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Policy handbook on National Emerging Technology Policy Strategising (NETS)

Exploring effective practices, tools, and lessons learned for strategic and systematic analysis of emerging technologies

Centre for Science, Technology & Innovation Policy (CSTI) in collaboration with the Department for Science, Innovation & Technology (DSIT)

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Policy Handbook on National Emerging Technology Policy Strategising (NETS)

Foreword

Emerging technologies have the potential to drive innovation-led economic growth and address critical societal challenges. Capturing value from emerging technologies within national economies, however, requires developing and aligning the right innovation and industrial capabilities, and deploying them at the right time. Effective foresight, systems analysis, and international benchmarking can be critical to shaping emerging technology strategies, policies and programmes that secure long-term competitive advantage.

Developing effective emerging technology strategies, however, is far from straightforward. Policy making is complex and dynamic, and emerging technology analysis may be needed at different stages of the policy lifecycle, sometimes at short notice, and must respond to shifting political and economic priorities. Furthermore, the evolving nature of technological, innovation and industrial systems make them difficult to characterise and measure, while organisational changes over time can make it harder to retain and build on previous experience.

Although there have been some excellent recent analyses of individual emerging technologies, there is scope to strengthen the overall approach, including: adopting systematic and iterative methods, drawing on international practice, sharing lessons and experiences, and sequencing analyses to optimise evidence and insight.

This Handbook responds to these opportunities. It captures lessons from past exercises and offers practical frameworks, concepts, and tools to support continuity and systems thinking. Designed as a 'living' resource (with plans to update and expand on a regular basis), it aims to help policymakers and analysts develop more coordinated, systematic, evidence-based strategies for emerging technologies.

— Professor Eoin O'Sullivan, Director, CSTI, IfM, University of Cambridge
— Hannah Boardman, Director, Directorate of Technology & Innovative Regulation, DSIT

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Preface

We, the authors of this work, understand that the world of policy making is complex and non-linear and that it involves a variety of stakeholders often with different agendas. We also appreciate that the timelines at which policy makers and analysts work can vary largely – often working in short response mode reacting to a variety of questions posed by different actors. This inevitably has implications for strategic and systematic analysis of evidence for emerging technology policy.

Fully acknowledging the above, this Handbook aims to capture domestic and international best practice related to evidence gathering and strategic analysis of emerging technologies, institutionalising organizational knowledge. It also presents conceptual frameworks that can serve as mental shortcuts highlighting system parts that are important to consider when strategising for emerging technologies. While it does not provide the only or the perfect recipe, it is presented in a way that it can be adapted to a variety of objectives, audiences, timelines, during any time in the policy cycle and technology development stage, as needed.

The ideas in this Handbook may be apparent to some of the intended audience of policy makers and policy analysts, but as a joint effort with this community, we compiled the thoughts that were believed to be the most useful for the intended audience.

We hope for this work to be updated from time to time as thinking, frameworks, and methods evolve, and as new methods and policies are tested over time here. Likewise, we aim to update the glossary of key terms here.

Executive Summary

This Handbook aims to institutionalize tacit knowledge embedded within UK stakeholders involved in past and current emerging technology policy and analysis, enabling the transfer of insights gained to inform future strategy.

It outlines lessons learned and best practices for evidence gathering and analysis in emerging technologies by examining quantum technology and engineering biology going 10 years back, specifically focusing on the UK. This work draws on insights from interviews with key UK policy makers and analysts, and other relevant UK stakeholders, as well as key policy documents.

Its key output is **a glossary of key terms and a flexible and adaptable step-by-step process for undertaking strategic analysis of emerging technologies for policy**. This is accompanied by academic and practitioner-based frameworks and tools that can help guide systematic analysis of emerging technologies. A Short Guide was also developed to summarise the proposed process, while conceptual underpinnings, templates and use cases are presented in more detail here.

Key takeaways for evidence gathering and strategic analysis

- ✓ Define objective and technology scope of strategic analysis
- ✓ Identify technology system elements and key terms and definitions
- ✓ Understand stage of technology development, which has implications for current state of evidence available and sequencing of strategic analysis
- ✓ Explore past domestic and international policies and evidence to determine what is available and what is missing
- ✓ Sequence strategic analysis according to objective stated, stage of technology development and current state of policy and evidence available
- ✓ Ensure each step of strategic analysis feeds back into the next step of the analysis
- ✓ Map system parts, including technologies and their pathways to sectoral applications, key actors and their interactions, capability and resource requirements, and interdependencies using conceptual frameworks
- ✓ Undertake international benchmarking along each step

Glossary

In this section, short definitions of key terms and concepts related to innovation and emerging technology policy are provided (see link to the web version to be updated regularly).

