INNOVATION & RESEARCH CAUCUS

LESSONS FROM THE HISTORY OF TECHNOLOGY ADOPTION AND DIFFUSION

IRC Report No: 016

REPORT PREPARED BY

Dr Jen Nelles
Oxford Brookes University

Dr Hamisu Salihu
Warwick University

Dr Lauren Tuckerman
University of Glasgow

Prof Tim Vorley
Oxford Brookes University

Delivered with ESRC and Innovate UK

Authors

The core members of the research team for this project were as follows:

- Dr Jen Nelles – Oxford Brookes University
- Dr Hamisu Salihu – University of Warick
- Dr Lauren Tuckerman – University of Glasgow
- Prof Tim Vorley – Oxford Brookes University

This document relates to IRC Project IRCP0017: Technology adoption and diffusion

Acknowledgements

This work was supported by the Economic and Social Research Council (ESRC) grant ES/X010759/1 to the Innovation and Research Caucus (IRC) and was commissioned by UK Research and Innovation (UKRI). We are very grateful to the project sponsors at UKRI for their input into this research. The interpretations and opinions within this report are those of the authors and may not reflect the policy positions of UKRI.

We would also like to acknowledge and appreciate the efforts of the IRC Project Administration Team involved in proofreading and formatting, for their meticulous attention to detail and support.

About the Innovation and Research Caucus

The IRC supports the use of robust evidence and insights in UKRI's strategies and investments, as well as undertaking a co-produced programme of research. Our members are leading academics from across the social science community, who are engaged in different aspects of innovation and research system. We connect the social sciences, UKRI, Innovate UK IUK) and the ESRC, by providing research insights to inform policy and practice. Professor Tim Vorley and Professor Stephen Roper are Co-Directors. The IRC is funded by UKRI via the ESRC and IUK. The support of the funders is acknowledged. The views expressed in this piece are those of the authors and do not necessarily represent those of the funders

Cite as: Nelles, J., Salihu, H., Tuckerman, L. & Vorley, T. Nov 2024. *Lessons from the History of Technology Adoption and Diffusion*. Oxford, UK: Innovation and Research Caucus.

Executive Summary

The adoption and diffusion of innovations or new technologies play crucial roles in driving economic growth and societal transformation (Rodríguez-Pose, 1999; Zheng et al., 2024). However, it is important to note that both within the UK and internationally, the diffusion of technologies across industries, regions or countries has been uneven. Society is facing concurrent paradigm-shifting opportunities and challenges from rapid technological advancements in, for example, digital/AI, robotics, and bioengineering. To maximize economic, societal and environmental benefits of emerging technologies, adequately manage the risks, and do so responsibly, is likely to depend on widespread adoption and diffusion of beneficial applications of technology across businesses and society. Ideally, those technological transitions will occur within an appropriately regulated environment. The IUK's Horizon Scanning team initiated this project to understand what lessons from the past can help us to overcome adoption and diffusion challenges. This report reflects on the many barriers to adoption and diffusion of technologies, drawing lessons from the past and present to inform future innovation support.

Rather than focusing on early adopters, this research explores the factors that enable or constrain mass adoption (and hence, broad diffusion) of innovation. It is in this phase where cultural, behavioural, and social factors exert influence on adoption decisions in addition to more frequently cited constraints or enablers such as cost, regulatory environment, labour, and skills. While this report acknowledges the gamut of factors that affect technology adoption decisions, we are particularly interested in exploring issues beyond the bottom line to engage with how questions of fairness, responsibility, and risk management have shaped diffusion patterns.

This report has two main contributions:

(1) **A set of frameworks** for UKRI and government departments to sense check issues associated with the adoption and diffusion of innovations with a view to better inform and improve the design of interventions.

(2) **A series of case studies** that trace technology adoption and diffusion stories from the past and present, with reflections on how these can inform thinking about the future. We focus on three technology families: advanced materials & manufacturing, energy & environmental, and health & wellbeing. Through these examples, we want to understand what factors influenced how previous examples played out, how barriers were overcome, whether any government interventions helped improve the rate and experiences of adoption and diffusion and how we can learn from these to support adoption and diffusion of modern and emerging technologies for optimised outcomes.

The frameworks were designed to be a tool to help policy makers and programme designers develop an understanding of what kinds of barriers might exist to getting specific technologies to spread from early adopters to a wider community, and how public stakeholders might intervene to reduce constraints and multiply opportunities for adoption.

The adoption and dissemination frameworks are both designed around a series of questions that can be used either directly with target communities or to help structure programmes.

We specifically focus on how policy and interventions can support the diffusion of innovations to the critical point in technological development where they become widely adopted. There is role for policy actors in affecting both the dissemination and adoption of innovations and it is likely that targeted interventions can help individual firms or classes of firm become more receptive to innovation. However, there is no one answer that is appropriate to every firm, industry, or context. Different factors will affect businesses, and their innovation adoption decisions, differently. As the structure of the adoption framework demonstrates especially, adoption decisions are complicated and can be impacted at different stages. That is why it is crucial to understand the specific context of the target business, group of businesses, or industry and where in the decision-making process to intervene to select the appropriate factors for intervention. These frameworks are specifically designed to develop that understanding to enable more precise and effective interventions.

Exploring these case studies, which vary significantly in terms of the nature of technologies and the markets within which they have diffused, provided an opportunity to test the value of the frameworks and enabled us to revise them to fill in any gaps. This iterative process enabled us to strengthen the frameworks as well as provide a robust approach to understanding the cases themselves. The process also generated the following lessons:

- **Intermediaries can accelerate diffusion:** For many of these cases, intermediaries (most frequently governments and their stakeholders) have played an important role in shaping diffusion. This can happen on the supply side or the demand side. On the supply side, government intervention can help technologies reach appropriate levels of development for market, provide assistance so that production can be scaled to a point to where more widespread adoption is possible, or help technologies develop features or production methods to the point where they are cost effective. On the demand side, governments can also affect costs by negotiating supply, can increase the attractiveness of certain technologies through regulatory activities (see the mRNA case for good examples of both of these), provide resources (information or material) to boost capabilities, and more.

- **Labour and workforce implications can disrupt adoption:** Degree of workforce buy in and broader impacts on labour are often considered secondary in adoption models but can be important considerations in adoption processes. Workers engaging in machine breaking slowed but did not impede the diffusion of steam powered factories. The case of industrial robotics shows that these kinds of disruptive behaviours continue to be a problem when workers have not bought into technological changes.

- **Cost/benefit analysis is shaped by a variety of factors across the willingness-capability-capacity nexus:** What the technology costs is different from what it costs business to integrate it. This is evident by how these considerations emerge at different points in the framework. For instance, the cost of a technology relative to alternatives can affect a business' willingness to consider the technology. Customer and demand patterns can also affect that willingness. Market conditions, such as demand cycles, can influence cost calculations of both capability and capacity. The capital cost of the technology influences capability whereas the costs of implementation affect both capability and capacity.

- **Technological systems matter:** Adoption of all these technologies required the development of further innovations to increase their utility, make them accessible to different industries, lower costs. Just as the boom in software was a key to the ICT revolution so too will the development of related technologies affect the perceived feasibility of the technology families studied here. Gas lighting was only possible because of developments in storage and transport infrastructure. Steam energy was only relevant to industry when a wider variety of machinery was developed to use its power. Gene editing will become more accessible when delivery methods are simplified and scalable. Solar becomes more feasible as battery storage technology improves.

- **The decision to adopt, or not adopt, a technology rarely comes down to just one consideration:** The adoption framework matrix attempts to capture the high-level considerations that influence adoption decisions – but it's still quite a lot! While case studies generalise lessons at the industry scale, they demonstrate how many factors can act on businesses and be considered simultaneously. This suggests that it may be difficult to narrow down a single barrier to adoption that is solely responsible for adoptions decisions and rather that the *combination* of factors, both positive and negative, ultimately shape outcomes.

- **Do not overlook social and behavioural influences on adoption decisions:** Adoption frameworks often privilege tangible factors such as costs or skills while reducing fewer tangible dimensions to categories such as “culture” or “attitudes”. This research shows that considerations about values, reputation, ambition, and risk can be equally important in shaping technology adoption decisions – particularly by influencing the willingness of businesses to consider (specific types of) technological solutions. Indeed, reinforcing the previous point, these kinds of social and behavioural factors should not be considered “in addition to” the more concrete factors, but should rather be understood as important lenses that colour firm perceptions and priorities as they consider things like cost. Given that the social and behavioural factors in our framework are typically inherent to firms and their leadership, they can be more difficult to overcome than capability (e.g., resource) limitations.

Increasing technology adoption and diffusion is an important ingredient in stimulating the innovation economy and increasing prosperity. However, this research demonstrates that it is an extremely complex set of problems that defy easy or expedient solutions. This report provides some context, and a set of tools, to enable stakeholders to make sense of the technology trajectories that they want to influence. It is accompanied by a summary guidance document, which provides a quicker and more accessible introduction to the frameworks, how we used them in our case studies, and how they can be applied in other contexts. These tools will be useful in interacting with individual businesses to understand their decisions and in considering trends within whole industries. They will also be useful to understand how to effectively align public policy goals with practice to ensure that technology adoption supports sustainable, responsible, and equitable innovation.

1 Introduction

As the first industrializer in the world, the United Kingdom has a rich history of spearheading invention, innovation, and the widespread diffusion of new technologies. From as early as the invention of the steam engine in 1668 to more recent breakthroughs like the Astra Zeneca anti-COVID-19 vaccine, the UK has consistently been at the forefront of technological advancement.

The adoption and diffusion of innovations or new technologies play crucial roles in driving economic growth and societal transformation (Rodríguez-Pose, 1999; Zheng et al., 2024). However, it is important to note that both within the UK and internationally, the diffusion of technologies across industries, regions or countries has been uneven. Society is facing concurrent paradigm-shifting opportunities and challenges from rapid technological advancements in, for example, digital/AI, robotics, and bioengineering. To maximize economic, societal and environmental benefits of emerging technologies, adequately manage the risks, and do so responsibly, is likely to depend on widespread adoption and diffusion of beneficial applications of technology across businesses and society. Ideally, those technological transitions will occur within an appropriately regulated environment.

However, despite notable successes, challenges persist in the UK with respect to ensuring profitable, equitable and inclusive adoption and diffusion of new technologies across all segments of businesses and society. Haldane (2018, p.7) reflects that:

> Typically, we think of “Research and Development” (R&D) as a rhyming couplet. In the UK’s case, the R and the D do not seem to rhyme. The UK does R well, as a world-leading innovation hub. But it does D poorly, where the D refers not just to development but the diffusion and dissemination of innovation to the long, lengthening, languishing lower tail. When it comes to innovation, the UK is a hub without spokes.

In the same vein, others have drawn attention to the so-called ‘valley of death’ between the UK research and innovation successes and commercialization of new technologies or services. In fact, the UK’s stagnant productivity has been attributed to low levels of technological uptake in businesses (Mudie, 2022).

1.1 “Those who do not learn from the past are doomed to repeat it”

The IUK’s Horizon Scanning team initiated this project to understand what lessons from the past can help us to overcome adoption and diffusion challenges. This report reflects on the many barriers to adoption and diffusion of technologies, drawing lessons from the past and present to inform future innovation support. Technologies tend to emerge in waves and each wave has had a massive and irreversible impact on wealth, society, culture and the environment. As we look to reap the benefits of emerging technological trends, we need to learn from the past to avoid repeating mistakes. Many of the challenges we are facing now with adoption and diffusion, such as lack of necessary skills, lack of understanding in society and the workforce, uncertainty on how to teach or train young people, senior management of firms who are unwilling to invest early, and fear of jobs being replaced by technology, have been experienced in every new wave of technology. Exploring the obstacles experienced in the past and present can help us foresee, and mitigate, the challenges of the future. Similarly, in learning from the past, we may be able to position ourselves better to ensure that the adoption of, and benefits from, technology are fairer and more equitable and that they are more likely to offer solutions to grand challenges than exacerbate them.

Rather than focusing on early adopters, this research explores the factors that enable or constrain mass adoption (and hence, broad diffusion) of innovation. It is in this phase where cultural, behavioural, and social factors exert influence on adoption decisions in addition to more frequently cited constraints or enablers such as cost, regulatory environment, labour, and skills. While this report acknowledges the gamut of factors that affect technology adoption decisions, we are particularly interested in exploring issues beyond the bottom line to engage with how questions of fairness, responsibility, and risk management have shaped diffusion patterns.

1.2 Contributions

To that end, this report consists of two main contributions:

(1) **A set of frameworks** for UKRI and government departments to sense check issues associated with the adoption and diffusion of innovations with a view to better inform and improve the design of interventions. The adoption framework breaks factors affecting technology adoption decisions down into those shaped by willingness, capability, and capacity across four parts of the business (workforce, management, production, and external-customers/markets). The diffusion framework offers insight into the different social structures that enable information about new technologies to travel through and across sectors. The frameworks are structured around key questions and considerations to help stakeholders diagnose and predict pinch points affecting adoption decisions.

(2) **A series of case studies** that trace technology adoption and diffusion stories from the past and present, with reflections on how these can inform thinking about the future. We focus on three technology families: advanced materials & manufacturing, energy & environmental, and health & wellbeing. The adopters in these case studies differ – from purely private sector, a mix of public and private, and the public sector – offering a variety of perspectives on adoption dynamics. Through these examples, we want to understand what factors influenced how

previous examples played out, how barriers were overcome, whether any government interventions helped improve the rate and experiences of adoption and diffusion (though noting policy intervention approaches were undertaken in very different social and economic times) and how we can learn from these to support adoption and diffusion of modern and emerging technologies for optimised outcomes.

The frameworks and case studies were developed in parallel. The frameworks were initially informed by a literature review but were then adjusted as case studies revealed gaps and issues that were not initially addressed. We explored the case studies through the lens of the frameworks, both to draw out lessons for that technology family and stress test the frameworks to ensure robustness.

In what follows, this report establishes the conceptual background, defining adoption and diffusion and situating them as foundation to innovation and prosperity. It then presents the adoption and diffusion frameworks. These sections focus on explaining the structure of the frameworks and elaborating their innovative features, which are designed to enable more insightful diagnosis of adoption constraints and of diffusion barriers. These frameworks were tested in, and reciprocally informed by, the case studies. The case study section begins with an extended summary of interesting findings by time period before turning to the nine detailed accounts for each technology (3 technology families x 3 time periods). The report concludes with a summary of key lessons from the case studies and looks forward to how they can be leveraged to achieve more effective, but also more responsible, sustainable, and equitable adoption and diffusion.

2 Conceptual background

2.1 Defining adoption and diffusion

This report focuses on the adoption and diffusion of technologies. These concepts are related and often conflated so it is important to be precise about how they are defined and are associated with one another.

Technology adoption refers to individual or organisational decisions to use or implement the technology. Per Lewis and Seibold (1993) in Bui (2015, p.3) adoption is commonly described as “the implementation and assimilation of an innovation within an organization”. The study of technology adoption, therefore, focuses on what affects the decisions of principals within businesses to use specific technologies.

Technology diffusion refers to the spread of technology through economies. We use the Strang and Soule (1998, p.266) definition which describes it as "the spread of something within a social system. The key term here is "spread", and it should be taken viscerally (as far as one's constructionism permits) to denote flow or movement from a source to an adopter, paradigmatically via communication and influence". The study of diffusion typically focuses on the social and systemic spread of ideas, innovations, or technologies – tracking the speed of transmission and characteristics of populations through which certain ideas travel and are implemented more quickly (Rogers, 2003; Valente, 2005; Strang & Soule, 1998). Diffusion is also sometimes discussed in terms of mechanisms or pathways (Zhou et al. 2023). This is about how ideas spread, whether through face-to-face contact, media, or some other methods.

Adoption and diffusion are closely related concepts to the degree that diffusion is typically measured in terms of rates of adoption. The process of diffusion is rarely linear or straightforward (see Figure 1).[1] Furthermore, decisions around adoption differ from business to business, from industry to industry, and innovation system to innovation system etc.

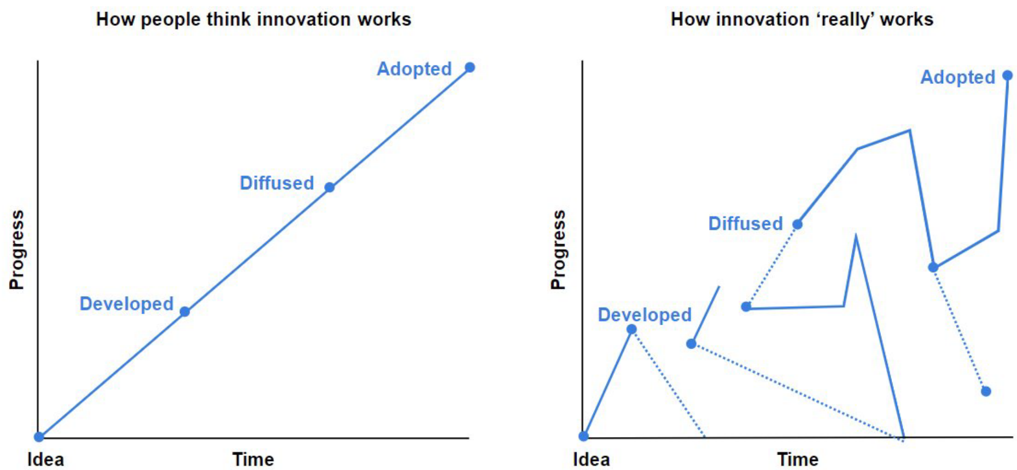

Figure 1: Differences between perception and reality of how adoption and diffusion work (DSIT 2023)

[1] Note that this diagram positions diffusion before adoption along the time axis. This recognises that while diffusion is a function of adoption and that they are nearly simultaneous. The gradual accretion of individual adoptions provides signals to other potential adopters. Therefore, as technologies diffuse, they precede the next wave of adoptions.

Diffusion is typically considered at a high level – a technology spreading through an economy. As a result, some nuance is can be lost. The assumption often is that more is better. But a myopic focus on "more" may risk exacerbating inequalities or externalities that cascade through the system. By considering technology diffusion in the context of broader policy priorities and thinking critically about lessons and consequences from the past, policymakers can encourage adoption intelligently and more effectively.

For instance, from a public policy perspective, encouraging diffusion should not be aimless. It may be about aiming to make innovations known and accessible to industries that have not yet realised the value of a technology that has proliferated across other (this has been the goal of digital manufacturing initiatives). Or it may be about reaching types of businesses that are lagging because they have not yet adopted proven innovations (such as smaller or family-owned businesses). Unpacking adoption decisions might be about removing barriers and accelerating diffusion, but it might also be about learning how technological change affects behaviours or can adversely affect workers or the environment.

