progressive supply side initiatives with the intention of improving the UK's economy.

To the extent that policy ideas are commercialised, it is often by the plethora of economic consultants and think tanks that dot the policy discourse landscape. The data we have collected would suggest that the UK has a particularly large number of think tanks and consultancies in general, and a brief inspection of the outputs of these bodies reveals that many of them do indeed promote what could be described as MSSE concepts (even if this terminology is not consistently used).

The question, therefore, is how it is that such a successful research base and large and active think tank community results in such disappointing policy outcomes. One explanation is the slow uptake of new ideas. Work by Richard Nelson and Sidney Winter identifies the importance of *legitimisation* in facilitating the adoption of different ideas, policies, and business models. This suggests that even if a new idea, policy, or model is demonstrably an improvement on previous iterations – for example, if it produces superior outcomes everywhere it has been utilised – it will only be accepted or adopted once it is seen as "legitimate" by the majority of actors, leading to a form of technological or ideological "lock-in" until that point is reached (Nelson & Winter, 1982). Although their work focuses on private sector firms, it is also relevant to the public sector. It may be that the UK policy community is slow to recognise any new idea as being legitimate until the evidence becomes overwhelming, leading to a large (and undesirable) time-lag between the development of new policy approaches and their implementation.

This would also explain the substantial mismatch between the policy ideas being discussed within the academic research community and those being promoted by the think tank community. While many think tanks draw on recent academic work for their inspiration, others look back further in time to ideas that many current academics would describe as outdated.[10] The conveyor belt of evidence-based policy ideas from independent academic research through to policy makers can therefore get confused, making it both harder for policy makers to identify the right policy actions and less likely that those ideas are fully legitimised as swiftly as they otherwise might be.

There is a final caveat: think tanks and other policy advocacy groups, especially those that are not academic, or that are less transparently funded, often have strongly ideological leanings. Ideology can trump evidence for groups that want the government to act in specific ways to fulfil a partisan or political agenda. One measure of success for think tanks is whether the government picks up and implements their recommendations, so these groups may try to mirror the economic thinking of the government of the day, regardless of the extent to which the evidence base supports that thinking. Thus, the actors involved in disseminating the fruits of economic research (think tanks and others) are not always incentivised to provide the newest, most evidenced, or best advice.

3.10 Innovative Galleries

Galleries, museums, and exhibition spaces are engaging in innovation by introducing new practices and technologies to enhance visitor experiences. These innovations include experiments with ticketing and admissions, websites and information systems, gallery layouts, lighting, documentation, interactivity, audiovisual components, composition, and display of collections. Recently, the adoption of advanced digital technologies has transformed what is possible in exhibition spaces.

The most prominent examples of innovation in galleries are often the adoption of cutting-edge visual and interactive technologies – for example, augmented reality (AR) and virtual reality (VR), 360 projection technology, interactive displays, and digital offerings that allow people to explore collections remotely. VR and immersive interactions transform the experience of an exhibition from observation to participation to emotional engagement. An entire subfield of audiovisual and interactive technologies has emerged to design, customise, build, and operate displays.

AI is also opening up new possibilities at the intersection of digital technologies. In 2022 the Louvre introduced "Leonardo", an AI-driven virtual assistant. The Smithsonian Museum is employing AI-powered humanoid robots to answer visitor questions and tell stories using voice, gestures, and interactive screens. This technology is also being used to curate art, generate descriptions of artwork and collections, predict and enhance navigation, and understand user experiences using facial and sentiment analysis (Nelson 2024; Ratten 2024).

The gallery and museum sector is one in which scholarly research is not as significant a