The glossary aims to:

- showcase the importance of setting out key terms upfront ensuring targeted and clear communication, and
- aid communication across different parts of the government as well as consistency across the Handbook,
- quickly introduce concepts related to innovation and emerging technology policy for those who are new to the topic.

It does not suggest that these definitions are the only correct understanding of these terms. Instead, the definitions try to identify key elements that make up the term, so that it can be adapted to various settings and needs.

- **Emerging technologies** can most usefully be defined relative to their stage of development as technologies that do not yet have an established knowledge, technology, and/or application base. In other words, there is no universally used core technology platform, standard configuration, dominant product design, set of materials and components, and thus clear supply and demand. Emerging technologies require the development of 1) novel research and engineering innovations, including knowledge and infrastructure; 2) new supply chains and industrial capabilities; as well as 3) the exploration of market applications and formation of a user base. See Section 2.1 for more details.

> One prevalent example of a critical technology is **semiconductors**, which in general do not really require new knowledge and tools (1) or market-pull (3) but require reconfiguring supply chains and developing new industrial capabilities (2) if a country is to strengthen strategic importance. This is in contrast with **semiconductor technologies that are still emerging** such as heterogeneous integration and compound semiconductors, whose knowledge base is still under development (1).

- **Critical technologies** differ from emerging technologies as they are not defined relative to their stage of development but relative to their strategic importance, which could be related to growth, value creation or security considerations. This does not provide information about its stage of technology development, as represented by points 1, 2 and 3 defining an emerging technology. This is important as critical technologies often do not require the development of 1) novel research and engineering innovations or 3) understanding and creating new markets, as both already exist. Instead, in most instances, they require strengthening and developing new industrial capabilities, and reconfiguring current supply chains.

- **Technology family** is an umbrella term encompassing related and complementary technologies that share a common and evolving knowledge and technology base. It is different from ‘technology’, which is a single unit of technology, suggesting that technology families are made up of several technologies, including core platform technologies and their pathway from science to a final product/service, while relying on several other necessary technologies which are required for their development and production. It is essentially an umbrella term that can be used to categorize technologies based on their knowledge and technology base. See definition of technology strata below, which lists the elements that make up a technology family.

- **Technology strata** represent the different elements that make up a technology family. The technology strata include 1) core technology platforms (here used interchangeably with core technologies, but are also often referred to as generic technologies, or general purpose technologies) underpinned by 2) scientific principles, 3) integrated technologies, 4) final solutions product or service, 5) production technologies, 6) research tools, 7) engineering tools, 8) demonstration environments and 9) external infrastructural technologies. They matter for policy as each of these technologies have different innovation economics and require the attention of different actors. Thinking about the different technology strata enables strategising for technology system elements more holistically, enabling forward-looking strategy. Furthermore, as the different technology strata build on each other, the development of one technology affects the trajectory of another technology.[1] Other related terms include product/process technologies, general purpose technologies. See Section 2.2 for more details.

- **Technology lifecycle** signifies the development of technologies over time usually measured with time on the x-axis and some type of output measure on the y-axis (e.g., market share, number of products sold, etc.). As every technology undergoes development from research to diffusion, at the wider emerging technology family level, it is expected that technologies will be at different stages of lifecycle, which in turn affects the development of and availability for other complementary technologies and capabilities. There is an effect of technology cumulativeness. Other related terms include technology readiness levels, manufacturing readiness levels, systems readiness levels, and user readiness levels. See Section 2.5 for more details.

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[1] Döme & O’Sullivan (2026). Technology ‘strata’ system framework (version 2, forthcoming). Link to version 1.