Importantly, influencing diffusion is not only about removing barriers to adoption in target populations – facilitating the internal calculus that gets firms to "yes" once they are aware of the technology and its benefits to their business. It is also about ensuring that businesses have been exposed and have built awareness of the technological options in the first place. In this case, a first step in diffusion, particularly of the strategic variety that aims to reach target businesses/industries etc. - is about *transmitting knowledge and experience* about the technology. This is not necessarily about ensuring that businesses have knowledge about how the technology works but of its value to their enterprise. For example, an accounting firm does not have to know how a circuit board functions to understand the value of a computer. Therefore, improving technology diffusion – rates and reach of adoption – is often less about the qualities of the technology itself but about understanding the how to improve the reach and characteristics of *knowledge* about the technology (Nambisian and Wang 2000, Ravichandran 2001, Edmondson et al. 2003). It is also affected by how knowledge and experiences can be effectively transmitted and translated to encourage target users to perceive the potential of that technology in their own contexts. You can't adopt what you don't know about, so effective dissemination of knowledge and facilitating access are crucial first steps to promoting widespread adoption.

Then, assuming that diffusion is functioning effectively, and target businesses are aware of technologies and its potential benefits, improving technology adoption is about recognising and removing barriers to technology uptake.

2.2 Big questions and key considerations for framework development

What drives successful technology adoption and diffusion? What can past experiences teach us about what to expect in current and future technology transitions? In compiling the adoption and diffusion frameworks, we established some key assumptions and guiding questions (Figure 2).

For **technology adoption**, we highlight what factors influence organisations' decisions to use, replicate, or adapt innovations. For **technology diffusion**, we explore how information about innovations that have been adopted spread effectively through the economy.

Our first core assumption is that the technologies in question solve a real problem or otherwise have beneficial use cases. This allows us to focus on technologies for which there are clear benefits to *at least some users*, even if that benefit is not clear or is being debated in other communities. Artificial intelligence is an example of a technology that, even though the value of certain manifestations and its broader social costs are contested, still presents beneficial use cases to some and in some contexts. Part of the purpose of this exercise is to capture in a framework how debates around social, community, environmental (etc) benefits and costs shape diffusion narratives and adoption decisions and so we consider contested technologies in scope if they have some evangelist communities.

Our focus is on the "chasm" shown in Figure 2 between early adopters and the mass adoption (or the "early majority"). We are also predominantly interested in transmission and uptake between businesses and organisations rather than individuals in the broader public. For example, we are interested in what influences a business' decision to adopt digital technologies to enhance their offering, such as mobile enabled point of sale devices, rather than individuals' decisions to buy a particular smartphone.

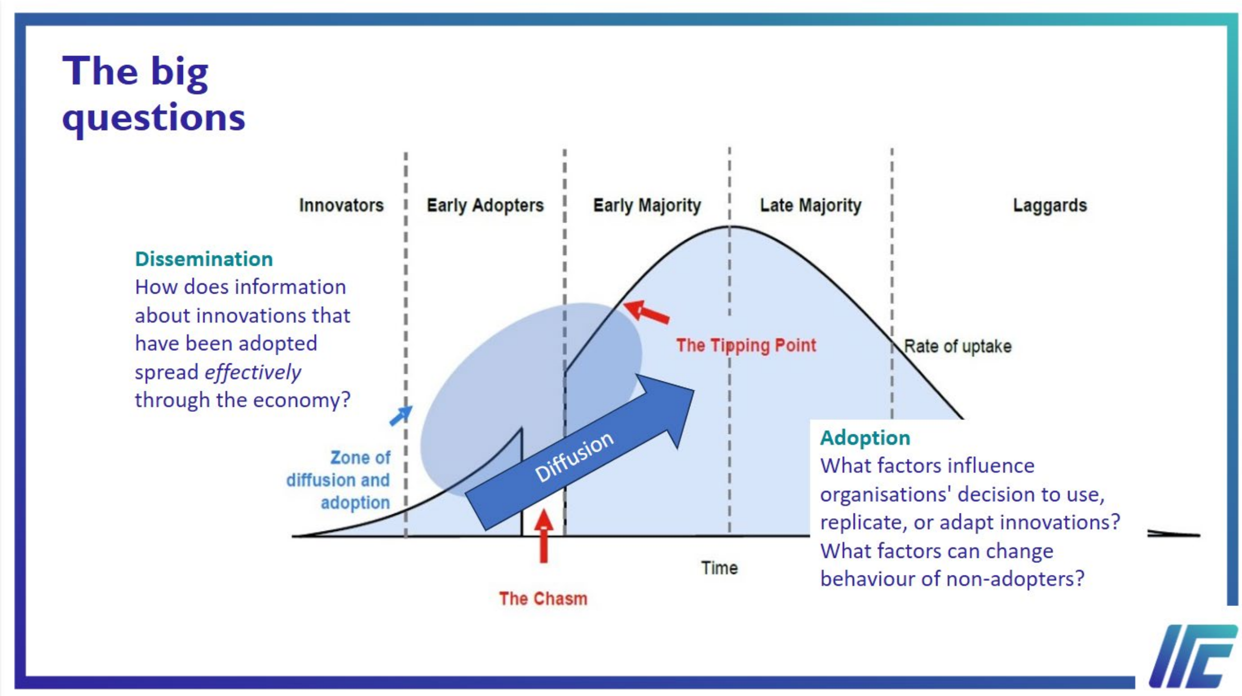

Figure 2: Key questions and considerations informing the adoption and diffusion frameworks.

Source: Adapted from DSIT (2023, p13)

Another core assumption is that, for the technologies that we're interested in, governments or innovators themselves are not actively preventing diffusion. Knowledge about some technologies, and access to them, is sometimes tightly controlled. We are more interested in understanding the diffusion of technologies that can be and are freely shared through the marketplace. Even if the details of how the innovation was created or functions might be considered a protected trade secret, if there are no externally imposed barriers to purchasing the innovation, we consider it in scope.

Given the purpose of this framework is to inform public support and investment decisions, we constructed them with the assumption that the technologies in question are those in which there is a public interest in understanding or intervention and that diffusion would be taking place in the UK context.

2.3 Case selection

Three technology families were selected in a collaborative brainstorming session with UKRI

Table 1: Technology families with the three selected cases highlighted

Tech Family	Past	Present	Future
Energy & Environmental	Combustion Engine Propulsion	Electric Motor Propulsion	Hypersonic Propulsion
Energy & Environmental	Gas Lighting/ Coal Power	Solar/Renewable Power	Fusion Power
Health and Wellbeing	Antibiotic treatments	M-RNA treatments	CRISPR-based treatments
Electronics, Photonics, Quantum and Sensing	Telegraph Communications	Social Network/ Internet/ Electronic Communications	Immersive Computing Communications
Advanced Materials and Manufacturing	Loom (woven) Materials	Composite Materials	Metamaterials
Electronics, Photonics, Quantum and Sensing	Camera (light imaging)	Computer Tomography Imaging	Quantum Imaging
Biotechnology	Artificial Limbs	Bionic Prosthetic Limbs	Sensation Detection Implants
Robotics and Autonomous Systems	Manufacturing Robots	Domestic/Surgical Robots	Nanoscale Robots
Advanced Materials and Manufacturing	Steam powered mills or early production lines	Industrial Automation	Cobotics / Industry 5.0

Because we are interested in the mass adoption of innovations and not as much in the earliest examples, the technologies that we describe in the case studies are frontier technologies, but span the experimenting, piloting, and scaling phases of development. To illustrate this, Figure 3 shows the trajectory of technology development (Yee et al. 2024) superimposed over the Rogers adoption curve shown in Figure 2. Note that this alignment is highly stylized but is meant to convey how adoption typically increases with technology maturity.

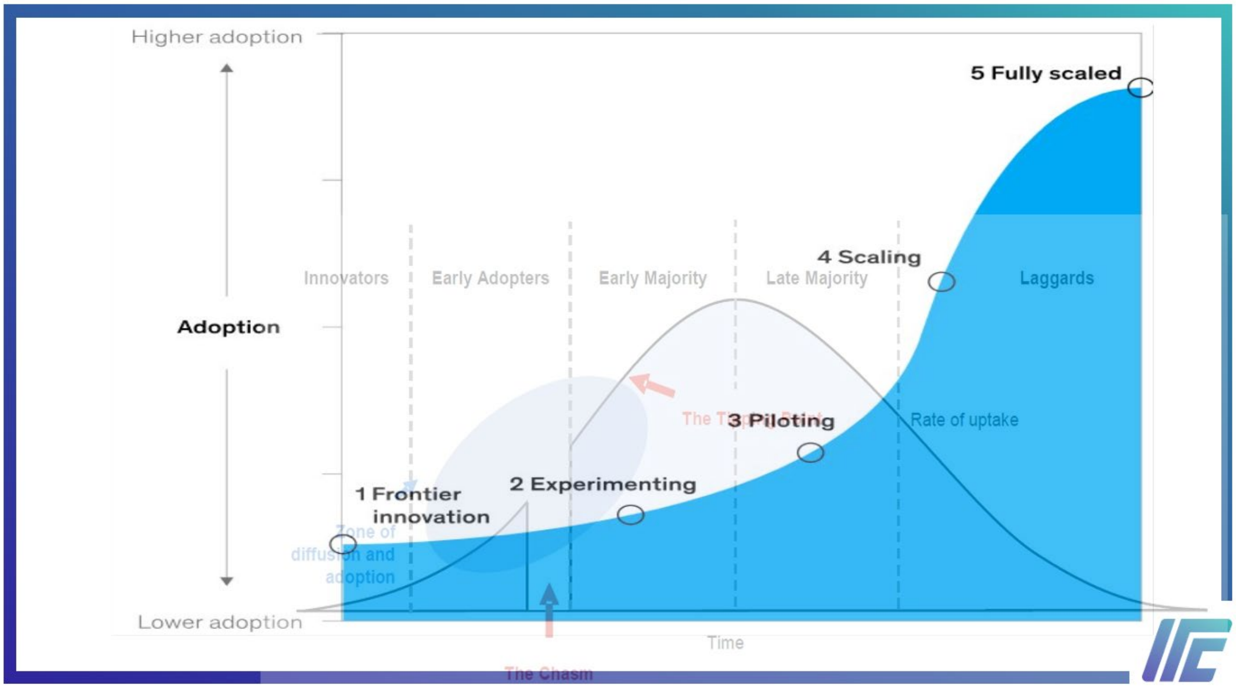

Figure 3: McKinsey technology development trajectory superimposed over the Rogers adoption curve to show a stylized alignment between tech maturity and adoption behaviours.

Source: Adapted from DSIT (2023, p13) and Yee et al. (2024).

While we have tried to keep technology readiness relatively constant, our selected cases offer a glimpse into the adoption and diffusion trajectories of very different technologies but also variation across time frames and adopters. For instance, innovations in advanced materials and manufacturing are predominantly adopted by businesses in the private sector while advances in medicine, such as antibiotics, are in the UK typically publicly regulated and adopted by healthcare providers (e.g., the NHS). Innovation in power sources and transmission in the UK have been adopted by utilities that are privately owned but publicly regulated. This mix of contexts provides a spectrum of examples that demonstrate both how adoption and diffusion can occur in free markets as well as how the public sector has exercised varying degrees of influence to increase diffusion by facilitating access and/or to favour the adoption of certain technologies over others.

Each of the case studies illustrate interesting lessons about adoption and diffusion that together help to expand our understanding of what barriers and opportunities exist in affected technology trajectories. We developed a draft of the frameworks presented in the next section first and used these to explore each of the cases. As the cases themselves revealed aspects that were not initially in the framework, we added these in later before finalising the matrices.

3 Adoption and diffusion frameworks

These frameworks were created to help UKRI and government departments to sense check issues associated with the adoption and diffusion of technologies with a view to better inform and improve the design of interventions. They are structured as a set of questions organised thematically, as informed by literature and road testing with case studies, to guide stakeholders as they seek to understand the diffusions and adoption dynamics for technologies of interest – past, present, or future. While we drew heavily on existing research to inform the frameworks, the process of applying them in the case studies highlighted aspects that were not initially incorporated based on the literature review.

Note that while the frameworks aim for comprehensiveness by presenting a wide range of issues that may influence adoption and diffusion, they may not effectively anticipate issues that may arise in the future. We expect that the frameworks can accommodate revisions to absorb the lessons of changing circumstances (as they have done in response to new issues that arose in the review of the case studies). It is also worth noting that each technology will present a different set of issues and challenges. Consequently, not every cell in the frameworks will be relevant to every technology family or wave.

The adoption and dissemination frameworks are both designed around a series of questions that can be used either directly with target communities or that can help structure programmes of research (as we have done with the historical case studies in the main report). This report includes both the frameworks but we provide additional guidance about how to apply them and interpret results, and how these can be used to develop targeted and effective policy interventions in a separate document.

The most important point is that there is role for policy actors in affecting both the dissemination and adoption of innovations and it is likely that targeted interventions can help individual firms or classes of firm become more receptive to innovation. However, there is no one answer that is appropriate to every firm, industry, or context. Different factors will affect businesses, and their innovation adoption decisions, differently. Furthermore, as the structure of the adoption framework demonstrates especially, adoption decisions are complicated and can be impacted at different stages. That is why it is crucial to understand the specific context of the target business, group of businesses, or industry and where in the decision-making process to intervene to select the appropriate factors for intervention. These frameworks are specifically designed to develop that understanding to enable more precise and effective interventions by those in the public sector and beyond.

3.1 Adoption

Adoption occurs when a business implements or replicates a new technology in their own processes. In this framework, we focus primarily on the factors that influence the decision to adopt a technology and do not explore in depth the related, but sometimes different, conditions that determine whether adoption is successful or not. While the process of adoption is often portrayed as a binary choice – to use the technology or not – it is actually the product of many different decisions, sometimes made by different individuals within the business. For instance, a business – or people within it – may be excited to use the technology but not have the resources to implement it at scale. Or a business may be excited to adopt the technology and have resources available but may not be able to divert them to implementation without disrupting existing product delivery.

We opted to draw from several major existing models of adoption to build a harmonised framework that captures details about what aspect of the business is challenged (or enables) decisions to adopt as well as what factors affect those decisions. We also added to and adapted the framework in response to the case studies (presented in section 5). The result is a matrix that acknowledges that each factor can affect willingness, capability, and/or capacity to adopt a given technology. This multidimensional framework provides a greater spectrum of tools to diagnose where certain factors create barriers, which enables more effective interventions. First, we outline the groups of factors that can influence adoption decisions before turning to a discussion of how they affect willingness, capability, and capacity to adopt.

3.1.1 Factors affecting adoption

We distil the range of different factors affecting adoption decisions into four large categories: workforce, management/firm structure, production, and external. While these categories are quite broad, they capture all factors discussed in other major models and, paired with the additional lens of willingness, capability, and capacity (see the next section) enable us to contextualise how similar factors can have different impacts across business decision processes.

Models we drew on to inform this framework configuration include the Technology – Organisation – Environment (TOE) model (Tornatzky and Fleischer 1990); Technology Acceptance Model (TAM) (Davis, 1989; Davis, Bagozzi, & Warshaw, 1989); the ORGANISER behavioural model (Department of Energy and Climate Change 2016); Task-Technology Fit Model (TTF) (Goodhue 1995); Rogers' innovation diffusion model (Rogers 2003), and the Innovation Caucus framework for innovation readiness in foundation industries (Nelles et al. 2022). The summaries below document, at a high level, the content of the major framework categories and links to existing models. The details of these are developed further in the rows of the framework (Table 3).

Workforce pertains to the perspective, reactions, level of preparedness, and acceptance of workers. Often, adoption decisions focus on management or key decision makers, but workforce buy in is crucial to the success of technology integration. This category draws strongly on the technology acceptance model to the extent that it focuses on perceptions that workers have of the technology (Dishaw & Strong 1999). However, it moves beyond perceived use and usefulness of the technology that underpin acceptance in TAM and many related models. It also embraces the idea that workers face costs as new technologies are adopted. These may be related to additional training required or the addition of new tasks associated with the technology, both of which can fundamentally change their functions, roles, and ways of working. Furthermore, workers derive pride and fulfilment with the work that they do. Even if what they do appears to outsiders as menial, dangerous, or tedious, workers do not always welcome the arrival of technologies that render their functions obsolete or fundamentally change their roles. Instances of machine breaking and systems sabotage to the present day are testament to the importance of workforce perceptions on adoption decisions.

Management/Firm structure refers to the wide variety of factors that can influence management attitudes and structure decision making processes. These encompass the aims, norms, and structures elements of the ORGANISER model (Department of Energy and Climate Change 2016) but also includes other dimensions, such as awareness and knowledge of the technology, perceived usefulness, compatibility with existing business strategies, and alignment with the personal motivations of business leadership.[2] It also considers how the internal organisation of a firm, including hierarchies, decision making processes, and change management practices (or lack thereof) may constrain or enable implementation. Crucial considerations about resources, costs, and risk are a fundamental component of this category.

Production is related to integration and compatibility with existing production processes and practices. This category also includes considerations about compatibility of the technology relative to existing ways of working, but here refers to more technical integration with production processes (Rogers 2003) than strategic alignment. Drawing on the task-technology fit model, this category also considers the alignment of the technology with the tasks required of it and the abilities of the users. It also covers resource constraints related to production

[2] This came up in our case study research, where factory owners were more willing to adopt steam technology and machinery increase their social standing among industrialists.

integration such as the need for additional equipment, retooling, or any requirements to switch to different types of inputs.

External Context relates to customers, markets, and other conditions external to the business. This is roughly analogous to the "Environment" component of the TOE model and the "External" category of the ORGANISER model. As with both of those models, this category includes considerations of customer demand and the effects of technology adoption on business reputation as well as the reliability of supply chains. It also includes competitive pressures and norms and expectations related to customer demand.

While the factors we have selected are wide ranging and not contained within the boundaries of any existing models. However, the wide variety of considerations related to technology adoption discussed here, and evident in the rows of the framework, are difficult to process conceptually without further structure. To add more coherence, reduce the complexity, and enhance the value of the model, we further subdivide these factors based on their relationship to different high level decision gates; namely, willingness, capability, and capacity.

3.1.2 Willingness, Capability, and Capacity

Adoption models often do not explore how different factors can exert variable weights on business decisions or how the factors can influence the people involved in the decision process in different ways. This framework attempts to address these gaps in two ways – first, by acknowledging that workforce and leadership may have different incentive structures and secondly, through a stylized deconstruction of the decision-making process into three parts (Nelles et al. 2022).