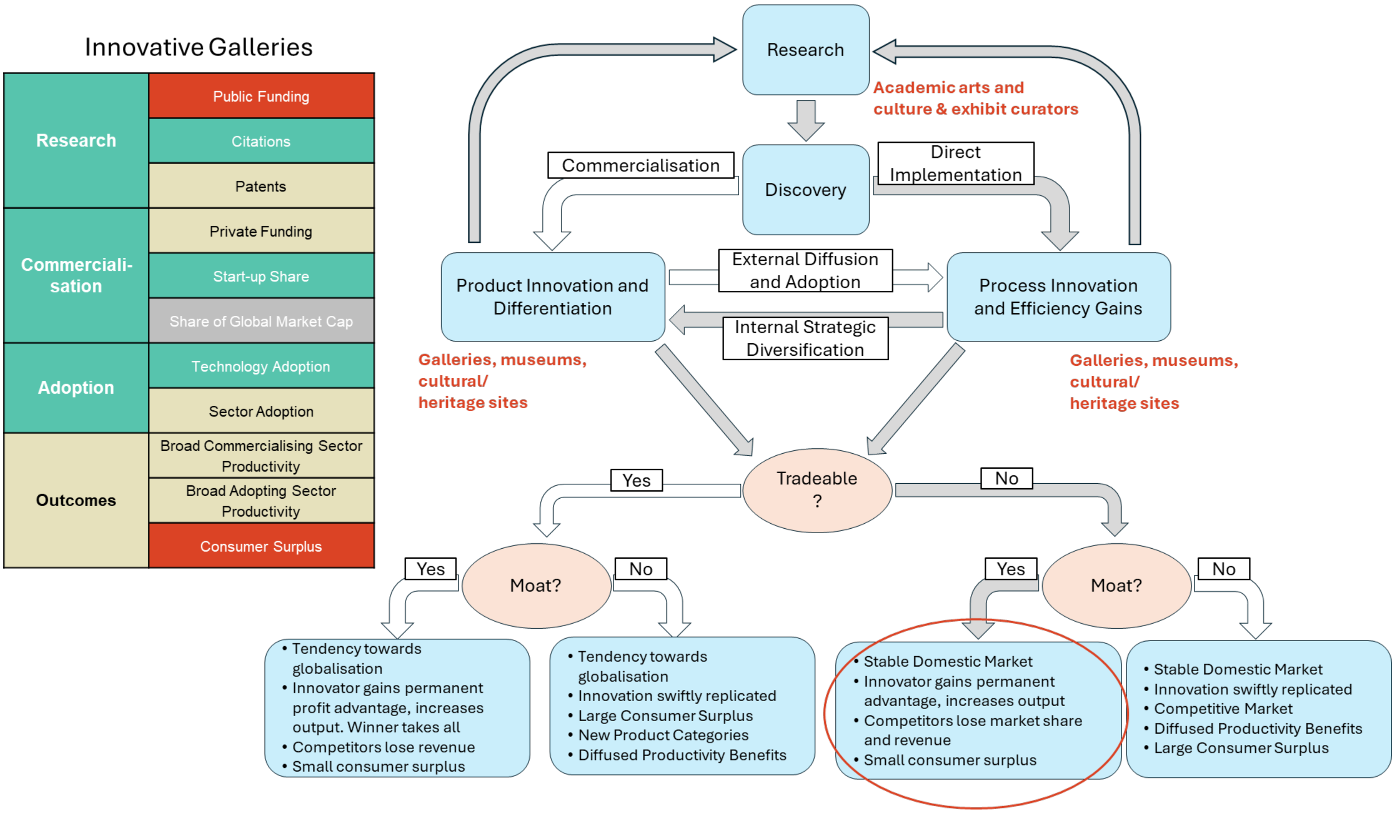
[10] One recent example would be the prominent Foundations essay which advocates for a neoclassical supply side approach of deregulation in answer to the UK's problems, written by fellows of think tanks Policy Exchange, the Centre for Policy Studies, and the Adam Smith Institute. Despite the claims of this paper being rapidly debunked by academic and professional experts (Edgerton 2024), its mixed reception in policy circles demonstrated that it had the effect of muddying the policy waters.

driver of technology and where more innovations are developed in practice. However, the intensification of digitalisation has added new innovation pathways for cultural institutions that have their origin in academic and industrial R&D. For instance, the University of Southampton has developed a VR experience designed to bring art exhibitions from around the world directly to users. The VR experience aims to make art more accessible to those who face barriers such as financial constraints or mobility issues, allowing them to interact with exhibitions online. The University of Birmingham Immersive Audience Report (Immersive Experience Network 2024) highlights that immersive experiences attract younger and more diverse audiences compared with traditional arts and culture. This research is crucial for developing strategies to engage broader audiences and enhance the cultural impact of immersive art.

Academic research on museology and related topics is strong with the UK ranking 2nd (behind the US) with 11% of citations. It performs less well on patents (3.2% of patents, 6th globally). This could be explained by the relative youth (average firm age only 12 years) and small size (70 firms) of the industry.