- **Innovation system** concepts suggest that innovations emerge as part of complex interactions between innovation actors – including a wide variety of public and private sector actors. These actors generate, share and use a variety of knowledge, while their interactions are shaped by institutions such as laws, norms, routines, standards, etc. The innovation functions of these actors can be summarized as knowledge generation, knowledge diffusion and knowledge absorption.[2] The structure of interactions differs (most notably) across countries, but also across regions, sectors and technologies with implications for innovation performance. Related terms such as national, global, regional, technological, and sectoral innovation systems, and innovation functions are explored in Section 2.3.

- A **supply chain** is essentially defined as the sequence of processes involved in the production and distribution of a product or service, starting with the supply of raw materials and ending with the delivery of the finished commodity.[3] In essence, it enables tracking the flow of inputs and outputs through firms. It is a useful strategic planning tool for assessing supply chain resilience and risk; however, it does not necessarily enable the understanding of competitive advantage and market opportunities. The term value chain captures this point as presented in the definition below. See more on supply and value chains in Section 2.4.

- The concept of the **value chain** complements that of supply chains by placing an emphasis on the processes of value addition alongside the set of activities involved in creating a product or service.[4] A broad definition of a value chain would be "the interconnected set of firms and wider activities that together create the value added of the product".[5] Each step in the sequence contributes to the overall value creation within the chain. These activities include, for example, R&D, design, logistics and after-sales services. Such a cumulative effect is particularly important to consider as it highlights that a rate-limiting factor in one step can lead to large losses in later steps, diminishing the overall value of earlier efforts. This perspective can thus help to identify activities that underpin the competitive advantage of firms and industries. Other related terms include supply networks and global value chains. See more on supply and value chains in Section 2.4.

- **Own-collaborate-access (OCA)** is a framework that was developed in the *'2021 Integrated Review'*[6] aiming to create a unified vision across security, defence,

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[2] OECD (1999). Managing national innovation systems.

[3] Other related definitions can be found in Cambridge Industrial Innovation Policy (forthcoming). Industrial innovation policy handbook: A primer for practitioners.

[4] Ibid.

[5] UNIDO (2009). Value chain diagnostics for industrial development.

[6] HMG (2021). Global Britain in a Competitive Age.

development and foreign policy, with science and technology playing a significant role across each of these. It essentially helps to guide strategic decisions about the sources of capabilities and resources required for emerging technology development and commercialisation. It suggests that there are capabilities that may be available domestically, and others that require international collaboration and/or access, or a mix of these. There are strategic choices that need to be made related to OCA including different options, risks and benefits. See further explanation in Section 3, Step 4: Actors with capabilities and resources.

- **Technology diffusion** refers to the process by which the use of a technology spreads across entities. The meaning of the word technology (often substituted by innovation or knowledge) as well as the entities across which the technology spreads (e.g., individuals, firms, organisations or markets) vary depending on the analytical lens. In contrast, **technology adoption** refers to the point at which an entity of interest first begins to use a new technology. Adoption is usually thus referred to as a discrete event, while diffusion is a systemic and ongoing process.

  Technology diffusion is not a linear or isolated process, and it unfolds within innovation ecosystems where multiple actors (firms, researchers, institutions, regulators, users, etc.) interact. From a policy perspective, it is most useful to understand technology diffusion through the lens of innovation ecosystems. This approach captures the complexity of interactions among diverse actors and the functions they perform to support the uptake of new technologies. Diffusion is successful when knowledge flows, entrepreneurial activity is supported, and resistance to change is managed.

Abbreviations

AI	artificial intelligence
ARDA	Advanced Research and Development Activity Agency (US)
BBSRC	Biotechnology and Biological Sciences Research Council
BEIS	Department of Business, Energy and Industrial Strategy
BIS	Department for Business Innovation and Skills
CAP	Fraunhofer Centre for Applied Photonics
CSTI	Centre for Science, Technology and Innovation Policy
DARPA	Defence Advanced Projects Research Agency (US)
DBT	Department for Business and Trade
DSIT	Department for Science, Innovation and Technology
Dstl	Defence Science and Technology Laboratory
EBAP	Engineering Biology Advisory Panel
EBLC	Engineering Biology Leadership Council
EBSG	Engineering Biology Steering Group
EC	European Commission (EU)
EPO	European Patent Office (EU)
EPSRC	Engineering and Physical Sciences Research Council
ERA	European Research Area (EU)
ESRC	Economic and Social Research Council
GCHQ	Government Communications Headquarters
GDP	Gross Domestic Product
GO-Science	Government Office for Science
HMG	His Majesty’s Government
HMT	His Majesty’s Treasury
IfM	Institute for Manufacturing
ISCF	Industrial Strategy Challenge Fund
IUK	Innovate UK
KTN	Knowledge Transfer Network
MoD	Ministry of Defence
MRL	manufacturing readiness level
NASA	National Aeronautics and Space Agency (US)
NGO	non-governmental organisation
NIST	National Institute of Standards and Technology (US)
NPL	National Physical Laboratory