We argue that first actors must be **willing** to consider new technologies as part of organisational strategy or as a response to a specific problem in the business. Without this crucial first step, things like cost or skillsets are moot. Secondly, the business must have the **capability** to implement the technology, which covers a variety of factors from resources available to skills profiles. A lack of capability can reduce the attractiveness of new technology adoption. Finally, the business must perceive that is has the **capacity** to devote the resources it has to implementation and to weather change to achieve expected returns on investment. A business might, all things being equal, have the willingness to consider a technology and the capability to implement it but decide that change will take too long to bear fruit or that it would be too disruptive to existing ways of working. Higher perceived opportunity costs can also derail adoption decisions.

Willingness to consider a technology. This encompasses appetite and openness to considering a technological solution, which is shaped by attitudes and expectations related to potential benefits (and costs) to the business. This includes managerial and worker mindsets related to innovation, including perceptions of need for change, confidence in engaging with external resources and partners, and overall risk profile. Note that this is not willingness to adopt the technology but a willingness to consider a technological solution to a problem in the first place.

Capability to implement change. This refers to the degree to which willing businesses are able to adopt innovations with the resources they currently have or are able to access (either by acquiring new resources or using external ones). We think of adoption capability as resources across categories such as financial resources, technical skills, management skills, strategic planning, etc.

Capacity to devote resources. This is the ease with which willing businesses with the requisite capabilities can direct and devote resources to technology adoption at a particular moment in time. While businesses may be willing and have internal capabilities (and external resources might exist), capacity reflects their ability to dedicate these to technology implementation specifically. There may be competing needs that mean existing capability is engaged in other aspects of the business (e.g. skills or budget need to be used elsewhere). As such, this evaluates how businesses plan for, balance, and perceive the opportunity costs of technology adoption.

Describing business technology adoption decisions in this tripartite way is admittedly a vast simplification of the considerations at play, particularly for very large organisations. We acknowledge that while we have set this up as a sequential set of distinctive considerations these can be deliberated in parallel and inform one another. Elsewhere, we have developed a more detailed systems approach to this question (Verian, forthcoming). However, this perspective enables a more nuanced understanding of the different points at which decisions to adopt can fail, which can help underpin more appropriate interventions. Furthermore, it helps to highlight that an adoption decision does not typically proceed or stall because of a single factor but rather is usually influenced by a constellation of considerations. Again, the willingness, capability, and capacity lens on the framework is useful for diagnosing where, broadly, businesses struggled with (or were emboldened towards) adoption before delving into the specific factors that influenced those decisions.

3.1.3 The adoption framework

The framework (Table 3) combines the factors discussed above and the willingness, capability, and capacity lenses into a matrix. Each cell contains headings that group more detailed explanations of considerations, phrased as questions. These questions can be used rhetorically by a policy researcher or more actively by investigators working with businesses to explore the genesis of their decisions. Similarly, these questions can be used as part of foresight exercises to develop expectations of adoption decisions in emerging and future technologies.

Table 2 – landscape view of adoption framework

	Willingness **Openness to considering new innovations**	**Capability** **Ability to implement the innovation**	**Capacity** **Ease with which resources can be dedicated to innovation adoption**
Workforce Related to worker willingness, capability, and capacity	**Worker openness to new innovations** To what degree are employees open to the innovation/technology within the firm? This may be influenced by perceptions of impacts on ways of working, changing roles, or identity that are specific to the technology or there may be more generalised resistence to change (e.g., "not invented here syndrome") To what degree is behavioural change required from the workforce over time (and what type) and how likely are workers to accept changes? Are there any cultural barriers at play related to communities of practice or sectoral norms?	**Worker skills** Do workers have the appropriate skills to implement the innovation? Do they have access to skills training/retraining required to drive implementation? Can an appropriately skilled workforce be accessed and trained?	**Worker capacity and alignment** Are workers appropriately matched with implementation roles? Is there sufficient flexibility in the workforce to enable implementation without adversely affecting production targets?
Management/Firm structure Related to management cultures, outlooks, and firm resources	**Management awareness of innovative solutions** Are relevant actors within the organisation aware of innovations through networks or other means? Do relevant actors understand and accept of value of innovation to the business? **Innovation alignment with business strategy and ambition** How do innovations and their adoption align with the personal ambitions of business leaders? Do leaders see the alignment of innovation with values and vision of the company? Does the innovation align with risk tolerance profiles? **Board and/or shareholder influence on innovation adoption** To what extent are governance structures supportive of technology adoption?	**Acceptability of costs** Can the business shoulder the costs of adopting the technology? Costs include both financial outlays related to purchasing the technology, supportive equipment, developing skills, and other costs of implementation. **Accessibility of resources** Do business leaders know about and have access to innovation implementation support resources? **Alignment of management skills with implementation demands** Do business leaders have relevant skills to manage innovation implementation? **Existence of structures/processes to facilitate change** Are there processes in place to facilitate change management? Do hierarchies or organisation configurations create barriers to implementation? To what degree do working arrangements/management structures support change?	**Appropriateness of return on investment** Are investments in implementation likely to generate an acceptable return over time? **Adaptability of management and firm structures** Are appropriate resources available within sufficient time frames to enable implementation? What are the opportunity costs of devoting management attention to implementation?

	Willingness **Openness to considering new innovations**	**Capability** **Ability to implement the innovation**	**Capacity** **Ease with which resources can be dedicated to innovation adoption**
Production Related to integration and compatibility with existing production processes	**Alignment of innovation with production processes and ways of working** To what degree is the innovation compatible with typical ways of working? To what extent does the innovation provide an appropriate solution to and fit with tasks in the production process?	**Production constraints** Are there technological or resource constraints to integrating innovation into production processes? (e.g., access to related supply chains) Are there environmental constraints (e.g., lack of access to power or infrastructure) to adopting innovation into production?	**Expectations of resilience in the face of system downtime** Can production systems accommodate downtime to incorporate innovation while maintaining output to meet demand? What are the (opportunity) costs associated with integration of innovation in production processes (includes time, retooling, etc)? What kinds of system effects are anticipated or likely beyond the immediate implementation of the technology and how are these expected to influence business outcomes?
External Context Related to customers, markets, and other conditions external to the business	**Attitudes and demands of customers and markets** To what degree are customers/downstream markets demanding innovation that might require adopting new approaches? How will adopting the innovation affect business reputation and influence? **Influence of regulations** To what degree does the regulatory environment appear to be likley to support adoption of this innovation over the long term? How consistent or clear is regulation that might influence adoption decisions? **Market inducements** What is happening in the markets for alternatives or substitutes (e.g., exogenous impacts on price or reliability of supply etc. of alternative products)? Have external events affected the urgency to develop and distribute the innovation or created market opportunities? What types of events might impact this and how likely are they? **Competitive pressures and norms** To what degree are competitors adopting technologies or have advantages that may drive the business to seek technological solutions? Are there any industry standards, cultures, norms, or practices that may influence businesses to seek technological solutions or avoid doing so?	**Access to and appropriateness of support resources** Are there external incentives or resources to assist with adoption? **Appropriateness and reliability of infrastructure and supply chains** What kinds of external/market developments are necessary to make adoption feasible (e.g., infrastructure, scale of markets for inputs, etc?) Is access to the technology likely to be reliable?	**Anticipated impacts on existing production lines and pipelines** To what degree will innovation adoption enhance or detract from customer/market demand (e.g., subtract resources from crucial/core revenue streams)? Will technology adoption affect other pipelines of innovation support that sustain the business (e.g., tax credits)?

3.2 Diffusion

Diffusion is a measure of the extent to which technology has been adopted in an economy. This is ultimately a function of hundreds (or millions!) of adoption decisions, made by individual businesses and their leaders. In this report, we focus on how to improve diffusion processes through influencing how technologies are framed, communicated, and demonstrated. While policy makers and funding councils can design interventions to influence (or not impede) business decisions to adopt new technologies, they can also use various levers to promote adoption of specific technologies or to drive diffusion across specific target communities by understanding how to funnel relevant and actionable information to intended audiences. Acting on the dissemination of information of technologies can enable governments to more purposefully *drive* diffusion rather than simply reacting to it as an emergent phenomenon. By helping businesses learn about opportunities, framing the benefits of adoption in terms that make sense for target business environments (not just expecting that those benefits will be obvious), and by promoting accessible examples of businesses that have successfully implemented the technology, stakeholders can help enhance business willingness and bridge the divide between adoption and diffusion. This concerns not only the pathways through which and who is spreading information about the technology but also the quality of that information, which can influence how different communities receive and perceive the innovation.

3.2.1 Pathways

The diffusion framework presents three stylised pathways (Figure 3) through which information about technologies can travel and poses questions related to the characteristics of the message being transmitted through these pathways.

		B2B	Intermediary	Network
Relative advantage	Does the way the innovation is framed make a clear case that it is better than the idea it supersedes?			
Complexity	Is the innovation framed in terms that are widely understandable to maximise accessibility?			
Trialability	To what degree can the innovation be adopted on a limited or trial basis (this refers to both opportunity and suitability) or seen in action?			
Observability	Are the results of adopting the innovation visible to others?			

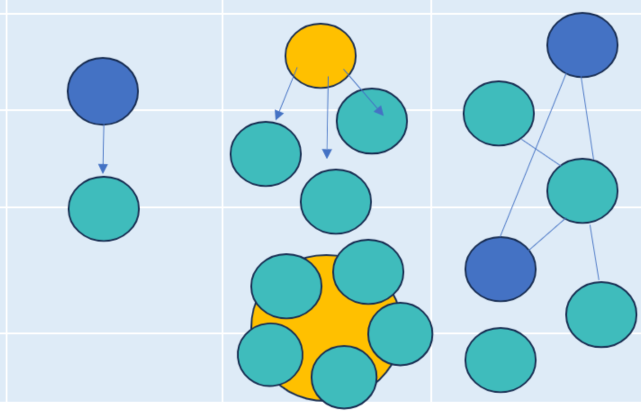

Figure 3: Visualising different pathways of dissemination.

These three pathways are not mutually exclusive but distinguishing between them offers some insights into where interventions might be most effective. The first pathway is **business to business** as one firm attempts to deliberately influence the adoption decisions of the other and information and narratives around the technology are presented through the lens of that particular relationship. This is typical of a client relationship where a producer of a technology aims to sell their products to a potential user or partnerships in which technologies are collaboratively developed to specification. However, this may also describe relationships in which downstream clients ask or demand that their suppliers consider adoption of certain technologies to produce to their standards (Vowles et al. 2011). A second pathway through which information about a technology can diffuse is through **intermediaries** such as public research organisations, industry associations, government agencies, and the like (Abi Saad et al. 2024, Colovic et al. 2024). Transmission of information through intermediaries can take a variety of forms, two of which we describe here: bilaterally from intermediary to individual businesses or multilaterally through collaborative labs, meetings, or events.

In both of the first two pathways, the transmission of information about the technology is *deliberate.* The choice of target (a business or business community) is focused, and the framing is tailored to specific audiences. Transmission occurs through direct communication. Businesses outside of those specific relationships are less likely to be able to access that knowledge unless it is made public, and they are searching for it.

Information transmitted through the third pathway – networks – may be targeted at particular communities but is more accessible to those outside of them that are also connected to the network. Mechanisms can include interpersonal communication (e.g., "did you hear that company X is using technology Y?"), media, social media, and any other pathway through which individuals and organisations passively obtain information. Note that in this case, information transmission is an *emergent*, rather than controlled, phenomenon. As it spreads through networks, innovators and those promoting technology adoption cannot shape narratives or control how information is presented. For instance, information transmitted through social networks may be negative or emphasise negative aspects of the technology; or it could be positive or neutral.

For any innovation, it is likely that diffusion occurs to different degrees through all three pathways. Which is most influential will vary by technology. For funding councils and their stakeholders seeking to shape diffusion and influence adoption, recognising these different pathways offers a clearer perspective about where their efforts are most likely to bear fruit such as encouraging business to business relationships and shaping narratives through intermediaries. Establishing a clear and effective narrative and creating opportunities for targets to interact with technologies can, in turn, generate more juice through networks (although whether that is positive or negative can be difficult to control).

3.2.2 Technology diffusion framework

The technology diffusion framework lays out four factors that shape perceptions of innovations across the three different pathways. The four factors shaping perceptions are adapted from Rogers (1962, 2003)[3]: relative advantage, complexity, trialability, and observability. Table 2 provides detail about the meaning of these concepts and questions to help guide observers and strategists/policymakers in understanding how these can be used to drive more effective diffusion. We interpret Roger's (2003) communication channels as the three pathways discussed above - B2B, intermediaries, and network – in which the first two are definitionally direct communication while communication through networks can be indirect (e.g., media) or direct (e.g., interpersonal). The role of opinion leaders, change agents, and peers is incorporated within the questions in the framework as these can exert influence across any of the pathways.

[3] Note that Rogers' framework also includes "compatibility", which describes the degree to which an innovation is compatible with a firms' existing structure, business models, and/or practices. We include this as part of the adoption decision cycle because this judgement will be unique to each business where all other factors in the model can be more effectively generalised to a community, industry, or economy.

Table 3 - landscape view of the diffusion framework

		B2B partnerships	Intermediaries	Social networks
Relative advantage	*Does the way the innovation is framed make a clear case that it is better than the idea it supersedes?*	Does the specific pitch take into account the interests, values, positionality, needs, and constraints of the potential adopter? To what degree has feedback and iteration shaped innovation framing?	Is the pitch aimed at an appropriate audience and relevant to a variety of circumstances (e.g. anticipating and acknowledging differences) enabling technology to transcend barriers? Are benefits being described in ways that enable them to be successfully reproduced in other contexts? Are there specific rules and regulations that encourage exploration of the innovation in question and are intermediaries effectively communicating these incentives?	How are early adopters (firms, but also of specific groups, e.g., labour, management, etc) discussing the innovation? To what extent are downstream and social reactions positive? To what degree are competitive pressures being transmitted through networks (e.g., FOMO)?
Complexity	*Is the innovation framed in terms that are widely understandable to maximise accessibility?*	How effectively has the simplicity of change and its implementation been communicated? If adaptation is required, to what degree is this evident and mitigated in sales and marketing pitches?	To what degree are there adoption support services and mechanisms to reduce appearances and effects of implementation complexity? To what degree does communication by intermediaries about the technology and support take into account differences either between firms or between industries?	Is the innovation applicable and appealing across sectoral boundaries? Is there a potential for relatedness? To what extent does the complexity of adoption shape framing (positive or negative) about the innovation? Do narratives discuss ideas, behaviours, etc have to change in order to adopt the innovation? Do any of these factors vary by audience type? If so, how?

		B2B partnerships	Intermediaries	Social networks
Observability	*Are the results of adopting the innovation visible to others (and regarded as credible)?*	To what degree are technology providers able to share evidence of adoption success with potential clients? Do positive examples cover a range of circumstances such that potential adopters can translate those experiences to their own contexts? To what degree are accounts of successful adoption seen as credible?	How are examples of success being communicated to target communities? Are they being communicated to the right stakeholders (e.g., not just firms but to the right people within them)? Are acheivements within intermediaries' communities being celebrated and shared? What role do change champions/peer leadership play in efforts to spread innovation?	How fast and visible is uptake by peers? How do network characteristics and number of channels affect spread? - geography, proximity, frequency of interactions, degree of proximity between champions and potential adopters To what degree are peers visibly demonstrating/communicating outcomes? To what degree is information regarding the innovation and its implementation available and effective for those that seek it independently? (How is it codeified, by whom, and for what purposes?) To what degree is information about the innovation being disseminated by respected peers, champions, or change agents?
Trialability	*To what degree can the innovation be adopted on a limited or trial basis (this refers to both opportunity and suitability) or seen in action?*	To what degree can the innovation be demonstrated and trialed through the partnership?	Are there accessible, publicised trial and demonstration projects that show the innovation in action? Are potential adopters able to experiment with the innovation without fully adopting?	Do peer networks permit exposure to innovation in action (e.g., peers sharing access and experience)?

4 Adoption and diffusion patterns in three technology families

The case study portion of this project aims to add some context to the framework to help imagine different scenarios in which these factors exercised influence on adoption decisions and diffusion processes. The cases also enabled us to test and refine our framework.

Learning from the past...

In each of these cases, the technologies were transformative in their eras, representing major and disruptive step changes that shaped and reshaped entire industries. Steam power combined with a boom in machinery innovation reorganised industry around the factory system. Gas lighting, in turn, expanded productivity by increasing working hours and improving living conditions. The advent of antibiotics also increased productivity by dramatically improving lifespans, reducing sick times, and transforming medical practice and pharmaceutical manufacturing.

Diffusion patterns and timelines differed substantially across technology families where the nearly hundred years that it took from the construction of the first steam powered factory to the total domination of that model of industrial production stands in stark contrast to the decade that it took for antibiotics to become widely available. This is partly a function of the different time periods and contexts in which these technologies developed as well as the different market structures of the industries in question. Steam factories diffused more slowly predominantly through market mechanisms; whereas for gas lighting and antibiotics, public investment in infrastructure development and governance meant that they were not spreading exclusively through private markets. In these latter examples, intermediaries played an important role in deployment strategies and were critical in shaping narratives

For all of these technologies, adopters were highly willing to implement these advances. This is not to say that there was no opposition to adoption, but that where objections emerged, they were poorly organised and weak relative to decisions makers of the period. For instance, while the labour movements of the 19th and 20th centuries were successful at securing a greater voice for workers in business and government decisions, they were relatively nascent at the time of steam mills and gas lighting.

Consequently, constraints to adoption were most likely to emerge in the realm of capability– particularly cost, resources, and expertise to implement the technology – and capacity where holdouts had differing views of the opportunity costs of adoption. On the capability side, costs (predominantly capital costs) undoubtedly played a role, but were overshadowed in the historical record by things such as access, reliable supply, and availability of appropriate skills. For instance, lack of local infrastructure was one of the biggest barriers to widespread adoption of gas lighting. Constraints in skilled labour supply caused delays in wider adoption across all the cases in one way or another. Difficulties in producing antibiotics at scale held back wider use of the drug. The fact that infrastructure and public support have been vital to the advancement of many technology families over time suggests that it is highly likely that this is still true today and that contemporary public policy will play a vital role in the progress of future industries. It also highlights how important it is to look to the past to develop an understanding of how bold policies have shaped previous generations of technological evolution, to gather inspiration to design interventions to achieve similar goals today, and to justify public action. These are some of the key aims of this report and the examples contained within it.

In many of these cases, public investment and regulatory decisions helped to accelerate technologies to more widespread adoption. In the case of gas lighting, governments paid to have networks installed for street lighting, which was then available for commercial and private use. This investment in public infrastructure helped to defray high capital costs of gas networks, which reduced the price of individual connections and made the technology more accessible to businesses. The race to produce antibiotics at scale required significant public investment and laid the foundations for the modern pharmaceutical industry. In both cases, private innovation, industrial expansion, and wider adoption was possible by investment in public goods.