Figure 3.10.1 shows the innovative galleries knowledge chain. We characterise the innovative galleries market as being domestic, non-tradeable, extremely dilute, but with divergent levels of technology implementation and pricing power.

Figure 3.10.1: Innovative galleries knowledge chain and RAG chart



Galleries and exhibition spaces in the UK have been leading the way in experimenting with digital technologies. For example, Frameless London is one of the largest immersive art experiences in the UK, featuring digital interpretations of masterpieces by famous artists such as Klimt, Monet, and Rousseau. The exhibition uses motion sensors to change the artwork as visitors move through themed spaces, offering an engaging journey through different artistic styles and periods. The British Museum is a pioneer in integrating VR and mixed reality (MR) technology into its experiences; as early as 2015 it was offering visitors

3D VR tours of Bronze Age villages and sites. The museum also hosts virtual galleries, virtual tours, and audiovisual experiences designed for use on mobile devices.

In addition to these large-scale, innovative installations, there has been a gradual “digital turn” in museums and galleries that accelerated during the COVID-19 pandemic. Museums responded to the shock of the pandemic to their traditional business models by using various digital media and formats (e.g., websites, social media) – not necessarily groundbreaking technologies – to deliver their services and reach their audiences. Those institutions that were more digitally mature prior to the pandemic were in a stronger position to respond, and there are some concerns that a digital divide has emerged in the arts and cultural sector more broadly (Nikolaou 2024).

Many smaller organisations require support to get digital “basics” in place, either in improving infrastructure or in getting collections online (Cultural Associates Oxford 2021). Research has found that adding digital resources has improved attendance but not totally mitigated declines due to COVID-19. Adoption rates and profit outcomes differ substantially between institutions (based on size, prosperity, and location), many of which have had or are experiencing funding challenges (Nesta 2019; Kidd, Nieto McAvoy & Ostrowska 2022; UK Parliament 2022). Skills gaps across the sector – both on the technical side and in digital leadership – have constrained adoption. Notably, digital competence is perceived as being not just a technology issue, but a mindset for thinking about and doing things in ways that are different from, but complementary to, “physical” practice on site (Kidd, Nieto McAvoy & Ostrowska 2021).

Innovations in galleries and exhibition spaces have direct, but difficult to quantify, productivity impacts in increasing visitor numbers and diversifying audiences, sustaining higher ticket prices, and magnifying cultural impact. Productivity studies in the field of culture are based on Baumol and Bowen (1966), who argued that the production structure of cultural industries (in their case, the performing arts) limits their productivity because these industries involve factors that are indivisible and hard to replace, such that the rise in costs cannot be offset by significant gains in productivity. This approach has also been applied to other sectors, such as cultural heritage institutions, since these are also labour-intensive institutions that involve an intrinsic cultural capital that is unique and therefore irreplaceable. Studies of whether improvements triggered by technological changes could impact the productivity of these institutions have found very slight positive productivity impacts from digital technology adoption (del Barrio-Tellado & Herrero-Prieto 2022). Museums and other cultural institutions are also thought to have broader impacts on innovation by making proximate creative and cultural industries more creative through knowledge spillovers (Bakhshi & McVittie 2009; Nogare Dalle & Murzyn-Kupisz 2022). As soft location factors, they are also cited as talent attractors (that can drive innovation in other parts of the economy.

Zooming out, Domenech, Molina, and Köster (2023) estimate the impact of cultural and creative industries on per capita income of countries, regions, and municipalities. They find that average effects of these industries are positive in all territorial scales, in both low- and high-income locations, with highly and very highly developed places showing greater impacts. However, they found that these industries can also act as a double-edged sword, as they increase inequalities between places.

The UK’s adoption of these technologies has, on the whole, been impressive, and they have added to the UK’s visitor offer. However, deployment of this technology has been lumpy and primarily benefited major urban areas. As long as diffusion of the technology to a wider variety of museums and galleries remains limited, those that do adopt innovative approaches will maintain a position of monopolistic competitive advantage, and consumer surplus will be limited. Although there are actions that the government could take to try to disseminate innovative, interactive, and immersive technologies more widely across the cultural sector, it is unlikely that this would be an obvious priority for government intervention.