NQCC	National Quantum Computing Centre
NQTP	National Quantum Technologies Programme
NSF	National Science Foundation (US)
NSSIF	National Security Strategic Investment Fund
NSTC	National Science and Technology Council (US)
OCA	Own-collaborate-access framework
OECD	Organisation for Economic Co-operation and Development
ONS	Office for National Statistics
QIPC	quantum information processing and communication
QIS/T	quantum information science/technology
QMI	Quantum Metrology Institute
QT	quantum technology
QT/NQTP SAB	Quantum Technology Strategic Advisory Board, newly NQTP SAB
R&D	research and development
RAEng	Royal Academy of Engineering
S&T	Science and technology
SBLC	Synthetic Biology Leadership Council
SBRI	Small Business Research Initiative
SIC	Standard Industry Classification
SME	small medium enterprise
SRL	system readiness level
STFC	Science and Technology Facilities Council
TRL	technology readiness level
TSB	Technology Strategy Board, now Innovate UK
TSMC	Taiwan Semiconductor Manufacturing Company
UK IPO	UK Intellectual Property Office
UKRI	UK Research & Innovation
URL	user readiness level
USPTO	US Patent and Trademark Office (US)
WIPO	World Intellectual Property Office

1 Introduction

This Handbook attempts to capture lessons learned and effective practices for emerging technology evidence gathering and analysis for policy. It aims to inform strategic analysis of complex emerging technology landscapes with a potential to inform current and future government strategy processes.[7] An adaptable six step process is developed for emerging technology policy as presented in Section 3 and summarised in a Short Guide accompanying this document.

Given UK's recent growth-driving sector priorities and its six frontier technology priorities published under *The UK's Modern Industrial Strategy,*[8] the Handbook focuses on evidence gathering and analysis related to already selected priorities, as opposed to the prioritisation process. Nevertheless, links to the earlier stage of prioritisation and later stage of implementation are also made. This is explored within the scope of quantum technologies and engineering biology given the importance of these technologies for UK's competitive advantage and the government support these have received over the past decade.

This work relies on the analysis of UK emerging technology strategies, interviews with UK policy makers and analysts, and other UK stakeholders involved in past or current emerging technology policy. In addition, the Handbook is informed by relevant academic literature and international policy practice.

1.1 Objectives

The Handbook seeks to achieve the following objectives:

- To institutionalize tacit knowledge embedded within UK stakeholders involved in past and current emerging technology policy and analysis, enabling the transfer of insights gained to inform future strategy
- To enable more systematic analysis of complex emerging technology landscapes by identifying and defining key system parts and their interdependencies
- To introduce conceptual systems frameworks as shortcuts to organizing the inherent complexity
- To provide examples of successful domestic and international emerging technology policy analysis
- To describe and unpack the process of strategic analysis and provide examples of tools and best practices

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[7] Strategy here refers to the process of strategising for emerging technology, including the long and short-listing of technologies, prioritization, strategic analysis of evidence, capabilities, opportunities and challenges. Final 'Strategy' documents are viewed as a result of this process in most cases unable to comprehensively capture the process.

[8] DBT (2025). The UK's Modern Industrial Strategy.

1.2 Background

In June 2025, the UK government identified eight growth-driving sectors and their subsectors based on UK's existing and emerging strengths.[9] *The Digital and Technologies Sector Plan*[10] specifically focuses on emerging technologies identifying six frontier technologies of particular interest to the UK. This includes advanced connectivity technologies, artificial intelligence, cyber security, engineering biology, quantum technologies, and semiconductors.