Finally, it is important to remember that adoption stories are varied, complex, and, in many ways, serendipitous to the extent that they often rely on the development of ancillary innovations to be viable. Steam powered factories took a long time to proliferate in part because of the slower development of machinery to take advantage of the new power/production model. Gas lighting was only possible because of advances in distillation systems and pressure tanks. These developments were not recognised or highly coordinated at the time but in hindsight were nonetheless crucial to evolution along technological trajectories. While we may not be able to recognise a “perfect storm” of fortuitous technological evolution in the moment, this insight is useful in that it leads us to ask what complementary technological impediments might be holding back the development of a target technology and explore whether interventions might be needed to unblock latent potential.

Examining the present...

The present case studies offer a contemporary glimpse into adoption and diffusion patterns. Viewing these technologies in the midst of their diffusion journeys makes it difficult to evaluate with certainty whether these will ultimately be success stories or whether, looking back, we will consider their rollouts slow or challenged. This is also complicated variations in technology maturities. Industrial robotics and solar panels can be considered relatively mature technologies that have become more frequently adopted as efficiency has increased, costs have fallen, and improvements have increased the variety of offerings available. mRNA vaccines, by contrast, are still relatively new, though arguably have enjoyed the most widespread adoption.[4]

Certainly, from this vantage it is easier to observe and understand constraints to widespread adoption and diffusion of these technologies. Our research for these cases relied on interviews with experts as well as secondary sources. Consequently, it was much easier to assess willingness than in the past case studies where the reasoning of firm leadership was often lost to time.

Willingness varied significantly across technologies and different types of target adopters. For instance, for mRNA vaccines, adopters were predominantly health systems and the clinicians within them. External factors, such as the pandemic, increased the overall willingness of these actors to consider novel drugs. Strong public demand coupled with accelerated regulatory approvals and public health campaigns to drive acceptance also strengthened the willingness of adopters. Note that government here has played a strong enabling role in contrast to its more constraining role in the solar panel industry. Willingness to consider solar panel adoption, by contrast, has increased over time as adopters have become more aware, and convinced of, potential benefits of solar installations. Adopters in this space include organisations[5] developing solar farms to sell energy into the grid as well as business and individuals installing solar panels on their premises to lower their energy costs. Willingness has particularly expanded as the size and efficiency of panels has increased the potential benefits and lowered costs of adoption. The UK has seen a boom in recent solar projects and installations, indicating a broader acceptance of the technology. Most of the constraints in this industry are related to capability than willingness although as we detail below, current capability challenges may have a significant effect on willingness to consider solar for commercial clean energy generation. The UK ranks less well internationally on industrial robotics adoption. Here, willingness is tempered by a perception (and perhaps, in many cases, reality) that robotics are not suitable to existing production processes and market structures as well as some behavioural reluctance in certain market segments. This explains vastly different patterns of technology uptake across different industries, where automotive and logistics have high levels of adoption in contrast to other manufacturing industries.

Adoption of some of these technologies has also been slowed by capability constraints. Cost is a perennial, though not only, constraint on capability. In solar and industrial robotics, for example, high costs have played an important role in dampening adoption rates. While costs continue to fall and efficiency increases cost remain prohibitive for some adopters in both industries. Technology implementation for both has also been constrained by skills availability as robotics requires significant upskilling while solar installers are struggling to

[4] This is measured predominantly through the widespread deployment of the COVID vaccine. However, it is worth considering whether mRNA vaccines will be as widely accepted in less acute and widespread health crises.

[5] These can be private corporations, public-private partnerships, or community groups.

keep up with demand. In solar, a massive backlog of grid connections has left viable projects stranded with some estimates citing a 10-year delay to integrating new sites into the energy system. These backlogs send a powerful signal to investors to hold off adoption of solar technologies in energy projects. Capabilities do not appear to have been a significant constraint on mRNA vaccine rollouts to date.

Capacity is related to the ease with which resources can be dedicated to technology implementation, which particularly affects the adoption of industrial robotics. Integrating these systems requires downtime to production lines and diversion of staffing that creates opportunity costs for companies thinking about adopting this technology. Demand and production cycles create uncertainty about timing of return on investment. The flexibility and lower costs associated with alternatives to robotics – such as flexible labour – also generate reluctance to change course.

The present cases share some consistencies with the past but demonstrate that yesterday's adoption barriers are not the same as today's - even within the same technology families. This is important to keep in mind when drawing lessons from the past and present to inform our understanding of the challenges that might emerge in emerging technologies.

Looking to the future...

While we can learn from the past and explore whether similar adoption challenges have emerged in the present across technology families, it is also useful to apply what we have learned to understand what challenges might lie ahead for future generations. This provides an opportunity to use the frameworks to illuminate potential constraints to adoption that might not otherwise be obvious from within these evolving industries. For each of the cases, we ran through the frameworks and drew on lessons from the past from all technology families to inform what we thought might occur in the future. It is important to note that we explored all aspects of the framework, not just the ones that have proved relevant in previous generations, to more thoroughly explore potential constraints. This is particularly important given that even though there are some continuities across technology families, there have also been considerable differences in the challenges that have constrained adoption across time periods. We also used the frameworks to guide discussions with members of industry, prompting them to speculate on what was yet to come and probing them about how past experiences might inform the future. This process was valuable in ensuring that the frameworks had no glaring gaps, at least as seen from the vantage of the present, and challenged the participants to consider pathways of technological evolution they might not otherwise have. While we do not claim these frameworks enable perfect predictive power, we discovered that they were valuable in facilitating these speculative conversations and that examples of past and present challenges across all technology families made it easier to imagine how the future might play out.

Like in the past and present cases, the future technologies are at different stages of technological development, which makes future adoption challenges and diffusion patterns difficult to predict. While genetic (CRISPR) medical interventions are still in their infancy, one has already reached market and been adopted. Cobots, the next generation of industrial robotics, are even more advanced, with different prototypes and applications rapidly evolving and market proliferation already underway, if tentatively. Nuclear fusion has been under development for a long time and is relatively technologically advanced, has not yet evolved to the point where market applications are possible, even in the medium term. However, drawing some lessons from the past and present, and relying on the framework, we can look forward to document and anticipate potential opportunities and constraints to adoption. Here the framework is important as it helps to consider potential blind spots.

Genetic solutions to medical conditions are the cutting edge of healthcare interventions. However, the intervention that does exist is currently incredibly expensive. Even though willingness to use experimental treatments is relatively high, adoption is, limited and only possible through government negotiated preferential pricing to the NHS. Costs are much higher per patient than other forms of intervention because treatments are individualised and require precision to administer. For the foreseeable future, many emerging CRISPR derived treatments will challenge the means of government health systems and are likely to only be available in selected locations that concentrate access and expertise. While willingness to consider genetic treatments is currently relatively high, this is partly because it is dramatically more effective in treating sickle cell disease, a painful and debilitating blood disorder and because of its cost it is available only to people with extreme cases. However, ethical concerns regarding the use of genetic modification may constrain adoption of this and other genetic therapies. As in previous generations of drug and treatment evolution studied here – antibiotics and mRNA vaccines – the UK government is likely to play a decisive role in shaping the adoption trajectory on both the supply and demand side. On the supply side, supporting researchers to enable the development of more gene therapies as well as the technologies that enable them will be crucial to reducing costs and scaling up access. During the pandemic, we saw how important government support was in both accelerating vaccine development, managing approvals, and enabling production. In the interim, the NHS will likely negotiate directly with providers to drive down costs. On the dissemination side, the government and its intermediaries can play an important role in spreading information and making sure potential providers have access to appropriate resources. Public and industry focused education about the benefits of genetic treatments will reduce resistance, drive demand, and increase uptake.

Cobots, a type of industrial robot designed to operate in close proximity with human workers, pose a different set of challenges. UK companies have not generally adopted industrial robotics at the same rates as international competitors. In the present, this is partly a function of the nature of manufacturing and market cycles. However, the greater customisability expected of the new wave of cobots suggests that the emerging generation of industrial robots may be better suited to the bespoke, smaller volume production environments of manufacturers that have so far been reluctant to adopt robotics. This potential advantage, however, may not detract sufficiently from some of the constraints that are likely to carry over, such as the benefits of relying on more flexible and relatively inexpensive labour, behavioural considerations about alignment of robotics with existing ways of working or business values, or workforce resistance. Or allay new concerns around ethics or privacy of these highly connected devices or related to worker safety, fulfilment, or productivity. Stakeholders seeking to shape the diffusion of cobots can use the framework to ensure that businesses and intermediaries are communicating effectively with potential adopters and develop a clearer sense of which factors are impinging most on adoption decisions.

Nuclear fusion is still a long way from being a reality. The most immediate barriers to commercialisation relate to technical and economic feasibility. Supply chain issues related to sourcing specialised materials are also likely to raise costs. However, expectations are that these challenges will diminish over time, while other obstacles may rise to take their places. Once nuclear projects become more realistic, public perception may exert more of an influence on whether and where facilities can be developed. These perceptions, and their effects on adoption decisions, may be tempered by geopolitical and social changes that might increase the attractiveness of clean and locally generated energy. The solar case study showed that backlogs in connecting new energy projects to the grid can slow energy project development and can therefore act as a brake on new energy technology adoption.

The challenges the future holds are far from certain but reflecting on them with the benefit of the framework and knowledge of past and present experiences helps to illuminate likely pinch points. One consistent point across all of the cases is that there appears to be a strong role for public intervention. Whether that is through leadership within the NHS negotiating terms that make mRNA treatments more accessible, shaping regulatory environments (for example) to mitigate privacy concerns associated with networked cobotics, in providing funding for and education to reduce public anxiety about nuclear fusion, or in ensuring that complementary technologies and practices are supported to evolve in parallel, the Government may play a decisive part in accelerating future technology adoption.

Charting a path

There is no such thing as a crystal ball, but combining insights from case studies with the adoption and diffusion frameworks can help those interested in accelerating diffusion understand what questions to ask to understand existing and unfolding adoption patterns. In what follows, we detail the adoption and diffusions trajectories of three different technology families, applying the framework in practice. The summary above, and the more detailed case studies below, make it clear that while the categories of questions set out in the frameworks apply across technology families and across time, how they play out in each context is very different. Looking at technologies over time demonstrates how the conditions and considerations of previous generations do not always carry over to subsequent generations. Consequently, making assumptions about technology adoption based on past experience alone can lead to significant blind spots in emerging technologies. In presenting a framework that formulated around high-level questions, the adoption and diffusion tools we provide here provides guidance to help uncover and diagnose factors that might affect the ongoing and future diffusion of technologies and to offer solutions to improve adoption outcomes.

4.1 Advanced materials & manufacturing

4.1.1 Steam powered mills, factories, and early production lines

The earliest known factory in the UK, the Lombe silk mill, was founded in Derby in 1721 (Calladine 1993). The factory model brought together several innovations – technological, architectural, organisational, and beyond – that came to characterise the “factory system” that we continue to recognise today. These include the combination of a large workforce engaged in coordinated production using externally powered equipment. While we now see this model of production as standard, at the time this degree of centralisation of labour and resources combined with machinery capable of producing at unprecedented scales represented the “beginning of a new world” (Freeman 2018, 2).

Despite ushering in this “new world” of industrial production, the factory model initially spread quite gradually (Floud et al. 2014, Musson 1976) reflecting the power of management and leadership interests in adoption considerations. Different models of production, including craft and protoindustrial, driven by different power sources (animal, water, and steam) co-existed until the mid-19th century with considerable evolution in the machinery available occurring during this period. In part, this was due to weaker diffusion processes. The relatively small number of factories made observability and trialability quite low. Also, it took time for people to recognise that technology relevant to the textile industry could be applicable in others.

Factory inspection records from the 19th century confirm that the textile industry – particularly cotton – were early adopters of steam-powered factories and that as late as 1870 over half of total manufacturing steam power (excluding coal mining) was operating in this sector (Musson 1976, Bottomly 2024). While a diverse set of industries began using steam power, the next boom in steam-powered factories occurred in large scale smelting and metalworking as the parallel development of the steam locomotive and rise of railway development fuelled demand for iron, and then steel, building materials. Referring back to the framework, this demonstrates the power of external context – in this case demand for processed steel – in driving increased adoption of steam and other forms of industrialisation.

The fact that the transition to the steam-powered factory model took place over more than a century and proceeded at different paces for different industries documented with varying degrees of detail complicates an analysis of adoption patterns. However, at a high-level there were few significant non-financial barriers to willingness, capability, and capacity. The framework emphasises that technology’s ability to provide compelling solutions to real problems is one of the foundations of adoption. Steam power solved an important production problem by providing a solution to scaling industrial activity. The clear advantages to production speed and scale coupled with rising demand for industrial products (particularly textiles, metal, chemicals, and machine manufacture) created powerful economic incentives for those with the resources to invest in industrialisation. Widespread adoption of the factory model required associated innovation in the development of machinery for different industries and increased costs for early entrants. As a result, it relied on external factors to ensure effectively translate the value of steam power. These were not limited to technological innovations. Private experiments with consortia and corporate structure resulted from the high capital costs associated with building and equipping factories and drove innovation in business models. This development, in turn, changed the decision-making dynamics within businesses, making adoption decisions the collective remit of management and boards of directors rather than individual owners. Beyond the potential for profit, factory ownership and investment created a new class of wealthy industrialists and a social inducement for presumptive investors to shoulder the costs and risks associated with factory development (Freeman 2018).

While industrialisation and the broader adoption of the factory model certainly met resistance in the workforce these efforts were not enough to significantly derail or delay adoption in the face of sufficient corporate willingness. Our framework developed several elements of the workforce category in response to the "machine breaking" reactions of labourers of this period. In most cases, the introduction of steam machinery was a major departure from previous production processes. However, this misalignment was the point - perceived as an advantage rather than a constraint to adoption. Industrialisation also transformed ways of working – eliminating certain types of skilled labour and substantially changing the cadence of working life – which, in some cases, led to labour unrest such as strikes and machine breaking. However damaging these incidents were in the short term, they did not substantially discourage factory managers from adopting innovations. While modern resistance to automation among workers rarely adopts the more violent forms of protest that were employed in this period (e.g., riots, damaging or sabotaging machinery) it is important to consider workforce sentiment in understanding adoption decisions.

Lack of capability in adopting the factory model was more of a challenge. While the transition to mechanisation decreased demand for highly skilled workers, factories required more expertise in building, installing, operating, and maintaining equipment. Management practices also evolved requiring skills adapted to supervising systematised production. Inadequate access to coal to fuel steam machinery, or infrastructure to effectively centralise resources and move finished products could also function as a constraint. Given that many of the businesses that adopted the steam factory model were formed to take advantage of the new technology, capacity constraints associated with existing production were rare.[1]

The factory system ushered in a new era of industrial organisation that has shaped the modern world and its economy. In an era with weak labour protections, constraints to adoption were predominantly related to costs, availability of appropriate machinery, and access to resources rather than social, behavioural, or cultural factors.

4.1.2 Industrial Automation & Robotics

A robot is a versatile, programmable machine capable of performing different tasks by manipulating materials, parts, tools, or specialized equipment through pre-defined motions. Robots are widely used to replace or assist human physical labour in numerous industries, spanning from the primary sector and manufacturing to transport and logistics.

Industrial robots were first introduced in the 1950s and became more common by the 1980s when robotics shifted from heavy lifting to tasks like materials handling and precision work. By the late 1970s, robots were capable of more complex functions, such as material transfer, painting, and arc welding (Misiti 2020). Since the early 2000s, advancements in software have been the primary driver of progress in industrial robotics. Emerging technologies like machine learning (ML) and artificial intelligence (AI) are now expanding robotic capabilities, enabling them to learn, adapt, and make independent decisions without human guidance.

Evidence shows that the UK manufacturing sector significantly lags competitors in industrial robotic systems adoption rates, with one of the lowest robot densities among major industrialized countries. Recent data shows the UK has approximately 98 robots per 10,000 workers — significantly below the global average of 126 units (Industrial Compliance 2024). According to The Economist (2024), some UK industries have effectively adopted robotics, such as the automotive sector, which boasts 734 robots per 10,000 employees. Jaguar Land Rover's Solihull plant alone employs over 615 advanced robots (The Economist 2024). Automation is also widely implemented in logistics. Yet other industries lag considerably behind. MakeUK (2023) reports that most UK manufacturing firms invest less than 6% of their revenue in automation technologies.

The questions in the adoption framework offers some explanation. For instance, exploring the production category led us to understand that robotics technology is not perceived to align effectively with production processes and that these perceptions can differ across the segments of the industry. Most industrial robotics are well suited to large scale manufacturing environments characterised by high volume and low variability in items produced or tasks performed. This is why the automotive and logistics industries have traditionally had relatively high adoption rates. But much of UK industry is the opposite and characterised by more bespoke production runs or tasks and lower volumes. For businesses that fall into this category, robotics on offer may not be flexible enough to integrate into production or, if they are, may not be cost effective to constantly retool/repurpose. Rather than beginning with the assumption that industrial robots are right for every business in a given industry, diffusion efforts may need to start with a clearer understanding of opportunities and needs and how the current market may be failing to meet them (at a competitive cost).

However, in many instances, business leaders are aware of potential benefits of incorporating robotics into their production processes but struggle with other dimensions of willingness, capability, and capacity. In terms of willingness, observers in the industry continue to cite a focus on short-term payback rather than longer-term total cost of equipment ownership and maintenance. Robots are expensive, even if their prices have come down on average over the past decade, and so economic arguments for implementation need to be compelling. For many businesses, amortization times need to be relatively short but estimating these is complicated by the difficult to predict and cyclical nature of demand for their (limited volume, highly variable) product. For many, the risks associated with committing to an investment with highly uncertain payback timescales is too much to overcome. This is particularly acute as small average firm sized mean that businesses are less able to shoulder the high fixed costs of robots (The Economist 2024). The availability of an inexpensive alternative – cheap labour – also creates negative incentives to automation (Industrial Compliance 2024). For businesses with these highly variable demand profiles, relying on comparatively inexpensive labour enables them to increase or decrease employment in response to shifting demand much more quickly and cost effectively than idling expensive machinery.

Other behavioural issues related to management and firm structure also affect willingness. Family-owned businesses in UK manufacturing and foundation industries often profess to operate by traditional values of high quality, bespoke, craftsmanship or rely on processes that have historically not changed much. Often these businesses espouse family values, feel responsible for their employees, and will work to protect their livelihoods rather than replacing them with machinery. If things have always “just worked” the way they have always been done, business leaders may fear and avoid change. The idea of introducing automation into these contexts can be met with reluctance regardless of cost or risk.