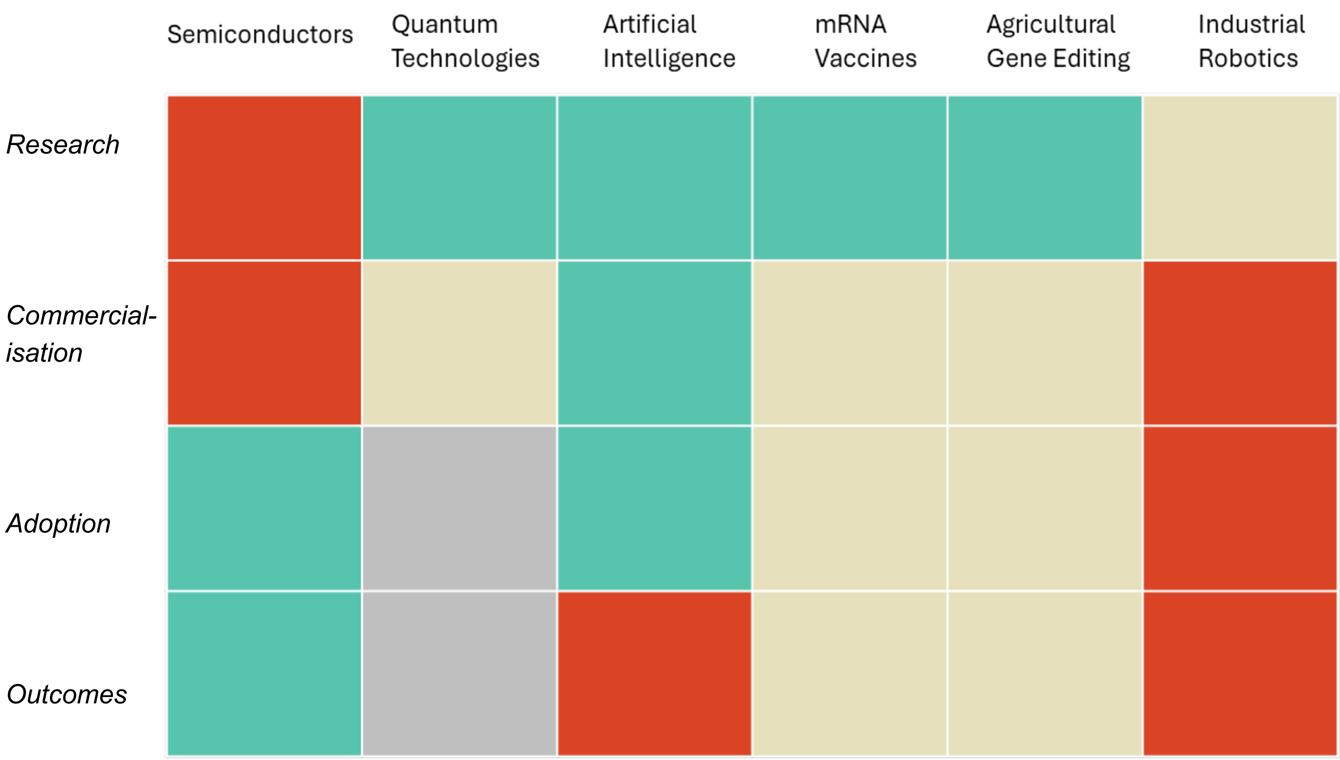
4. Conclusions

4.1 Cross-Cutting Observations

Having investigated each of our ten technologies in turn, we now take a step back to try to identify if there are any general conclusions we can draw from the trends and emerging patterns. In particular, we are interested in whether any evidence has emerged that either supports or falsifies our four key hypotheses identified in chapter 1. We begin by making some cross-cutting observations about the findings so far.

Six of the technologies we studied were in tradeable products – that is, technologies that underpin products that can readily be transmitted or transported across administrative and geographical boundaries. As we observed in the introduction, these product categories tend towards globally integrated supply chains and markets, in which value creation and value capture may occur in different countries and locations. For example, while much of the innovation value is created in the research and commercialisation stages, much of the deployment value is captured downstream in productivity benefits and consumer surplus as a result of technological adoption.