The primary characteristic of emerging technologies is that their knowledge, technology, and application base needed for their R&D, production, and diffusion are not well established. Essentially, emerging technologies require the 1) development of novel research and engineering innovations[11,12] including the creation of new knowledge and infrastructure, 2) establishment of new and reconfiguration of old supply chains and industrial capabilities, as well as 3) the exploration of market applications and formation of a user base. All the above activities are resource-intensive in terms of capital, time and research and development (R&D) efforts.

There are thus significant challenges to strategising for emerging technologies, especially for those domains which are still making the transition from promising applied science (perhaps with early niche/specialist applications) to engineered industrial technologies (with established design rules, supply chains, engineering 'tools', standardised production processes, etc).

In this context, strategy processes must manage large stakeholder groups, drawn from different parts of the research base, different stages of the innovation lifecycle, and different industrial value chain stages. This complexity inherent to emerging technologies is further exacerbated by the uncertainty of potential impact of emerging technologies as well as their impact on adjacent technologies and sectors.

Furthermore, effective strategic analysis of national strengths and opportunities requires detailed intelligence on other countries' capabilities, resources and future plans. Finally, national emerging technology strategy must also navigate variations in policy stakeholder motivations, incentives and priorities, as well as ever-changing policy contexts, including strategic efforts in complementary or competing technology domains.

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[9] DBT (2025). The UK's Modern Industrial Strategy.

[10] DSIT (2025). Digital and Technologies Sector Plan.

[11] RAEng (2023). State of UK deep tech.

[12] Nanda, R. (2020). Financing "tough tech" innovation. Global Innovation Index 2020: Who will finance innovation?

1.3 National and international emerging technology priorities

Governments around the world recognise the strategic importance of emerging technologies given their potential to enhance competitive advantage and domestic capabilities, impact economic growth and national security, and address societal and environmental challenges. Some examples of recently published international strategies prioritizing a set of emerging technologies include the *US Critical and Emerging Technologies List Updat*e, China's document on *Promoting the Innovative Development of Future Industries,* the EU's *key enabling technologies* and others as summarized in Table 1.

Table 1 Emerging technology priorities across different governments.

UK's Digital and Technologies Sector Plan 2025[13]	*US Critical and Emerging Technologies List Update 2024*[14]	*China's Promoting the Innovative Development of Future Industries 2024*[15]	*EU's Key Enabling Technologies Policy 2018*[16]	*Australia's List of Critical Technologies in the National Interest 2023*[17]
•AI •Engineering Biology •Advanced Connectivity Technologies •Quantum Technologies •Semiconductors •Cyber Security	•Advanced Computing •Advanced Engineering Materials •Advanced Gas Turbine Engine Technologies •Advanced Manufacturing •Advanced and Networked Sensing and Signature Management •AI •Biotechnologies •Clean Energy Generation and Storage •Data Privacy, Data Security, and Cybersecurity Technologies •Directed Energy •Highly Automated, Autonomous, and Uncrewed Systems (UxS), and Robotics •Human-Machine Interfaces •Hypersonics •Integrated Communication and Networking Technologies •Positioning, Navigation, and Timing (PNT) Technologies •Quantum Information and Enabling Technologies •Semiconductors and Microelectronics •Space Technologies and Systems	Future Industries: • Future Manufacturing • Future Information • Future Materials • Future Energy • Future Space • Future Health Future-oriented industries: • Humanoid Robots • Quantum Computers • New Displays • Brain-Computer Interface • 6G Network Equipment • Ultra-large-scale New Intelligent Computing Centres • Web 3.0 • High-End Cultural and Tourism Equipment • Advanced and Efficient Aviation Equipment • Deep Resource Exploration and Development Equipment	Production Technologies: •Advanced Manufacturing Technologies •Advanced Materials and Nanotechnologies •Life-Science Technologies Digital Technologies: •Micro-/Nano-Electronics and Photonics •AI Cyber Technologies: •Security and Connectivity	•Advanced Manufacturing and Materials Technologies •AI Technologies •Advanced Information and Communication Technologies •Quantum Technologies •Autonomous Systems, Robotics, Positioning, Timing and Sensing •Biotechnologies •Clean Energy Generation and Storage Technologies

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[13] DSIT (2025). Digital and Technologies Sector Plan.

[14] US NSTC (2024). US critical and emerging technologies list update.

[15] Chinese Ministry of Industry and Information Technology et al. (2024). Translation of the Implementation opinions of seven ministries on promoting the innovative development of future industries.