These issues are largely understood by the people running programmes to increase technology adoption in manufacturing and beyond. Those in charge of delivering the Made Smart UK initiative offering digital manufacturing advice acknowledge that the behavioural barriers are among the most difficult to overcome. This is borne out by data that shows that firms have failed to take advantage of incentive schemes in large numbers (The Economist 2024).

Capability issues also hamper adoption due to workforce, management, production, and market considerations. 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. Many industries are facing skills shortages for roles that could operate and maintain robots. While lack of willingness of workers to adopt robotics was not cited in our interviews as a specific impediment to adoption, one interviewee mentioned that it was not uncommon for workers to sabotage robots (and that the disruptions are often calibrated to look like normal malfunctions that can be difficult to detect) if they were not consulted in the transition.

While workforce flexibility and cyclical demand might offer opportunities for training/retraining production line workers to use robots, lack of workforce capacity was also raised as an impediment to adoption. Tight margins mean that production systems cannot always accommodate the downtime required to integrate robotics. And while there may be resources available to support adoption, one commentator suggested that they were difficult to get and were often not accessible in feasible timeframes.

Despite the difficulties in encouraging more widespread adoption, data suggests that increasing adoption rates would pay significant dividends. The annual global economic impact of advanced robotics is estimated to be between $1.7 to $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 robotics 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 and Sorenson 2019).

4.1.3 Cobots & Industry 5.0

The diffusion of gas lighting revolutionised the manufacturing industry by permitting, for the first time, around the clock production. Along with the first wave of mechanisation, this development transformed the industry reshaping social behaviours and labour relationships in the process. The introduction of industrial robotics was the beginning of a new manufacturing revolution, spurring dreams of fully automated production lines capable of operating at higher speeds and efficiencies that minimised the need for human labour.

This automation underpinned the evolution of Industry 4.0 and focused on implementing, combining and integrating several technologies, such as AI, the Internet of Things (IoT), cloud computing, cyber physical systems (CPSs), and cognitive computing to drive "smart" manufacturing. The core challenge in this phase of evolution has been effectively linking machines and devices that can control each other throughout the life cycle in order to improve productivity and minimise human intervention in production processes (Maddikunta et al. 2022). While these challenges remain, a transition to Industry 5.0 is now on the horizon. This paradigm, coined by the European Commission in 2021, shifts focus from improving efficiencies in mass production towards increased customisation and consumer personalisation and recognises the importance of human ingenuity and creativity in enabling dynamic production processes. Where Industry 4.0 aimed to remove the human element from manufacturing, the evolving digital and automation technologies that underpinned the previous industrial revolution are now seen as tools to empower human workers rather than replace them (Rahman et al. 2024). This transition has modified approaches to industrial robotics design and applications and catalysed the emergence of cobots.

Collaborative robots ("cobots") are a relatively new type of robot designed to operate safely in proximity or in direct contact with humans. They use 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). Unlike traditional industrial robots that are often physically separated from other production for safety reasons, cobots are specifically conceived to share workspace with human workers, facilitating cooperation and teamwork between humans and machines and, eventually, learning from human behaviours (Weiss et al. 2021). The primary goal of cobotics is to augment human capabilities, enhance productivity, improve efficiency, and ensure a safer, more creative, and more flexible work environment.

As the age of cobotics dawns, the adoption framework offers some clues to the barriers that might affect decisions to explore adopting and implementing these technologies. In many respects, cobots share similarities with previous generations of industrial automation and adoption trajectories are likely to be similar. Like industrial robots, they are designed to take on repetitive, dangerous, and monotonous tasks that require dexterity and accuracy. Existing and prototype cobots have been designed for sorting and inspection tasks; packaging and palletisation; precision welding, cutting, and fastening activities. The aspiration is that cobots will be increasingly reprogrammable and flexible – capable of rapidly adapting to new tasks.

Depending on degree of flexibility, this feature may mitigate one of the largest challenges identified to industrial robotics adoption related to alignment with production processes. That is, that previous generations of robotics have been insufficiently adaptable to bespoke and lower volume production models. Adoption of these technologies is likely to be more widespread as the potential for cobot flexibility increases. However, it is important to recognise that advances in flexibility may not be enough to mitigate barriers to adoption willingness such as the significant cost considerations (capital costs are likely to, at least initially, be high) or sufficiently offset risk in the context of cyclical production demand that characterises many UK manufacturing industries. Large industries with high volume and standardised production models were the earliest and most successful adopters of industrial robotics in the UK, but cobots may challenge this pattern. Interviewees we consulted noted that because they are designed to work with humans, cobots typically operate at slower speeds and lower capacities than other industrial robots, making them less suitable for higher volume production environments. Interestingly, research suggests that this design feature makes them more suited to the higher variability, lower volume production (European Parliamentary Research Service 2023) that characterises the UK manufacturing landscape leading to the possibility that cobots could enable businesses in this category to leapfrog larger more standardised industries in adoption. While this may be likely in the longer term, current studies suggest that larger industries have been more active in adopting these technologies (Weiss et al. 2021).[6]

Historically, the consideration of worker rights and wellbeing has been portrayed as secondary to profit maximisation in manufacturing industries. While the case of industrial automation and reported reluctance to adopt technologies that might make workers redundant (especially in smaller family firms) challenges this perception, the advent of Industry 5.0 may usher in broader changes. The emphasis of the importance of humans in production by leveraging their creativity, problem-solving abilities, and decision-making skills re-centres workers, their capabilities, and their wellbeing as well as themes of sustainability and industrial resilience (Narkhede et al. 2023). This recentring and revaluing of their creative (etc) skills may increase the willingness of workers to accept and integrate cobot technologies relative to earlier waves of industrial robotics. Recent research exploring technology acceptance suggests that there are quite a lot of nuances in this position. The nature of the cobot, its capabilities and how well it complements, rather than replaces, human agency is likely to be determinative of worker attitudes towards adoption and their use of cobot

[6] Note that this could be because it is easier to profile larger firms (such a Coca Cola, Boeing, and Amazon) because they publicise their innovations more.

technology (Liao et al. 2023). Similarly, worker skill level and availability of training will also shape attitudes towards the technology and determine if business have the appropriate capabilities to implement cobots into their production systems.

These concerns about functional relationships between worker and robot may also be compounded by ethical and legal considerations related to liability, data privacy, and ethical AI usage (Rahman 2024) - external factors that can significantly influence firm decision making. These concerns are likely to affect both willingness and capability to adopt. Industrial regulatory structures have not (yet) produced clear guidance on these matters, and this challenge is likely to compound as different types of cobots, with different data and AI use profiles, become available.

The link between Industry 5.0 and sustainability may represent an opportunity and reduce barriers to adoption through changing external and market conditions. Social responsibility expectations and customer demand for sustainably produced goods may drive cobot adoption on reputational grounds. For this to be a reality, much will hinge on cobots' ability to deliver sustainability gains. But, to the extent that they materialise, this messaging may be useful to stakeholders seeking to increase diffusion.

In addition to skills, ethical, and legal concerns, complications around cobot integration may challenge the capabilities of business to adopt this technology. Working in close proximity with humans may require additional infrastructure and technology adoption, such as wearables, IoT connectivity, sensor networks, and other smart technologies. These are external resources, cost and access to which can affect capability considerations. Similarly, cobots are likely to change ways of working in significant ways, requiring the implementation of new processes and procedures as well as considerations of workforce buy in. Each additional technological and behavioural change requirement strains business implementation capabilities and reduces the likelihood of adoption.

As with industrial robotics, capacity constraints to adoption are likely to be linked to opportunity costs associated with cost and flexibility advantages of relying on human workers for many manufacturing business models, with availability and potential alternative uses of resources (including management time), and with risks associated with disruptions to production lines.

4.2 Energy & Environmental

4.2.1 Gas lighting

Early gas lighting technologies consisted of the equipment needed to generate gas (in the UK this was typically from coal by a process of heat distillation that produced coke and gas), the pipes and storage tanks (and eventually meters) needed to distribute the gas to lighting, and the lighting fixtures themselves. While much of this technology existed (for example airtight pipes and storage for steam), it was not used for lighting until the late 18th and early 19th century. Prior to this tallow and oil lamps were the primary source of light, however, they were expensive, highly polluting and required high levels of labour intervention to keep safe

(Falkus 1982). In many ways, the innovation of this period was putting together existing technologies that made gas lighting widespread.

The light fixtures that enabled gas lighting had been proposed across Europe since 1775; however, the technological capabilities only developed into an industry in 1795 (Tomory 2011). Technologies such as Alessandro Volta's 'inflammable air lighter' (1776) and Jan-Pieter Minckeler's gas lighting in his lecture hall (1784) demonstrated the feasibility of gas for lighting however Tomory (2011) suggests these were produced as curiosities rather than for commercial applications. While historians argue that a need for security and social order, or a desire for increased working hours might have created the impetus for gas light technology commercialisation, its proliferation was also driven by access to the natural resources available in the UK (coal in particular) and technological developments in other industries, namely distillation (Tomory 2011).

Initial efforts in gas lighting focused on installing supply (coal gas distillation systems) onsite where the lighting was required. It was this style of gas lighting system that Boulton & Watt – the steam engine manufacturing company - played a key role in developing and installing (Falkus 1982; Tomory 2011). The early customers of gas lighting were factories which had an existing relationship with Boulton & Watt and showed a strong willingness to adopt the technology. In this period, adoption decisions, and subsequent technology diffusion, were shaped by the productivity potential of the technology (relative advantage) and demonstration effects (observability) from trusted sources even though costs were relatively high. Despite early success, Boulton & Watt's interest in producing these onsite systems of gas lighting waned (Falkus 1982).

Boulton & Watt wound down operations around 1810 prior to the creation of the chartered London Gas and Coke company in 1812 which, rather than focusing on decentralised supply of gas, looked to create a centralised system of supply and pipe gas throughout the city – modelled on the water companies (Matthews 1985). This development significantly changed incentive structures and paved the way for wider spread adoption. The success of the London Gas and Coke model created a boom in the market for gas and therefore an uptick in incorporation of gas companies; many were set up over the period 1812 to 1860. The boom in supply activity was not limited to London and large metropolises. By 1826, even relatively small towns (those with populations of 10,000) had gas provision, predominantly for lighting (Falkus 1967). Adoption of gas into a new city or town typically started with a contract to provide to the municipality with street lighting (Falkus 1967). Installation of gas works in smaller areas relied on a small set of highly skilled engineers who typically came from London either on the invitation of local interested parties, or speculatively, and set up works using lines of credit from the bank and their suppliers rather than from raising investment as had been done in the larger metropolitan ventures (Falkus 1967). Consequently, adoption in this phase of development was limited to businesses that had the opportunity to connect to expanding infrastructure systems, a government decision, although one that was certainly influenced by business sentiment, and the availability of skilled labour to make the connections. Once connections were available, most businesses that were likely to reap productivity benefits – in our framework, that where relative advantage was clear (diffusion framework) and where it enhanced production practices (adoption framework) - were willing to adopt the technology. Given the geographical nature of infrastructure development, high levels of observability increased the speed of diffusion and the competitive pressure of peers using the technology, an external factor in our adoption framework, created high inducements to adopt. At the same time, businesses were highly receptive to new lighting sources as international conflict had increased the price of tallow, reducing its cost advantage over gas fittings. We see parallels in the present day where foreign conflagrations have had implications for energy prices, increasing the attractiveness of renewable sources of energy.

On the supply side, workforce availability significantly affected the timing of infrastructure rollouts. The other set of skilled workers involved in gas were on the generation side – the coal stokers in the gas works. General workers came from other industrial trades to work in production of gas bringing additional capabilities. These workers were often subject to seasonal demand which added complexity to industrial relations (Melling 1979). Skills and experience from the iron founding industry were supportive in making the transition into gas distillation in Boulton & Watt - particularly their experience of developing and manufacturing parts that could handle gas (Falkus 1982). This related too to their work in steam engine production. Interestingly, the introduction of gas lighting and power had significant impacts on labour organisation and, as with the diffusion of steam power, stoked labour discontent. Coal stokers were key in founding the Gas Workers and General Labourers Union (founded in 1886 and now GMB) (Melling 1979). There is a complex interrelationship between industrialisation, labour rights and artificial lighting. Cheaper, safer and more reliable artificial lighting for factories obviously allowed a continuation of long working hours for British workers. Yet the Gas Workers and General Labourer's Union are associated closely with the fight for an 8-hour working day. The formation of the Gas Workers' Union coincides with increasing electrification however and once more shifting technological landscape. Production was largely only hampered by strike action by stokers in the later part of the 19th century. This episode demonstrates how important labour considerations can be in adoption decisions. While the needs of labour were rarely taken into account during this period, the reaction of workers to the introduction of new, particularly disruptive, technologies likely to significantly change or eliminate jobs has become a much larger consideration. It is partly in response to historical resistance by labour to steam and gas technology that we added the workforce row to the adoption framework.

Capacity was mainly hampered by difficulties in providing consistent provision of early coal-gas (Tomory 2014) the parallel development of storage technologies ultimately helped to overcome those challenges (Tomory 2014). Economies of scale and demand provided the motivation for this - particularly once the London & Westminster Gas and Coke Company were founded. Overall market demand drove the commercialisation of gas lighting technologies, with the UK being best placed to exploit this opportunity due to its natural resources and well-developed similar technologies and skills in industries such as iron and steam. Solar Energy & Renewables

Solar panels are the key technology used in generating electricity from sunlight. They play a core role in the renewable energy sector and the global goal to reduce greenhouse gases to prevent global warming of above 1.5 degrees higher than pre-industrial levels. Solar panels are made up of a number of solar cells. The first solar cell was created by Charles Fritts in New York in 1883. This early cell lacked efficiency as it was only able to convert 1-2% of light into energy (Elliot 2024). The quest for increased efficiency in converting light into energy is a constant challenge in solar cell technology development. In the present context, solar energy is an important part of the renewable energy market in the UK and is seen as vital to achieving Net Zero goals by reducing the need for fossil fuels which emit high levels of greenhouse gases – the main cause of climate change. The UK recently recommitted to increasing solar energy generation by setting a target of 45-47 GW of solar energy generation by 2030; an increase of capacity of around 36% is therefore needed (HM Government 2024b).

Contemporary solar cells are made predominantly from silicon and have a maximum efficiency of 29% in converting light to energy (Carrington 2023). Up until recently, low relative efficiency levels had reduced the attractiveness of solar energy to both utilities and as commercial solutions. However, recent developments in perovskites (a crystalline compound) are set to enhance that efficiency as used in combination with silicon (tandem cells) they can capture different colours in the light spectrum, increasing their efficiency to up to 33.9% (Elliot 2024).

Solar is beginning to gain traction in the UK market: 1.6 GW of solar PV generation capacity was added to the UK's solar energy generation over the year of September 2023 - September 2024 (HM Government 2024(a)).

The largest growth in deployment has been in larger installations fuelled by the growth of solar plants (Barrett & Scamman 2023). With respect to the adoption framework, external and environmental factors play a large role in this market. The oldest solar plant was opened in 2015 (Sunsave Energy 20Large scale installation of solar farms typically have ground mounted panels and have specific requirements that land is flat and/or is south facing (Barrett & Scamman 2023) to maximise light capture. This limits where and how large industrial solar installations can get and shapes utility investment decisions. Presently, 43% of UK solar farms are in the south of England (Rankl 2024). Energy is distributed in the UK via the National Grid, which is owned by National Grid Plc in England and Wales, and Scottish Power Energy Networks and Scottish and Southern Energy Networks (SP Energy Networks n.d.).

However, sources from the industrial development side of renewables say that the grid is the number one hurdle holding back more solar energy development in the UK with challenges relating to old infrastructure, which in turn does not handle local site generation or variable generation well. This increases costs and expected returns from adopting solar technologies. Government regulation is also holding back further solar adoption. There is also a significant backlog of applications to be connected to the grid to feed energy with estimated wait times hovering at 10 years (Vattenfall 2024; NDT Group n.d.). Connection applications were paused in January 2025 to alleviate the backlog (Johnson 2025) but this severely limits the pace of investment in and adoption of solar technologies. Battery storage is one potential solution to manage feeding into the grid as well as storing for use on a local site. This is a potential area where government intervention could speed progress towards maturity of a complimentary technology (local batteries and microgrids) to ensure that momentum in solar adoption is not lost. However, ambitions are reportedly lagging need as the UK government has predicted the UK will need 23-27 GW of battery storage to support its 2030 clean power ambitions (HM Government 2024b).

Public resistance to solar farms can be another constraining factor to the development of large solar sites although solar records the lowest opposition out of all renewable installations with just 9% of people saying they would be very or fairly unhappy with having a solar farm constructed in their local area, compared to 83% who said they'd be happy or very happy (HM Government 2024c). However, rural communities were more likely than urban ones to express concern over land use (20% compared to 10%) and oppose solar farms on the basis that there would be a lack of benefit to local communities (45% versus 29%) and to the local economy (40% compared to 29%) (HM Government 2024c).[7] There is also a role here for government intervention to address community opposition where it flares up. That said, increasing the pace of grid connections is presently a higher priority to accelerating development and adoption.

Outside of utilities, the adoption of solar energy generation relies on the willingness, capability, and capacity of users to install solar panels across domestic and industrial sites. In the domestic market, the decision to adopt solar panelling at scale is largely in the hands of developers. As with many of their inputs, they are sensitive to costs and regulatory considerations that may increase the attractiveness of solar. They are also influenced by consumer demand, which is increasingly receptive to sustainable development. Rising energy prices (another external variable) are likely to raise the attractiveness of having local, renewable energy as an option in new developments, which will likely increase pressure on developers in the future. However, installing solar panels and associated infrastructure requires specialised skills, which may limit developers' capability to deliver solar as an option. Similarly, other external factors, such as alternative energy saving options are also increasingly available (e.g., heat pumps, more efficient and affordable window options, and energy conscious building techniques), may be more attractive to developers seeking to provide a more sustainable offering, thereby limiting adoption of solar solutions. There are

[7] Sector based bodies disagree about the potential impact of solar panels on land use, for solar farms versus for agriculture (Rankl, 2024). Large scale solar farms are typically owned by private firms, but community ownership of renewable energy has been increasingly popular, in particular, the biggest UK transfer of solar farms saw eight sites pass into community ownership in 2024 (Martins, 2024). Models such as community ownership can create a stronger support for solar farms in the future as communities benefit more directly from having them located nearby.

1,478,101 domestic solar PV sites in the UK as of December 2024, while this number represents significant process over the last 15 years, the total figure still represents a small fraction of domestic properties in the UK.