Figure 4.1.1: Overall pattern of performance in tradeable technologies. From top to bottom: research, commercialisation, adoption, outcomes



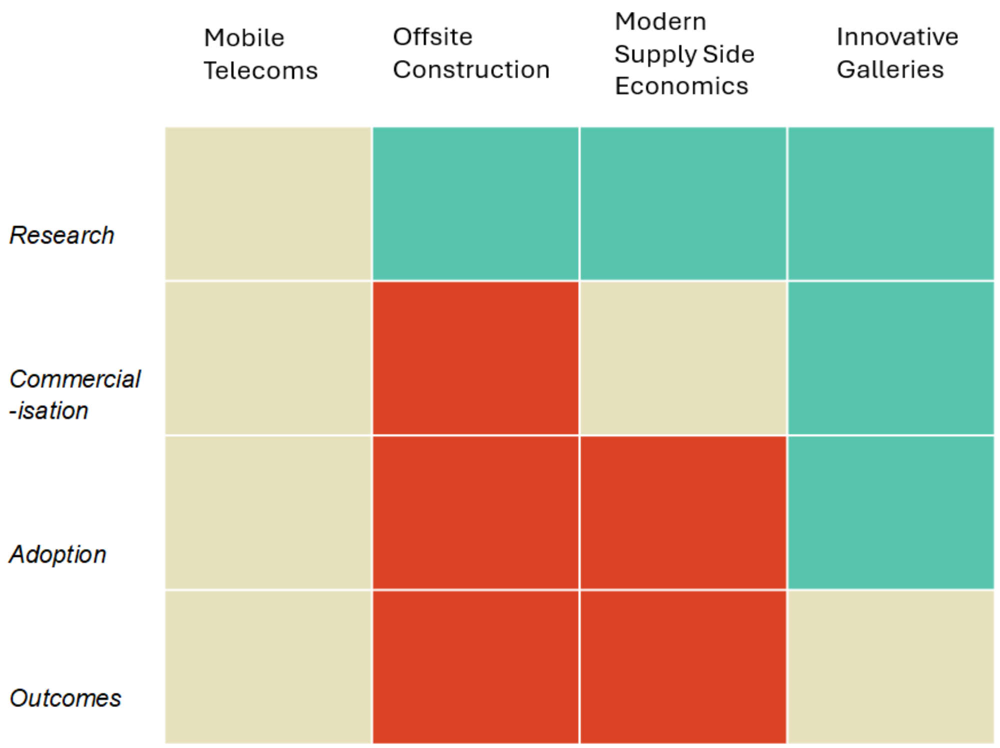
Our first observation is that the UK is a leading research nation in many of these technologies, but something of a laggard in terms of commercialisation, adoption, and economic outcomes. It is almost certain that the UK is more of a benefactor than a beneficiary in this global separation of value creation and value capture.

Of the technologies we identified above, we characterised two of them as being competitive, established global markets with high levels of productivity diffusion and consumer surplus; these are semiconductors and industrial robotics. There are still dominant global players in these markets; however, as highly successful general purpose technologies, there is enough "value" created to enrich actors at every stage of the knowledge chain. Here we find that high levels of adoption correlate with positive downstream economic outcomes. The UK has keenly adopted semiconductor-based devices and has therefore benefited; it has not, unfortunately, adopted the use of industrial robotics to the same degree, and has therefore not benefited.

Three technologies – AI, mRNA vaccines, and agricultural gene editing – we identified as being globally integrated markets currently dominated by a relatively small number of major multinational organisations with substantial market power. Productivity diffusion and consumer surplus are still very much possible in these industries; however, to date, much of the value is captured by these large commercialising firms, some of which are at least active, if not headquartered, in the UK. The UK is a world leader in biotechnology and genomics R&D and so should be benefiting more than we currently are from commercialising these emerging technologies in defensible markets.

The productivity benefits of AI adoption are still unclear: it is likely here that the key question is not "how much" but rather "what type" of AI should we encourage adoption of, with analytical AI potentially offering clearer productivity benefits than the higher-profile but perhaps overhyped benefits of generative AI. We also postulated that the lack of investment in AI-complementary technologies, for example robotic and autonomous technologies, or next-generation mobile communications, may be holding back the UK's ability to benefit from the full variety of AI innovations through the integration of AI with other emerging general purpose technologies. Quantum technologies are still broadly in their commercialisation and early adoption phase, and it is too early to tell what global market structure will emerge.