The potential for medium sized installations on industrial and warehouse buildings remains a key target for government as it has been suggested that warehouse rooftop space could provide 15GW of new solar capacity (UKWA 2022) given that 90% of the UK's total roof area is large factories, warehouses and agricultural buildings (Barrett & Scamman 2023). The UK's Warehousing Association (UKWA) has identified that although the payoff for installation costs can take 4-6 years and provide a return of 10-15% if self-financed, low levels of energy demand in many warehousing buildings means that for many they do not fit the typical cost/benefit profile of industrial buildings (UKWA 2022). This significantly reduces willingness of industrial units such as warehouses to adopt this technology. As with domestic applications, installations require specialist expertise further increasing costs to building/business owners. Furthermore, solar installations can complicate the liability relationships between landlords and tenants, affecting the capacity of businesses in leasehold situations to adopt the technology (UKWA 2022). Outdoor carparks are also identified as a key potential market for medium scale solar PV installation, however, the data available are limited (Barrett & Scamman 2023) and as such the government will call for evidence in 2025 to inform their approach to encouraging solar panels in car parks (UK Government 2024b). Business installations that make up the bulk of medium size installations are often motivated by reducing their energy bills by producing and using their own energy on site (Business Energy Scotland n.d.).

The UK Government has multiple motivations for encouraging wide scale adoption of renewable energies generally, including solar, beyond the environmental impact of fossil fuel energy generation and its link with climate change. A particularly strong motivator comes from Russia's invasion of Ukraine which highlighted the need for (local) reliable energy sources, that would not be affected by international conflicts.

4.2.2 Nuclear Fusion

Nuclear fusion refers to the process of combining two atomic nuclei to form one heavier nucleus, which generates large amounts of thermal energy (IAEA 2023). It is the same process which happens on the sun (IAEA 2023). Nuclear fusion requires extremely high heat and pressure to create a plasma state which allows the nuclei to overcome their natural repulsion (IAEA 2023). Early breakthroughs in fusion technology development came in the 1950 from the Soviet Union where the first tokamak and stellarator machines were created. The oil crises of the 1970s saw a renewed interest in nuclear energy from many countries (World Nuclear Association 2024), again highlighting the role of energy security as a motivator for increased public sector interest (and investment) in new energy sources.

Current research in nuclear fusion energy development focuses on two main methods of creating energy from nuclear fusion: inertial and magnetic confinement (IAEA, 2010; World Nuclear Association 2022). These processes refer to the technologies used to contain the plasma created when heat and pressure are applied. Inertial confinement typically uses lasers, while magnetic confinement relies on magnets. In the UK research was predominantly focussed on magnetic confinement through systems such as the tokamak which was at the heart of the Joint European Torus (JET) experiments in Culham, Oxfordshire. While the UK is not involved in JET's successor (International Thermonuclear Experimental Reactor (ITER)) there is still much activity in nuclear fusion R&D in the UK including £650 million invested in the development of the first fusion power plant in Nottingham (Whiting & Torkington 2024) which it is hoped will be operational by the early 20240s (Innovation News Network 2022).

In the UK, there is significant investment from both public and private sectors as well as a mix of organisations experimenting and developing technologies to commercialise fusion energy. The UK Atomic Energy Authority (UKAEA) is an executive non-departmental public body overseen by the UK Government's Department for Energy Security and Net Zero and tasked with leading the development of fusion energy in the UK and maximising social and economic benefits from the related research (HM Government n.d.). But there are only two firms currently involved in commercialising fusion technology: Tokamak Energy and First Light Fusion Costs and market conditions currently create high barriers to entrants to the market and thus anything other than very early adoption of fusion technology. The road to achieving sufficient energy generation from nuclear fusion, such that it outweighs the large amounts of energy required to make the reaction happen, remains a long one. So far, no one experiment has yet been able to generate net positive energy to cover the energy used to create the process, suggesting it will take some time before capacity is able to cover demand let alone consistency during downtime. Related to energy level challenges to capacity is the difficulty in maintaining the high temperatures and pressures required to create plasma for long enough periods to generate continuous energy (World Nuclear Association 2022).

At present, external factors such as availability of materials are the main challenge for nuclear fusion technology and are likely to remain a production constraint in capabilities to adopt in the future. Materials used in the process need to be low activity i.e. that they "can be dismantled and disposed of relatively rapidly, without the risk of radioactive contamination" (UKAEA n.d.). They must also typically be nuclear qualified as materials can change when exposed to neutrons (UKAEA n.d.). They must be resistant to the high heat, pressure and corrosive materials used to create plasma (UKAEA n.d.). Technologies such as superconducting magnets are an essential but expensive component in the generation of nuclear fusion energy. Despite these challenges there is a perception that existing technology and workforce expertise are available to expediate solutions to these challenges for example adapting techniques used in aerospace manufacturing to fusion materials (Innovation News Network 2022). Furthermore, developments in fusion could see spillover benefits for other industries for example robotics developed for fusion could benefit space exploration (Innovation News Network 2022) and the semiconducting magnets used in fusion could benefit medical technologies such as MRIs

Once proven, fusion energy is likely to face many of the same obstacles as solar – factors that largely fit into the external and environmental grids of the adoption framework. Distribution of nuclear energy will be reliant on large scale, centralised energy plants, rather than localised energy provision, although some private actors have investigated creating compact fusion reactors which could be installed at sites such as factories to provide more localised energy (see for example Lockheed Martin's (n.d.) Skunk Works compact fusion experiments). As a result, constraints around grid connections, unless alleviated, will delay investment returns on fusion enterprises. Another external factor - public perception of nuclear fusion - will be an important component to commercialising the technology. As it stands, nuclear fusion appears to have low levels of awareness among the general public (33% have never heard of it), but overall support is strong in general for developing nuclear fusion technologies (33% support, 17% strongly support) (HM Government, 2024d). Distinguishing nuclear fusion from nuclear fission will be important, as there is a high level of opposition to new nuclear fission sites being built in the respondents' local area (17% oppose, 24% strongly oppose) (HM Government 2024(d)). The government will have an important role to play in regulations and messaging around fusion to help shape public sentiment that might otherwise be a significant brake on the diffusion of fusion technology.

In January 2025, the UK Government announced £410 million investment of R&D funding to significantly advance fusion energy over 2025-2026 which included Fusion Futures - "a suite of measures aimed at building fusion capability, including skills development and LIBRTI, a new fusion fuel R&D facility (HM Government, 2025(b)). Areas of skills expansion include engineers in superconductivity, power systems, cryogenics and neutronics (The Fusion Cluster, 2023).

4.3 Health & Wellbeing

4.3.1 Antibiotics

While the practice of using microbes to prevent and treat disease can be traced back to over 2000 years ago (Hutchings et al. 2019) the scientific discovery of what is now called antibiotics is often credited to Alexander Flemming discovering penicillin in 1928. Despite this, it was not until a decade later that penicillin was introduced as an effective treatment for bacterial infections (Sneader 2001) and real shifts in modern medicine occurred. Flemming struggled to attract the interests of chemists who would take the discovery on and develop it into a widely accessible medicine and eventually abandoned the effort in 1940 to focus on other pursuits. Fortunately, that same year, pharmacologist Howard Florey and biochemist Ernst Chain, both working at Oxford, published a paper outlining a method for purifying penicillin (Aminov 2010; Gould 2016). This breakthrough paved the way for penicillin's eventual availability for limited medical use in 1945 (Gould 2016). A UK based team collaborated closely with American scientists to develop the drug (Bud 1998). Florey and Chain did not patent the discovery, believing it would be in poor taste to do so, however other antibiotics were eventually patented in the US. The Americans' ability to scale up production led to debates and questions in Parliament, during the Second World War, about the role of the Medical Research Council in funding the development of penicillin (Bud 1998) and questions as to why the discovery was not patented in the UK.

Following a successful trial of penicillin in mice in 1940, scaling production for adequate supply became a serious challenge since it took gallons of mould broth to produce tiny amounts of the drug. In fact, the first human patient to be given penicillin eventually died of his infection, as there was not enough to treat him fully (Science Museum 2021). This represents an early capability constraint—a key element in our framework i.e.: the innovation (penicillin) had proven its value (and elicited high willingness to adopt), but production processes lacked the technical maturity and resources to meet high demand. Outsourcing of production to US pharmaceutical companies helped to scale up production and to augment limited supply. This transfer of expertise and production reflects a deliberate use of intermediary pathways to accelerate diffusion domestically and internationally.

Initially penicillin was grown; cultivated from a fermentation process, and it was this method that the American medical industry was focused on to meet the high short-term demands of the ongoing war. The consensus at the time was that this was needed while work was ongoing to develop the means to synthesise the chemicals in antibiotics (Bud 1998). This reflects a pragmatic trade-off between willingness (urgent medical demand) and capability (limited synthetic routes available). Indeed, work on synthesising antibiotics during the period around 1944 required large teams of chemists and the efforts were described as secondary only to the Manhattan project developing the nuclear bomb (Bud 1998). However, the costs of deep fermentation fell when the molecular structure was discovered and as such, the Anglo-American synthesis project was abandoned (Bud 1998). This mirrors how technological evolution often shifts the balance between capability and capacity considerations over time. Deep fermentation in itself was a technological innovation: prior to its use in creating antibiotics, medicines had typically been synthesised or relied on slow, low yielding extraction processes (such as those used in early penicillin development) (Quinn 2013). This process revolutionised much of the medical industry signalling a shift from chemistry to microbiology (Quinn 2013). By enabling mass production of biological agents, deep fermentation shifted pharmaceutical production away from traditional chemistry and toward industrial-scale microbiology, dramatically improving trialability and observability—two key characteristics that, according to the framework, drive faster diffusion.

Following the successful trial of penicillin in mice in 1940, scaling production for adequate supply became a serious challenge/barrier since “gallons of mould broth was required to produce just a fingernail of penicillin” (Science Museum 2021). In fact, even the first human administration of penicillin in 1941 on a police officer, Albert Alexandre, while starting to display notable signs of healing, eventually resulted in the tragic loss of the patient’s life because “the supply of penicillin quickly ran out and Albert’s infection returned” (Science Museaum 2021). Consequently, the use of human urine to extract and recycle penicillin and outsourcing of production to US pharmaceutical companies was resorted to scale up production and to augment limited supply. Thus, in the initial stage, limited production/supply scale was a big barrier to the widespread adoption of antimicrobial drugs in the UK. Therefore, stocks of penicillin were not available to the civilian population in the UK until after World War II had ended. This led to ethical questions on treating with penicillin for medical professionals who were treating prisoners of war (POW) with penicillin while the civilian population did not benefit from the medical advancement (Justham 2015). In line with our diffusion framework, this reflects a profound constraint on dissemination and equitable diffusion: although knowledge of penicillin’s benefits was spreading (increased willingness), capability was bottlenecked by supply shortages, and capacity (resources) was strategically rationed toward military needs. Furthermore, human factors like trust and perceived risk—key considerations in adoption decisions—also emerged as major barriers: for instance, prisoners of war were reportedly convinced that the injections were to poison them, so practitioners would leave small amounts in the bottom of the vial used to treat the POW and collect the ends to give to very sick civilians[8] (Justham 2015). This highlights the importance of our framework's emphasis on social factors and their influence on adoption, particularly negative framing and lack of observability of treatment outcomes, which can sow mistrust among target users; hence policymakers need to take this into account. Penicillin was initially delivered intravenously which did not necessarily require any new training for practitioners, however, it was described as painful for the patient and involved challenging preparations (Justham 2015). The introduction of antibiotics did, however, change the practices and perceptions of nurses during WWII, with nurses from the time describing it as transformative as they spent less time treating infections (Justham 2015).

The golden era of antibiotics (typically described as 1940-1960) coincided with the postwar creation of the NHS in the UK (1948) which in turn changed the institutional structure and the ways in which medical care was delivered. Antibiotic resistance was identified even prior to the Golden Age of antibiotics driving the need to discover new variations to treat resistant cases (Lobanovska & Pilla 2017). As such the challenge of the 'discovery void' in developing and introducing new antimicrobial drugs and diagnostics (Renwick et al. 2016; Scannell & Bruce 2015) was and is increasingly important. This started to become an issue from 1987 onward. During this period, a marked decline in further research in antimicrobial drugs was observed (Durand et al., 2019; Chopra et al. 1997). This decline has been attributed to various scientific, regulatory, and economic challenges (Luepke et al. 2017).

In addition, the regulatory and policy framework was another significant barrier to widespread antibiotic adoption in the UK and globally. For instance, the pharmaceutical industry has struggled to discover new antibiotics due to flawed strategies and biased compound libraries (Livermore 2011). Other regulatory hurdles include increased scrutiny for safety and efficacy, as well as the need to demonstrate superiority to justify pricing (Fernandes 2015). Venkatesh et al. (2011) also stresses that generic antibiotic industries face complex markets and tightened regulations. All of these affected supply and pricing which, in turn, influenced the rate of adoption (ibid).

Similarly, the use of antibiotics in livestock production presents a complex challenge, balancing animal welfare with human health concerns related to antimicrobial resistance (AMR) (Scott et al. 2015). While antibiotics are crucial for treating animal diseases, their overuse contributes to AMR development (Aarestrup 2015). Veterinarians face conflicting demands between ensuring animal health and minimizing AMR risks (Adam 2019). Intensive farming practices often lead to higher antibiotic use compared to extensive systems (Dewulf et al., 2020). Evidence suggests that antibiotic-resistant bacteria can spread from animals to

---

[8] This illustrates how informal networks and peer-led interventions—elements identified as critical in **diffusion pathways**—can sometimes circumvent formal system constraints

humans through various pathways (Marshall & Levy 2011). Efforts to reduce antibiotic use in livestock include improving biosecurity, animal husbandry, and farm management practices (Aarestrup, 2015; Dewulf et al. 2020). The European Union is revising animal welfare legislation to address AMR by promoting higher welfare standards that reduce the need for antibiotics (Pegger et al. 2023). A harmonized approach to defining critically important antimicrobials is needed to balance human and animal health concerns (Scott et al. 2019).

4.3.2 MRNA Treatments

"Messenger ribonucleic acid" (mRNA) was first identified in 1961, and its isolation for *in vitro* protein expression was successfully achieved in 1969 (Brenner *et al*. 1961; Lockard & Lingrel 1969; Zhang *et al*. 2023). In 1993 and 1995, mRNA was shown to activate both innate and adaptive immunity (Jirikowski *et al*. 1992; Martinon *et al*.1993; Conry *et al*. 1995; Zhang *et al*. 2023). However, despite the encouraging results, development of mRNA faced significant capability and willingness barriers underscored by limited investment, largely due to concerns about their instability, inefficiency of in vivo delivery, and potential innate immunogenicity (the fear being that they would cause an adverse reaction). This reflects how risk perception—a key human factor influencing willingness—and technical complexity challenges around capability inhibited early adoption.

However, continued research into safety, design and manufacturing ultimately paid off, culminating in the development of highly effective mRNA vaccines for COVID-19, which have been crucial in efforts to control the pandemic (Zhang *et al*. 2023).

The UK has been at the forefront of biomedical research, with several institutions and companies actively engaged in the development of mRNA-based therapies. The success of the Pfizer-BioNTech and Moderna COVID-19 vaccines, which utilise mRNA technology, has catalysed interest and investment in this field (Polack et al. 2020). UK-based researchers have contributed significantly to the understanding of mRNA delivery systems, stabilisation techniques, and immunogenicity, which are critical for the efficacy of these treatments (see Sharpe *et al*. 2020; Wilkinson 2023). For instance, Imperial College London has been pivotal in advancing mRNA vaccine research, particularly through its self-amplifying RNA (saRNA) platform, which aims to enhance the potency and durability of immune responses (McKay et al. 2020).

In the UK, mRNA technologies have demonstrated immense potential to address a wide range of diseases, from infectious diseases to cancer and rare genetic disorders. The development of the Pfizer-BioNTech mRNA vaccine was underpinned by a robust B2B partnership between BioNTech, a German biotech firm, and Pfizer, a global pharmaceutical giant, with significant contributions from UK-based researchers and institutions (MHRA 2021). These partnerships enable the sharing of expertise, resources, and intellectual property, which accelerates the diffusion of mRNA technologies. However, the effectiveness of this pathway depends on the alignment of interests, values, and constraints between partners.

Social networks contribute to the spread of information about mRNA-based treatments. Public discourse, media coverage, and peer-to-peer communication influence perceptions of these technologies. While positive narratives, such as the success of mRNA vaccines in combating COVID-19, have enhanced public acceptance, misinformation and vaccine hesitancy remain significant challenges (Larson et al. 2021). The role of opinion leaders, such as scientists, healthcare professionals, and community influencers, is crucial in shaping these narratives and countering misinformation.

Healthcare professionals' willingness to adopt mRNA-based treatments may be heavily influenced by their understanding of the technology's impact on patient outcomes and their professional roles. Training programs and continuing education initiatives have proven effective in building confidence and competence among clinicians, thereby fostering a more receptive attitude toward these treatments (NHS England 2023). Similarly, at the organizational level, pharmaceutical and biotech companies were highly motivated to invest in mRNA vaccines technologies due to their transformative potential (Aoki 2024). However, leadership teams must carefully align innovation strategies with organizational values and risk tolerance profiles to ensure sustained commitment (Ajana et al. 2024). Public demand for mRNA vaccines was shaped by perceptions of safety, efficacy, and accessibility (Iqbal *et al*. 2024). Regulatory support and transparent communication from intermediaries such as the Medicines and Healthcare products Regulatory Agency (MHRA) and the National Health Service (NHS) have been instrumental in fostering trust and acceptance among the broader population (Larson et al. 2021). However, public perception and willingness to vaccinate vary across ethnicity, cultures and age (Iqbal *et al*. 2024)

Producing and administering mRNA treatments requires specialised skills and infrastructure, necessitating close collaborations between academia, pharmaceutical companies/industry, and government to address skill gaps and enhance workforce readiness (Department of Health & Social Care 2021). Pioneering firms such as Moderna and BioNTech, already possessed the necessary financial, and human resources, expertise, patents, development experience, digital infrastructure, efficient production facilities, strong partnerships, and a strategic corporate culture for the successful development and rollout of the mRNA vaccines (Aoki 2024). However, the high costs associated with mRNA-base treatments look set to affect its adoption especially in non-vaccine applications, which may require derisking or subsidisation by the UK government to facilitate diffusion and adoption and implementation. Hence, government funding and incentives are therefore essential to bridge this gap and enable broader participation in the mRNA ecosystem. Additionally, reliable access to raw materials, such as lipid nanoparticles, is crucial for scaling up production. Strengthening supply chain resilience has emerged as a priority for both private and public stakeholders, underscoring the interconnected nature of technological adoption (Zhang et al. 2022).

Workforce flexibility is a key concern in enabling capacity to deliver mRNA treatments, as integrating these treatments into existing healthcare systems requires reallocating resources and managing competing priorities. Ensuring sufficient flexibility in workforce allocation is essential to avoid disruptions in service delivery (NHS England 2023). Similarly, retrofitting manufacturing facilities to accommodate mRNA technologies involves significant opportunity costs, necessitating investments in infrastructure and process optimization to enhance capacity (Zhang et al. 2022). A supportive regulatory environment is also critical for enabling widespread adoption. The UK's streamlined medical approval processes and proactive engagement with stakeholders have set a benchmark for other countries, demonstrating the importance of regulatory clarity in accelerating diffusion (MHRA 2021; WHO 2023).

Provisional conclusions drawn from the analysis of mRNA-based treatments in the UK highlight several key lessons. First, public agencies such as the MHRA and the NHS have played a pivotal role in accelerating diffusion by providing regulatory clarity, fostering partnerships, and promoting public trust (see also Stratford *et al.* 2020; Ajana et al. 2024). Secondly, addressing workforce resistance and building capability through training and education are essential to ensuring equitable and sustainable adoption (see Iqbal 2024). Finally, geographical and sectoral variations in adoption patterns underscore the need for tailored approaches that consider local contexts and stakeholder needs. These insights collectively emphasize the multifaceted nature of mRNA technology adoption and the importance of a holistic strategy to maximize its benefits for the UK society and the economy.

4.3.3 CRISPR Treatments

CRISPR (Clustered Regularly Interspaced Short Palindromic Repeats) technology is a revolutionary gene-editing tool that has gained significant attention in the scientific and medical communities for its potential to transform the treatment of genetic disorders, cancers, and infectious diseases. CRISPR-based treatments medical therapy uses a powerful gene-editing tool (called CRISPR) to fix or modify genes in the body (Chanchal *et al*. 2024). The United Kingdom is at the forefront of implementing CRISPR-based treatments. In November 2023, the UK's Medicines and Healthcare products Regulatory Agency (MHRA) became the first regulatory body worldwide to authorise a therapy utilising CRISPR–Cas9 gene-editing technology (Wong 2023). This therapy, known as exagamglogene autotemcel (brand name Casgevy), was approved for the treatment of sickle cell disease (SCD) and transfusion-dependent beta thalassaemia (TDT) in patients aged 12 and over (Wong 2023).

The National Health Service (NHS) UK has commenced the rollout of Casgevy, offering the therapy at specialist centres in London, Manchester, and Birmingham. Despite its high cost—approximately £1.65 million per treatment course—the NHS has secured a confidential commercial agreement with Vertex Pharmaceuticals to provide the therapy at a discounted rate (Johnston 2024). This initiative is expected to benefit up to 460 patients with beta thalassaemia and around 50 patients annually with sickle cell disease, particularly those from Black African, Black Caribbean, and South Asian communities, who are disproportionately affected by these conditions (Johnston 2024). UK's proactive approach in adopting CRISPR-based therapies underscores its commitment to integrating cutting-edge scientific research into clinical practice. This not only offers hope to the nearly 17,000 people with inherited blood disorder in England with previously limited treatment options but also positions the UK as a leader in the application of gene-editing technologies in medicine.

However, looking back at the diffusion and adoption of the mRNA Covid-19 vaccines, several actual and potential challenges/barriers to the diffusion and adoption of CRISPR-based treatments in the UK can be discussed. The UK's strong pharmaceutical sector and research institutions provide a robust platform for collaboration between biotech firms and healthcare providers. The partnership between Vertex Pharmaceuticals and CRISPR Therapeutics in developing Casgevy exemplifies successful collaboration. However, high development and manufacturing costs pose financial risks, which could constrain interest from smaller biotech firms. Also, concerns about intellectual property rights and licensing agreements may hinder open collaboration.

Regulatory agencies such as the Medicines and Healthcare products Regulatory Agency MHRA, the National Institute for Health and Care Excellence (NICE), and Imperial College Hospitals have played pivotal roles in evaluating the efficacy and cost-effectiveness of CRISPR-based treatments. NHS England's commitment to providing treatment free at the point of access for eligible patients further supports diffusion. However, given that the subsidized costs were due to NHS and Vertex having a confidential commercial agreement to provide the drug at a discount (Johnston 2024), in the future costs of CRISPR-based treatments could pose real challenges to rolling out access to patients via the NHS. Moreover, while streamlined, the regulatory approval process still faces scrutiny over long-term safety and ethical implications. Also, should ethical concerns about gene-editing, including potential unintended consequences, materialize restrictive policies that slow down diffusion may ensue.

So far, positive media coverage and endorsements from healthcare professionals appear to have enhanced public trust in CRISPR therapies. However, observing successful patient outcomes can further encourage acceptance. Still, misinformation, similar to what was seen with mRNA vaccines during Covid-19, may lead to public scepticism. For instance, concerns about "playing God" or fear of genetic modification can result in resistance, particularly among religious and conservative communities. This concern is important to consider given the limitations of CRISPR-based treatments *in vivo* raised by some, thus, "ineffective delivery, unwanted immune responses, off-target effects, unpredictable repair outcomes, and cellular stress" (Modell *et al*. 2022). In general support for gene therapies for use in specific medical treatments is high among the UK public with 83% of respondents surveyed by the Royal Society supportive of gene editing for incurable diseases (The Royal Society 2018). However, only 46% of those surveyed said they agreed that gene editing should be used in a more general way to tackle grand challenges (The Royal Society 2018).

Physicians' acceptance is critical to their willingness to administer CRISPR treatments. While many clinicians support CRISPR-based treatments due to their transformative potential, concerns over long-term effects and lack of extensive real-world data (Laurent *et al*. 2024; Uddin, Rudin & Sen 2020) may limit willingness. Patients suffering from SCD and TDT, particularly within Black African, Black Caribbean, and South Asian communities, stand to benefit the most (NICE 2023). However, historical medical mistrust, lack of awareness, and religious beliefs may lead to reluctance in adopting gene-editing therapies.

Administering CRISPR-based treatments requires specialised interdisciplinary skills, particularly as currently many gene therapy treatments require narrow treatment sites, to limit gene mutations in healthy tissues, therefore treatments are often administered directly to the organ or system affected by disease and thus large medical teams are required to oversee the invasive procedure (Sacarakis 2023). For treatment of blood diseases, genetic material is taken from the patient, edited ex vitro and then administered via an infusion, with the patient also requiring chemotherapy beforehand, and a stay in hospital afterwards (NHS 2024). While the UK has a well-trained health workforce, additional training for clinicians and laboratory staff is necessary to ensure safe and effective implementation.

For patients, the high cost of Casgevy (approximately £1.65 million per treatment) could pose a major barrier in the future. While the NHS has negotiated discounts, the sustainability of funding and patient eligibility criteria remain could be major concerns in the future, especially if treatments are to last over an elongated period. The availability of specialized centres in London, Manchester, and Birmingham ensures initial access, but later expansion could be affected by geographical disparities which may hinder nationwide availability. Expanding capacity to regional hospitals may be necessary, especially in the aftermath of the success of the initial rollouts. While the transportation of ‘off-the-shelf' CRISPR treatments (i.e. in vivo and non-personalised) can rely on similar cold temperature logistics as many existing treatments, personalised treatments where genes are taken from the patient, treated and reintroduced (or ex vivo treatments) require strict tracking systems (Cencora, n.d.).

Similarly, the complexity of CRISPR-based therapies in health, agriculture and other applications requires robust supply chains for gene-editing tools, patient-specific cell processing, and reinfusion logistics. Ensuring consistent production and distribution of these tools/logistics should a priority.

5 Conclusions and insights

This report takes on the timely topic of adoption and diffusion turning to the past for inspiration about how to understand, and ultimately affect, the future. It first acknowledges that the concepts of adoption and diffusion are complicated and often misunderstood. These terms have risen in significance in public policy in recognition of the fact that technology research and development is only one part of a complex innovation process, and that productivity has typically benefitted from the adoption of new and innovative technologies. Forging pathways from technology commercialisation to wider and wider markets gives a boost to both the supply of innovation and economic growth through productivity gains.

Adoption, in this report, is the uptake and implementation of new technology while diffusion is an emergent phenomenon - the spread of those technologies through the economy, or the degree and rate to which they have been adopted. Policy makers seek to understand what drives adoption decisions so that they can intervene to accelerate or influence the direction of diffusion. While many diffusion strategies assume that more diffusion is generally better, it is important to recognise that other policy objectives may demand a more focused approach that encourages diffusion of specific technologies to specific communities – e.g., clean energy use to more heavily polluting industries. Whether broadly construed, or tightly focused, promoting diffusion means understanding how and why firms choose to adopt technologies.

This research adds to the rich literature on technology adoption and diffusion by proposing a set of frameworks to guide funders in their efforts to achieve policy goals through technology diffusion. The first framework focuses on adoption and lays out a series of factors that businesses consider in their adoption decisions. The main innovation of this framework is that it classifies factors both by the place within the business that the influence originates from (e.g., workforce, management/firm structure, production, and external context) but also in terms of what part of the decision process is most affected by those factors (e.g., willingness to consider technology, capability to implement technology, and capacity to dedicate resources to technology implementation). Conceptualising different parts of the adoption decision process in this way enables researchers to better diagnose and understand failure points and, consequently, how they might be mitigated. Adding these three dimensions unpacks, if still in a stylised way, the elements of decision making and introduces the idea that adoption depends on low barriers at each point in that process.

The diffusion framework is set up as a tool for stakeholders seeking to influence the speed, trajectories, and pathways of technology diffusion. It starts with the premise that the role of policy makers in diffusion is primarily related to disseminating information about and facilitating access to the technology. We acknowledge that there are roles for the public sector in working with technology producers and their markets to reduce costs of the technologies through production efficiencies, assisting with scaling, and the like, we consider these interventions upstream and out of the scope for this framework. The framework focuses on how communication about technology is disseminated and tailored to target industries with an emphasis on framing relative advantages of the technology, enhancing accessibility of the technology by reducing complexity, increasing opportunities for businesses to observe the technology and its impacts, and by improving business access to low-risk testing and trials. We lay out different pathways of dissemination that are not mutually exclusive – business to business, through intermediaries, and through networks – to demonstrate how potential adopters can acquire information about technologies and how these might frame expected benefits or enable access to practical experience with the technologies differently. This enables stakeholders interested in affecting diffusion patterns to step back and understand how they might intervene to coordinate messaging or counteract framings that might be creating barriers to adoption.

These frameworks were developed drawing first on literature on adoption and diffusion and then through road testing with case studies. In the case studies section, we explored the diffusion trajectory and adoption stories of three different technology families (advanced materials & manufacturing, energy & environmental, and health & wellbeing) across three timeframes (past, present, and future). Exploring these case studies, which vary significantly in terms of the nature of technologies and the markets within which they have diffused, provided an opportunity to test the value of the frameworks and enabled us to revise them to fill in any gaps. This iterative process enabled us to strengthen the frameworks as well as provide a robust approach to understanding the cases themselves. The process also generated the following lessons:

- **Intermediaries have a role in accelerating diffusion:** For many of these cases, intermediaries (most frequently governments and their stakeholders) have played an important role in shaping diffusion. This can happen on the supply side or the demand side. On the supply side, government intervention can help technologies reach appropriate levels of development for market, provide assistance so that production can be scaled to a point to where more widespread adoption is possible, or help technologies develop features or production methods to the point where they are cost effective. On the demand side, governments can also affect costs by negotiating supply, can increase the attractiveness of certain technologies through regulatory activities (see the mRNA case for good examples of both of these), provide resources (information or material) to boost capabilities, and more. Notably, government actions (and inaction) can impede technology uptake as lack of clarity on regulations or slowdowns in approvals processes can deter adoption or drive adopters to consider alternatives. The framework focusses more on the demand side but it is important to acknowledge the impact that government interventions in upstream activities can have on adoption decisions.

  This suggests that for many technologies there is an opportunity for intermediaries, including governments, their agents and/or stakeholders to shape diffusion trajectories. However, which roles might be appropriate, or effective, for any given technology will depend on understanding the constellation of considerations facing potential adopters and designing interventions that align government priorities with adopter incentives.

- **Labour and workforce implications can disrupt adoption:** Degree of workforce buy in and broader impacts on labour are often considered secondary in adoption models but can be important considerations in adoption processes. Workers engaging in machine breaking slowed but did not impede the diffusion of steam powered factories. The case of industrial robotics shows that these kinds of disruptive behaviours continue to be a problem when workers have not bought into technological changes. The robotics case suggests that business leaders do take worker viewpoints into consideration and sometimes cite employee wellbeing as a guiding value in technological decisions.

  Understanding impacts of technology change on workforce, employment, wellbeing, and labour force composition is important to visioning exercises, particularly those with an equity (etc) focus.

- **Adoption is shaped by a variety of factors across the willingness-capability-capacity nexus:** What the technology costs is different from what it costs business to integrate it. This is evident by how these considerations emerge at different points in the framework. For instance, the cost of a technology relative to alternatives can affect a business' willingness to consider the technology. Customer and demand patterns can also affect that willingness. Market conditions, such as demand cycles, can influence cost calculations of both capability and capacity. The capital cost of the technology influences capability whereas the costs of implementation affect both capability and capacity.

  Interventions should be designed with an understanding of what is driving cost considerations. For example, providing businesses with subsidies to buy robots if a key cost consideration is related to the cost of production downtime to implement the technology. Pricing a wider variety of issues into adoption support can increase uptake and effectiveness of interventions.

- **Technological systems matter:** Adoption of all these technologies required the development of further innovations to increase their utility, make them accessible to different industries, lower costs. Just as the boom in software was a key to the ICT revolution so too will the development of related technologies affect the perceived feasibility of the technology families studied here. Gas lighting was only possible because of developments in storage and transport infrastructure. Steam energy was only relevant to industry when a wider variety of machinery was developed to use its power. Gene editing will become more accessible when delivery methods are simplified and scalable. Solar becomes more feasible as battery storage technology improves.

  Understanding gaps that need to be filled to exploit the potential of technologies at scale is key to driving widespread adoption. While these will often fall outside of the boundaries of the adoption framework (to the extent that supply side developments often occur pre-adoption or as new uses for general purpose technologies evolve) it is important to understand that government roles in finding solutions adoption reluctance might lie upstream (with supply) or downstream (with demand).

- **The decision to adopt, or not adopt, a technology rarely comes down to just one consideration:** The adoption framework matrix attempts to capture the high-level considerations that influence adoption decisions – but it's still quite a lot! While case studies generalise lessons at the industry scale, they demonstrate how many factors can act on businesses and be considered simultaneously. This suggests that it may be difficult to narrow down a single barrier to adoption that is solely responsible for adoptions decisions and rather that the *combination* of factors, both positive and negative, ultimately shape outcomes.

There is no silver bullet. Effectively influencing technology adoption requires understanding how different factors play out, and combine, in any given firm's decision-making process. This means that intervention on one factor is unlikely to overcome reticence for a wide variety of firms. Policy design should adopt a systems perspective to consider both the range of factors that are likely to be most influential for target firms and how factors affect and may multiply the influence of one another.

- **Do not overlook social and behavioural influences on adoption decisions:** Adoption frameworks often privilege tangible factors such as costs or skills while reducing fewer tangible dimensions to categories such as "culture" or "attitudes". This research shows that considerations about values, reputation, ambition, and risk can be equally important in shaping technology adoption decisions – particularly by influencing the willingness of businesses to consider (specific types of) technological solutions. Indeed, reinforcing the previous point, these kinds of social and behavioural factors should not be considered "in addition to" the more concrete factors, but should rather be understood as important lenses that colour firm perceptions and priorities as they consider things like cost. Given that the social and behavioural factors in our framework are typically inherent to firms and their leadership, they can be more difficult to overcome than capability (e.g., resource) limitations.

  This is why, in shaping diffusion, it is so important to tailor communication about technology benefits to the social and behavioural characteristics of target businesses rather than focusing on generic appeals that highlight technological benefits. Adopters need to make technological investment decisions align with their identities and organisational narratives and so need to see that potential in the messaging around potential technologies. This may be about drawing out benefits to productivity and environmental impact, or employee wellbeing, increased social impact, or reinforcing a reputation as an innovative market leader. Whatever it is, understanding how messaging can attract or repel potential adopters based on their social and behavioural priorities is important to increasing diffusion.

Increasing technology adoption and diffusion is an important ingredient in stimulating the innovation economy and increasing prosperity. However, this research demonstrates that it is an extremely complex set of problems that defy easy or expedient solutions. This report provides some context, and a set of tools, to enable stakeholders to make sense of the technology trajectories that they want to influence. These tools will be useful in interacting with individual businesses to understand their decisions and in considering trends within whole industries. They will also be useful to understand how to effectively align public policy goals with practice to ensure that technology adoption supports sustainable, responsible, and equitable innovation.

Now that you have read our report, we would love to know if our research has provided you with new insights, improved your processes, or inspired innovative solutions.

Please let us know how our research is making a difference by completing our short feedback form via this link.

Thank you

The Innovation & Research Caucus

References

Aarestrup, F. M. (2015). The livestock reservoir for antimicrobial resistance: a personal view on changing patterns of risks, effects of interventions and the way forward. Philosophical Transactions of the Royal Society B: Biological Sciences, 370(1670), 20140085.

Abi Saad, E., Tremblay, N., & Agogué, M. (2024). A multi-level perspective on innovation intermediaries: The case of the diffusion of digital technologies in healthcare. Technovation, 129, 102899.

Adam, K. (2019). Balancing conflicting demands: Factors influencing vets' choice of antimicrobial agent. Veterinary Record, 184(26), 795-797.

Aoki, T. (2024). How Pharmaceutical Companies Utilize Platform Strategy: A Study of the COVID-19 mRNA Vaccine Development (Doctoral dissertation, Massachusetts Institute of Technology).

Ajana, B., Engstler, E., Ismail, A., & Kousta, M. (2022). Perceptions and attitudes towards COVID-19 vaccines: narratives from members of the UK public. *Z Gesundh Wiss.*, 31, 1699–1715. https://doi.org/10.1007/s10389-022-01728-w

ATAP (n.d.) *Superconducting Magnets for Fusion Energy* Available https://atap.lbl.gov/research/scientific-programs-and-centers/superconducting-magnet-program/superconducting-magnets-for-fusion-energy/.

Bottomly, S. (2024) Stationary steam power in the United Kingdom, 1800–70: An empirical reassessment. *The Economic History Review*. 1-24

Brenner, S., Jacob, F., & Meselson, M. (1961). An unstable intermediate carrying information from genes to ribosomes for protein synthesis. *Nature*, 190, 576–581.