Figure 4.1.2: Overall pattern of performance in non-tradeable technologies. From top to bottom: research, commercialisation, adoption, outcomes



The remaining four technologies were related to non-tradeable product categories. Here we found that although there was substantial knowledge sharing and innovation transmission across space, these technologies were commercialised, implemented, and transmitted along UK-specific pathways. In many cases this resulted in an approach by existing market players that was led more by direction implementation and process innovation, where the appetite for technological development and adoption was a function of the specifics of the UK (rather than the global) market.

In this case, therefore, the flow of causality is reversed. Commercialisation and product innovation is driven by adoption and process innovation, which themselves are driven by market opportunities, which varied greatly depending on which technology we studied.

In the UK, we have seen the initially high levels of adoption and deployment of mobile technologies begin to fall behind in the past decade, with negative consequences for consumer surplus and productivity. This sluggishness needs to be urgently rectified if we are to benefit from the rollout of 6G mobile technologies. We have also seen high but uneven levels of adoption in the consumer-focused innovative galleries sector, where a number of UK galleries are world-leading, but knowledge and technology diffusion outside major cities has been weak, leading to the accumulation of market power by leading providers and limited consumer surplus. Technology adoption in offsite construction has been held back by wider structural market defects in the UK construction sector that could easily be remedied with a more interventionalist strategic approach to procurement and land assembly, whereas the implementation of MSSE policies and ideas has been held back by ideological issues both within government and beyond.

If the UK wishes to see greater innovation, productivity growth, and consumer surplus in these domestic non-tradeable markets, then it needs to focus on creating the right incentives to encourage adoption. The necessary knowledge in many cases already exists, and commercialisation of these insights will follow if the right commercial and regulatory incentives for adoption are in place.

4.2 Hypotheses

We now refer back to the hypotheses we drew out of the literature in chapter 1 of this report. We discuss the evidence for each of these in turn.

UK struggles to effectively commercialise its own research

Hypothesis: (UK specific) The UK does high-quality basic research but is less successful at commercialisation of these ideas through the full spin-off to scale-up process. This is because of a combination of a small domestic market and a deficit of key generic enabling factors, including entrepreneurial know-how, access to funding and skilled workers, and the necessary government support.

Evidence: There does seem to be evidence of a general pattern of high UK performance in patents and citations not translating into a prominent position in terms of leading global firms. In technologies that are most easily commercialised as tradeable products or services – for example semiconductors, mRNA vaccines, industrial robotics, and AI – while there are healthy numbers of smaller companies and start-ups, we found that the larger an innovative firm in these sectors becomes, the more likely it is to be acquired by a larger, foreign-owned multinational.

In those technologies specifically, the qualitative evidence for specific technologies did suggest that the UK's relatively small domestic market, made functionally smaller by our exit from the EU single market, seems to be partly responsible for this. In fast-growing, tradeable sectors with integrated global markets, firms often expand by acquiring firms in neighbouring markets, partly to access new markets, partly to consolidate and merge intellectual capital. Although there are exceptions, firms from larger domestic markets, such as the US, generally acquire firms from smaller domestic markets, such as the UK. In many cases, the activity remains in place; however, there are cases where, either immediately or after a period, the activity itself has been displaced to the larger market. Part of the innovation value captured may flow to workers in the form of wage premia.

Other barriers to commercialisation that were identified in our qualitative research that did support this hypothesis included a lack of access to skilled workers, lack of entrepreneurial support and know-how, and difficulties in obtaining scale-up finance, particularly outside the Greater South East.

UK lacks innovation absorption capability

Hypothesis: The UK economy has weaker innovation absorption capability due to a combination of low demand, low skills, low funding, knowledge domain mismatches with fundamental research specialisms, and a lack of industrial capability. This makes it difficult to either adopt new products or directly implement new ideas, whether produced in the UK or elsewhere.

Evidence: There were a number of technologies where the evidence supported this hypothesis, including offsite construction, industrial robotics, and agricultural gene editing:

- Reports into the lack of offsite manufacturing progress in the construction industry identified barriers around access to suitably skilled workers and risks of capital investment in an uncertain macroeconomic and unsupportive policy environment.
- The UK also has low levels of adoption of industrial robotics, despite clear international evidence as to the positive productivity impacts of this. Reports suggested that UK market structure means firms are less well-equipped to shoulder the costs associated with adoption; skill gaps also affect capability; and the dominance of small family firms increases reluctance to change.
- In agricultural gene editing, the pathways of commercialisation are less well-developed due to the regulatory regime; however, this is changing, and we can expect higher levels of both commercialisation and adoption to follow, although this is complicated by the concentrated structure of the global market.
- The same issues also explain the lack of widespread technology diffusion to the broader museum and gallery sector, leading to a frontier and laggard market structure.