Bud, R. (1998). Penicillin and the new Elizabethans. *The British Journal for the History of Science, 31*(3), 305–333. Available at: https://www.cambridge.org/core/services/aop-cambridge-core/content/view/80D916A224CEF34FAEB39E7A15A4BE45/stamped-S000708749800331Xa.pdf/penicillin-and-the-new-elizabethans.pdf

Bui, Q. (2015). A review of innovation diffusion theories and mechanisms. DIGIT 2015 Proceeding. Available at: file:///D:/settings/ERCHS/Downloads/A_Review_of_Innovation_Diffusion_Theorie.pdf

Business Energy Scotland. (n.d.) *Solar PV – a quick guide* Available https://businessenergyscotland.org/guides/solar-pv-quick-guide/#:~:text=What%20is%20solar%20PV%20and,during%20the%20height%20of%20summer.

Calladine, A. (1993) Lombe's Mill: An Exercise in Reconstruction. *Industrial Archaeology Review* XVI (1): 82-99.

Carrington, D., (2023). 'Revolutionary' solar power cell innovations break key energy threshold. Available: https://www.theguardian.com/environment/2023/jul/06/revolutionary-solar-power-cell-innovations-break-key-energy-threshold

Cencora (n.d.) Tackling the complex nature of the cell and gene therapy supply chain. https://www.cencora.com/resources/pharma/tackling-the-complex-nature-of-the-cgt-supply-chain

Colovic, A., Caloffi, A., Rossi, F., Paladini, S., & Bagherzadeh, M. (2024). Innovation intermediaries and emerging digital technologies. Technovation, 133, 103022.

Conry, R. M., LoBuglio, A. F., Loechel, F., Moore, S. E., Sumerel, L. A., Barlow, D. L., Pike, J., & Curiel, D. T. (1995). A carcinoembryonic antigen polynucleotide vaccine for human clinical use. *Cancer Gene Therapy*, 2(1), 33–38.

Davis, F. D. (1989). Technology acceptance model: TAM. Al-Suqri, MN, Al-Aufi, AS: Information Seeking Behavior and Technology Adoption, 205(219), 5.

Davis, F. D., Bagozzi, R. P., & Warshaw, P. R. (1989). User acceptance of computer technology: A comparison of two theoretical models. Management science, 35(8), 982-1003.

Department for Energy & Climate Change (2016). ORGANISER: A behavioural approach for influencing organisations. https://www.gov.uk/government/publications/organiser-a-behavioural-approach-for-influencing-organisations

Department for Science, Innovation and Technology (DSIT) (2023). Making Innovation Matter How the UK can benefit from spreading and using innovative ideas, BEIS/DSIT Research Paper Number 2023/009. UK Government. Available at: https://assets.publishing.service.gov.uk/media/643fb40e8b86bb000cf1b4d2/making_innovation_matter.pdf

Dewulf, J., Sternberg-Lewerin, S., & Ryan, M. (2019). Tackling antimicrobial resistance in the food and livestock sector. In European Observatory on Health Systems and Policies.

Dishaw, M. T., & Strong, D. M. (1999). Extending the technology acceptance model with task–technology fit constructs. *Information & management*, 36(1), 9-21.

Edmondson, A. C., Winslow, A. B., Bohmer, R. M., & Pisano, G. P. (2003). Learning how and learning what: Effects of tacit and codified knowledge on performance improvement following technology adoption. *Decision Sciences*, 34(2), 197-224.

Elliot, D., (2024). The breakthroughs making solar panels more efficient. Available: https://www.weforum.org/stories/2024/10/solar-panel-innovations/#:~:text=Solar%20technology%20has%20come%20a,the%20efficiency%20of%20its%20technology.

Falkus, M. E. (1967). The British gas industry before 1850. *The Economic History Review*, 20(3), 494-508.

Falkus, M. E. (1982). The early development of the British Gas Industry, 1790-1815. *Economic History Review,* 217-234.

Fernandes, P. (2015). The global challenge of new classes of antibacterial agents: an industry perspective. Current opinion in pharmacology, 24, 7-11.

First Light Fusion (2025). About Us. https://firstlightfusion.com/about-us/

Floud, R., Humphries, J., & Johnson, P. (Eds.). (2014). *The Cambridge Economic History of Modern Britain: Volume 1, Industrialisation, 1700–1870*. Cambridge University Press.

Freeman, J.B. (2018) *Behemoth: A History of the Factory and the Making of the Modern World*. W.W. Norton & Company.

Goodhue, D. L. (1995). Understanding user evaluations of information systems. Management science, 41(12), 1827-1844.

Haldane, A. (2018). The UK's productivity problem: Hub no spokes. Academy of Social Sciences Annual Lecture, 28.

Chanchal, D. K., Chaudhary, J. S., Kumar, P., Agnihotri, N., & Porwal, P. (2024). CRISPR-based therapies: revolutionizing drug development and precision medicine. *Current Gene Therapy*, *24*(3), 193-207.

HM Government (n.d.) UK Atomic Energy Authority. Available: https://www.gov.uk/government/organisations/uk-atomic-energy-authority

HM Government (2024a). Energy Trends UK, July to September 2024, Available: https://www.gov.uk/government/statistics/energy-trends-section-6-renewables

HM Government (2024b). *Clean Power 2030 Action Plan*. Available: https://www.gov.uk/government/publications/clean-power-2030-action-plan

HM Government (2024c). *DESNZ Public Attitudes Tracker: Renewable energy, Spring 2024,* UK Available: https://www.gov.uk/government/statistics/desnz-public-attitudes-tracker-spring-2024/desnz-public-attitudes-tracker-renewable-energy-spring-2024-uk

IQVIA. (2023). *Cell and gene therapy logistics management* . Retrieved from https://www.iqvia.com/-/media/iqvia/pdfs/campaign/2023/cell-and-gene-therapy-logistics-management.pdf

HM Government (2024d). *DESNZ Public Attitudes Tracker: Energy infrastructure and energy security, Spring 2024, UK*. Available: https://www.gov.uk/government/statistics/desnz-public-attitudes-tracker-spring-2024/desnz-public-attitudes-tracker-energy-infrastructure-and-energy-security-spring-2024-uk

HM Government (2025a). *Solar Photovoltaics deployment in the UK - December 2024* https://www.gov.uk/government/statistics/solar-photovoltaics-deployment

HM Government (2025b). *Plan for Change to deliver jobs and growth in UK leading fusion industry*. Available https://www.gov.uk/government/news/plan-for-change-to-deliver-jobs-and-growth-in-uk-leading-fusion-industry

Holness-Mckenzie, S. (2025). *GB battery energy storage markets: 2024 year in review* Available: https://modoenergy.com/research/gb-battery-energy-storage-markets-2024-year-in-review-great-britain-wholesale-balancing-mechanism-frequency-response-reserve

IAEA (2023). *What is Nuclear Fusion?* https://www.iaea.org/newscenter/news/what-is-nuclear-fusion

Innovation News Network (2022). *The road to commercialising fusion energy in the UK.* https://www.innovationnewsnetwork.com/the-road-to-commercialising-fusion-energy-in-the-uk/25250/

Jirikowski, G. F., Sanna, P. P., Maciejewski-Lenoir, D., & Bloom, F. E. (1992). Reversal of diabetes insipidus in Brattleboro rats: Intrahypothalamic injection of vasopressin mRNA. *Science*, 255, 996–998.

Johnston, I. (2024, August 8). NHS in England to roll out £1.7mn Crispr gene editing drug. *Financial Times*. https://www.ft.com/content/061c5c18-487d-44aa-89e2-fe692b40c63d

Johnstone, T (2025). *Further details on grid connection reforms revealed by Neso as queue pause begins* Available: https://www.newcivilengineer.com/latest/further-details-on-grid-connection-reforms-revealed-by-neso-as-queue-pause-begins-28-01-2025/#:~:text=At%20the%20end%20of%20last,considered%20most%20viable%20and%20necessary.

Larson, H. J., Clarke, R. M., & Jarrett, C. (2021). Understanding vaccine hesitancy around the world: Insights from the Vaccine Confidence Project. *Nature Medicine*, 27(4), 625–632.

Lewis, L. K., & Seibold, D. R. (1993). Innovation modification during intraorganizational adoption. Academy of Management Review, 18(2), 322-354.

Livermore, David M., et al. "Discovery research: the scientific challenge of finding new antibiotics." Journal of antimicrobial chemotherapy 66.9 (2011): 1941-1944.

Lockard, R. E., & Lingrel, J. B. (1969). The synthesis of mouse hemoglobin chains in a rabbit reticulocyte cell-free system programmed with mouse reticulocyte 9S RNA. *Biochemical and Biophysical Research Communications*, 37, 204–212.

Lockheed Martin (n.d.). *Compact Fusion* Available:

https://www.lockheedmartin.com/en-us/products/compact-fusion.html

Marshall, B. M., & Levy, S. B. (2011). Food animals and antimicrobials: impacts on human health. Clinical microbiology reviews, 24(4), 718-733.

Matthews, D. (1985). Rogues, speculators and competing monopolies: The early London gas companies, 1812–1860. The London Journal, 11(1), 39-50.

Martin, L.D. (2024). *Eight solar farms pass into community ownership in ‘biggest ever’ UK transfer* Available: https://www.solarpowerportal.co.uk/eight-solar-farms-pass-into-community-ownership-in-biggest-ever-uk-transfer/

McGarry, B. (2014). Scientists Skeptical of Lockheed's Fusion Breakthrough. Available: https://www.military.com/defensetech/2014/10/16/scientists-skeptical-of-lockheeds-fusion-breakthrough

McKay, P. F., Hu, K., Blakney, A. K., Samnuan, K., Brown, J. C., Penn, R., ... & Shattock, R. J. (2020). Self-amplifying RNA SARS-CoV-2 lipid nanoparticle vaccine candidate induces high neutralizing antibody titers in mice. *Nature Communications*, 11(1), 1-7.

Melling, J. (1979). Industrial strife and business welfare philosophy: The case of the South Metropolitan Gas Company from the 1880s to the war. Business History, 21(2), 163-179.

MHRA. (2021). Regulatory approval of Pfizer/BioNTech vaccine for COVID-19. Retrieved from https://www.gov.uk/mhra

Modell, A. E., Lim, D., Nguyen, T. M., Sreekanth, V., & Choudhary, A. (2022). CRISPR-based therapeutics: current challenges and future applications. *Trends in pharmacological sciences, 43*(2), 151-161.

Musson, A. E. (1976). Industrial Motive Power in the United Kingdom, 1800-70. *The Economic History Review*, 29(3), 415–439. https://doi.org/10.2307/2595302

Nambisan, S., & Wang, Y. M. (2000). Web Technology Adoption and Knowledge Barriers. Journal of Organizational Computing and Electronic Commerce, 10(2), 129–147. https://doi.org/10.1207/S15327744JOCE1002_4

NDT Group., n.d. *How is the UK's grid hindering the transition to renewable energy?* https://www.ndtgroup.co.uk/latest-news/uks-grid-hindering-renewable-energy/#:~:text=One%20of%20the%20biggest%20challenges,like%20wind%20and%20solar%20power.

Nelles, J., Walsh, K. & Vorley, T. (2022). Transforming Foundation Industries: Engaging SMEs in Innovation. Innovation Caucus. https://innovationcaucus.co.uk/app/uploads/2022/06/TFI-Designed-report_FINAL-1.pdf

NHS (2024). *Gene-editing therapy that could cure blood disorder thalassaemia for NHS patients* Available: https://www.england.nhs.uk/2024/08/gene-editing-therapy-that-could-cure-blood-disorder-thalassaemia-for-nhs-patients/#:~:text=Blood%20stem%20cells%20are%20removed,the%20patient%20via%20an%20infusion.

National Institute for Health and Care Excellence (NICE). (n.d.). *NICE approves groundbreaking one-off gene therapy for severe sickle cell disease* . Retrieved from https://www.nice.org.uk/news/articles/nice-approves-groundbreaking-one-off-gene-therapy-for-severe-sickle-cell-disease

Palm, A. (2022). Innovation systems for technology diffusion: An analytical framework and two case studies. Technological Forecasting and Social Change, 182, 121821.

Pegger, T., Haager, D., Jamal, N., & Heidbuechel, K. (2023). How the EU animal welfare legislation can tackle AMR–a One Health perspective. European Journal of Public Health, 33(Supplement_2), ckad160-081.

Polack, F. P., Thomas, S. J., Kitchin, N., Absalon, J., Gurtman, A., Lockhart, S. P., ... & Gruber, W. C. (2020). Safety and efficacy of the BNT162b2 mRNA COVID-19 vaccine. *New England Journal of Medicine*, 383(27), 2603-2615.

Rankl, F. 2024. *Planning for Solar Farms*. Available: https://researchbriefings.files.parliament.uk/documents/CBP-7434/CBP-7434.pdf

Ravichandran, T. (2001, August). INNOVATION ASSIMILATION IN THE PRESENCE OF KNOWLEDGE BARRIERS, TECHNOLOGY UNCERTAINTY AND ADOPTION RISKS. In Academy of Management proceedings (Vol. 2001, No. 1, pp. C1-C6). Briarcliff Manor, NY 10510: Academy of Management.

Rodríguez-Pose, Andrěs. "Innovation prone and innovation averse societies: Economic performance in Europe." Growth and change 30, no. 1 (1999): 75-105

Rogers, E. M. 2003. Diffusion of Innovations (5th Edition). New York: Free Press.

Science Museum (2021) “How was penicillin developed?”, available at: https://www.sciencemuseum.org.uk/objects-and-stories/how-was-penicillin-developed

Scott, H. M., Midgley, G., & Loneragan, G. H. (2015). Antimicrobials in animal agriculture: parables and policy. Zoonoses and public health, 62, 3-9.

Scott, H. M., Acuff, G., Bergeron, G., Bourassa, M. W., Gill, J., Graham, D. W., ... & Wittum, T. E. (2019). Critically important antibiotics: criteria and approaches for measuring and reducing their use in food animal agriculture. Annals of the New York Academy of Sciences, 1441(1), 8-16.

Sharpe, R., Wilkinson, A., & McDonald, P. (2020). mRNA Vaccines: A New Paradigm in Vaccine Development. *Lancet Infectious Diseases*, 20(3), 264–267.

SP Energy Networks, n.d. *The Electrical Energy System* https://www.spenergynetworks.co.uk/pages/electricity_system.aspx

Stallard, E. (2024). *Nuclear fusion: new record brings dream of clean energy closer.* https://www.bbc.co.uk/news/science-environment-68233330

Strang, D., & Soule, S. A. (1998). Diffusion in organizations and social movements: From hybrid corn to poison pills. Annual review of sociology, 24(1), 265-290.

Sunsave Energy. (2025). *The Largest 7 Solar Farms in the UK*. https://www.sunsave.energy/solar-panels-advice/solar-energy/largest-solar-farms-uk

The Electrotechnical Skills Partnership (2023). The Solar Power Challenge 2035. Available:

https://www.the-esp.org.uk/wp-content/uploads/2023/12/898-TESP-Solar-PV-Dec-2023.pdf

The Fusion Cluster (2023). *Growing the Fusion Workforce.* Available https://thefusioncluster.com/wp-content/uploads/2023/11/Skillsreport_fusioncluster_07112023.pdf

The Royal Society. (2018). Public attitudes to gene editing. *The Royal Society*.

Tokamak Energy UK (n.d.) *About Us* https://tokamakenergy.com/about-us-fusion-energy-high-temperature-superconducting-magnets/

Tomory, L. (2011). Gaslight, distillation, and the Industrial Revolution. History of science, 49(4), 395-424.

Tomory, L. (2014). Competition and regulation in the early history of the London gas industry, 1800–1830. The London Journal, 39(2), 120-141.

Tornatzky, L. and Fleischer, M. (1990) The process of technology innovation, Lexington, MA, Lexington Books.

UKAEA (n.d.) *Fusion material challenges*. Available: https://ccfe.ukaea.uk/wp-content/uploads/2019/11/mtl-fusion-material-challenges.pdf

UKWA (2022). Investment Care for Rooftop Solar Power in Warehousing https://www.ukwa.org.uk/wp-content/uploads/2022/09/Investment-Case-for-Rootop-Solar-Power-in-Warehousing-August-2022.pdf

Vanttenfall (2024). *UK grid poses the biggest challenge for renewable energy developers.* Available: https://idno.vattenfall.co.uk/news-and-insights/news/uk-grid-challenges/#:~:text=Capacity%20constraints%20are%20another%20major,So%2C%20what%20is%20the%20solution?

Valente, T. W. (2005). Network models and methods for studying the diffusion of innovations. Models and methods in social network analysis, 28, 98-116.

Venkatesh, M., Bairavi, V. G., & Sasikumar, K. C. (2011). Generic antibiotic industries: Challenges and implied strategies with regulatory perspectives. Journal of Pharmacy and Bioallied Sciences, 3(1), 101-108.

Vowles, N., Thirkell, P., & Sinha, A. (2011). Different determinants at different times: B2B adoption of a radical innovation. Journal of Business Research, 64(11), 1162-1168.

Whiting, K., & Torkington, S., 2024. *Nuclear fusion news: The science behind the energy technology, explained.* https://www.weforum.org/stories/2024/02/nuclear-fusion-science-explained/

Wong, C. (2023, November 16). UK first to approve CRISPR treatment for diseases: what you need to know. *Nature*. https://doi.org/10.1038/d41586-023-03590-6

World Nuclear Association (2022). *Nuclear Fusion Power*. Available: https://world-nuclear.org/information-library/current-and-future-generation/nuclear-fusion-power#:~:text=The%20fundamental%20challenge%20is%20to%20achieve%20a,rate%20of%20energy%20injected%20into%20the%20plasma.&text=The%20difficulty%20has%20been%20to%20develop%20a,is%20used%20to%20get%20the%20reaction%20going.

World Nuclear Association (2024). *Nuclear Power and Energy Security*. Available: https://world-nuclear.org/information-library/economic-aspects/nuclear-power-and-energy-security#:~:text=The%201970%20energy%20crises%20led,greater%20role%20for%20nuclear%20energy.

Yirka, B, (2024). *NIF fusion breakeven claims peer reviewed and verified by multiple teams* Available: https://phys.org/news/2024-02-nif-fusion-breakeven-peer-multiple.html

Zhang, Y., Li, D., Wang, M., et al. (2022). Strengthening the mRNA Vaccine Manufacturing Infrastructure. *Nature Biotechnology*, 40(5), 551–558.

Zhang, Y., Li, D., Wang, M., et al. (2023). Advances in mRNA Vaccine Development: Challenges and Opportunities. *Nature Reviews Drug Discovery*, 22(6), 391–409.

Zhou, Y., Yang, Q., & Lu, S. (2023). Research on the identification and formation mechanism of the main path of digital technology diffusion: Empirical evidence from China. Technology in Society, 75, 102398.

www.ircaucus.ac.uk

Email info@ircaucus.ac.uk Twitter @IRCaucus

INNOVATION & RESEARCH CAUCUS

Delivered with ESRC and Innovate UK