We also found that low levels of adoption and low levels of commercialisation tended to correlate with one another, which appears to be the result of a bi-causal relationship. A lack of upstream commercial presence in certain technologies acts as a barrier to technological adoption, as commercial entities are incentivised to develop the market to diffuse their products. Similarly, if downstream firms are slow to adopt a technology for reasons other than availability, this limits the size of the product market and reduces the incentives for commercialisation activity in that geography.

Innovation value is captured outside the UK

Hypothesis: (General/UK specific) The global supply chains of tradeable technologies have high moats and oligopolistic market structures, meaning that the value of innovation is *captured by a relatively small number of commercialising firms. If very few of these are in the UK, then it is likely the value is being captured elsewhere.*

Evidence: In tradeable markets with integrated global supply chains, it is possible that fundamental research, commercialisation, and adoption all happen at different rates in different locations, meaning that value creation and value capture may occur to different extents in different places. This is further dependent upon the level of moats in the market, with higher moats leading to value capture by a more concentrated group of global leading commercialising firms.

The UK did not manage to win a large share of global market cap in any of the high-moat technologies we studied, and this, perhaps unsurprisingly, correlated with only average productivity performance in those sectors.

For lower-moat technologies, you would expect to see a correlation between adoption and adopting sector productivity and consumer surplus. We did indeed see this, with semiconductor adoption, in particular, leading to high consumer surplus, and low industrial robotics adoption leading to relatively poor manufacturing productivity.

Misalignment between innovation focus and welfare

Hypothesis: (General) A long-term investment or regulatory deficit in the key sectors with the highest productivity spillovers or most widespread consumer benefits has discouraged researchers and entrepreneurs from targeting these sectors, leading to a misalignment between innovation focus and productivity- and welfare-enhancing technologies.

Evidence: In a perfect world, with no externalities and with equitable purchasing power between individuals, we could expect the free market to organically identify the commercial opportunities that would maximise net social benefit. Unfortunately, we do not live in that world. Ultimately, there is a flow of incentives from final market to technology adoption and from technology adoption to technology innovation. The ideas that are developed and commercialised are those that will produce the most certain returns. In the absence of government intervention, these are by no means guaranteed to be those ideas that, when implemented, will provide the greatest social value.

When analysing the flow of investment into specific technologies, we found private investment tended to go to technologies with a high degree of value capture but a relatively low degree of social benefit. Public funding only partly made up for this.

4.3 Policy Implications

1. **Continue to fund foundational research and support spin-outs and start-ups but really focus on supporting and retaining scale-ups and encouraging them to grow in the UK.** As identified by many previous authors, the UK is good in creating knowledge and should take better advantage of that capability than it currently does by enhancing the ability to commercialise findings. Interventions here will be familiar to readers but remain as relevant today as they were a decade ago: these include increasing funding, particularly in near-market applications, in later capital-raising stages, and on riskier, longer-term ventures; issuing Skilled Worker visas to attract high-performing workers and entrepreneurs from abroad; and trying to make the UK as attractive and welcoming to highly skilled immigrants as possible.

2. **Tackle the specific barriers to technology adoption in different sectors.** Industrial robotics and offsite modular construction were just two examples for which we identified three key shortages as barriers to adoption: shortage of knowledge as to "what works"; shortage of capital; and a shortage of skilled workers. However, these two technologies also each demonstrated a set of sector-specific issues that require addressing: one size only partly fits all. Policy could and should seek to build these capacities through directly engaging the mid-tier firms most likely to be capable of making a technological leap. Levers include facilitating partnerships with academia and matching with preselected potential technology suppliers; providing subsidised technology-specific training courses and institutes; and providing matched funding with technology upgrade funds.

3. **Work backwards: use regulation and long-term procurement strategies to grow the market for technology adoption to make the UK a more attractive place to commercialise.** Some mechanisms to do so include regulatory sandboxes to test and refine products in a real-world environment with temporary exemptions from certain rules, accelerating commercialisation; implement technology mandates or compliance standards that require the adoption of specific technologies (e.g., offsite construction in the construction industry); and provide tax incentives for private companies that invest in or adopt emerging technologies in socially beneficial ways.

4. **The questions for general purpose technologies should not be "if" but "what" and "how".** As discussed in the introduction, general purpose technologies are those that impact multiple value chains, making them particularly valuable to both commercialise and adopt. The question here therefore shouldn't be whether the UK wishes to take part in knowledge chains relating to semiconductors, industrial robotics, AI, mobile communications, and many others, but how it can best position itself to both capture more value from existing research specialisms and ensure early access to the most innovative and socially beneficial products.

5. **Focus on facilitating the simultaneous adoption and development of complementary technologies**. It is widely understood that research breakthroughs often occur at intersection points between existing specialisations, but the case studies suggest that this may also be the case for the application of technology; for example, the UK is a world leader in the application of AI to genomics research, but not in the application of AI to robotics systems. The application of dispersed analytical AI will depend on the widespread deployment of 6G connectivity, where the UK is currently lagging. Whereas some degree of technological focus is welcome, too narrow a focus risks losing many of the most beneficial cross-technology spillovers.

6. **A consistent long-term focus on those sectors that provide the greatest level of social benefit, in order to incentivise innovation and investment in technologies that best deliver that benefit.** While innovation in online streaming services is useful for consumers and remunerative to streaming companies, it is never going to deliver the same radical change in social welfare as an improvement in productivities of large employment sectors such as health and social care, or large components of household spending such as food, energy, and housing. These are the sectors the government would get most "bang for its buck" by focusing on. In the

case of offsite construction, for example, government could encourage the adoption of this through public–private partnerships, grants or loans to help mitigate investment risk, and long-term procurement initiatives to build social housing projects by councils.

7. **Take a "whole value chain" approach to stimulating innovation in primarily domestic non-tradeable value chains.** For non-tradeable sectors, the government's goal should be to maximise net social benefit and minimise resource demand (physical and labour) over the entire value chain. Net social benefit is maximised by an equitable balance of consumer surplus and enough producer surplus at each stage to pay good wages without the dominant firms in any particular stage having too much market power. This implies the necessity of a "weakest link" evaluation approach to identifying the optimal leverage points within a value chain for government intervention. Looking from top to bottom, government should try to identify the main source of inefficiency or barrier to innovation that is holding the whole value chain back. Addressing this is likely to prove an effective investment..

8. **Take an approach focused on consumer surplus and productivity diffusion to encourage and facilitate adoption of technologies produced outside the UK.** Households and firms will always import some technologies from outside the UK that can't be or aren't being made in the UK at the same quality and cost. The strategic focus here should be on ensuring UK firms and households have access to and information about the technologies they need to maximise their productivity and consumer surplus, respectively. If it is strategically important, thought might be given to providing assistance in ensuring access, or even domestic replication of critical products or technologies. There are contrasting examples here in the successful adoption of imported semiconductor products compared with disappointingly low levels of adoption of industrial robotics.

9. **Take a pragmatic approach to globally integrated tradeable value chains.** For tradeable goods and services, there is no guarantee that research, commercialisation, and adoption need all happen in the same place. At each stage, there are individual "make versus buy" decisions for both the firms involved and, more strategically, the country as a whole. In a world with open and integrated capital markets, the national provenance of a leading firm matters less than whether UK firms and consumers have access to its products, and UK workers to its jobs and wages. This requires a separate focus on adoption and commercialisation. For example, the UK agricultural industry would benefit from both wider domestic commercialisation and adoption of globally traded agricultural products – but not necessarily the same products.

10. **Take a productivity- and innovation-focused approach to export-focused value chains**. Export markets are highly competitive, and constant innovation is required to maintain a competitive edge. Process innovation drives cost competitiveness, and product innovation creates and maintains bursts of market power. Generally, if the value chain is exporting, it suggests an existing comparative advantage. National champions with market power and higher moats are not as undesirable here as in other value chains – surplus loss to domestic customers is more than offset by the benefits of strengthened global market position. Equally, building a pool of skilled

workers and researchers means that, when UK firms are integrated into global markets, those high-value jobs are likely to remain in the UK a little longer than would otherwise be the case. An example of this would be development of mRNA vaccines, developed using research produced in the UK, but unlikely to be adopted in the UK in the short term – and so the best way to capture the most value of this research in the UK is to commercialise as much of it domestically as possible to sell to the rest of the world.

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