[16] European Commission (n.d.). Key enabling technologies of the European Commission.

[17] Department of Industry, Science and Resources (2023). Australia's list of critical technologies in the national interest.

1.4 'Layers' of national emerging technology strategy

National emerging technology strategy can be conceptualized as shown in Figure 1. This is a simplified depiction of a complex process, which is influenced by internal and external factors on one hand and data and evidence on the other hand. It essentially shows the process of prioritizing and strategising for emerging technologies through 'layers' proceeding from a long list of all emerging technologies, through a shorter priority list, to technology-specific strategy development, and finally to programme design. The layers are inherently connected to each other, where decisions made in one layer are then propagated through the following layers. The diversity of stakeholders involved, and evidence used across the different layers suggests the importance of feedback loops between layers.

Technology foresight tools for the top two stages are well summarized in the European Commission's Join Research Centre report.[18] However, given UK's recent history in prioritizing specific technologies and industries, this Handbook sets out to **focus on the third layer** as highlighted in Figure 1, which is when a priority list of technologies has already been decided each awaiting strategic analysis. The linkages to the layers above and, especially, below are also very important as strategic analysis in this step could potentially inform policy implementation as well.

The Handbook particularly delves into analysing the most recent strategy developments around **quantum technologies** and **engineering biology** given the importance of these technologies for UK's competitive advantage and the government support these have received over the past decade.

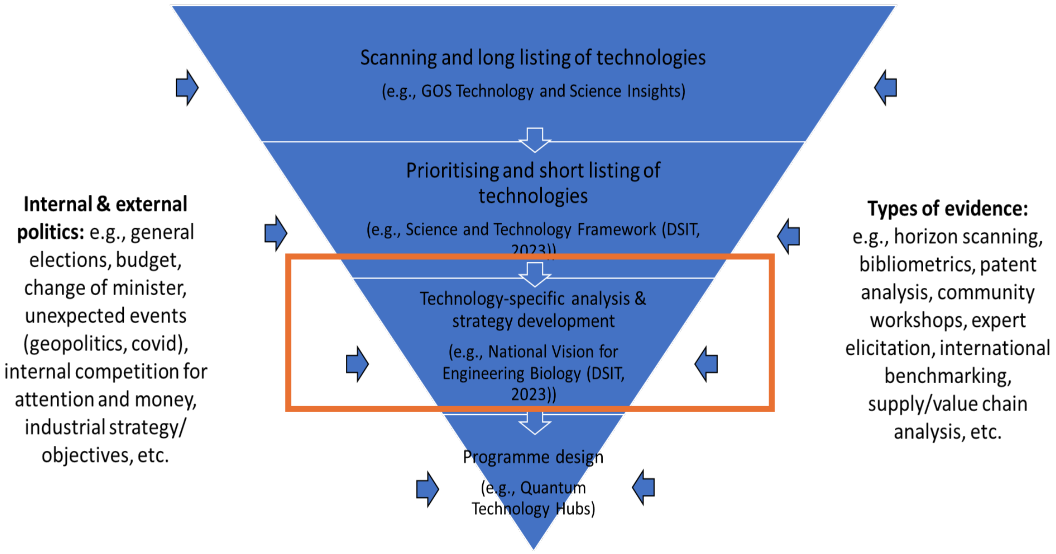

Figure 1 Conceptual view of national emerging technology strategy 'layers'. The focus of this Handbook is highlighted in the orange box. Source: NETS Handbook Project Team.

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[18] European Commission JRC (2023). Technology foresight for public funding of innovation: Methods and best practices.

1.5 Evolution of UK's technology policy

The UK has a recent, quite turbulent, history of prioritizing industrial and emerging technology policies to drive economic growth and maintain a competitive edge on the global stage. This strategic focus has been underscored by various governmental initiatives, particularly over the past decade, aimed at fostering science and innovation and positioning the UK as a leader in key technological domains.

Professor Richard Jones's recent article[19] highlights the often-shifting priorities (changing every 2.5 years on average in the past decade) and incoherence across priorities, including their different focus – sometimes referring to technologies and at other times grand challenges, missions, technology missions, industry sectors, sectors, etc. He explains how this may influence strategic thinking and offers a brief description of each term and what it means in terms of strategic analysis. Nevertheless, putting all the priorities of the past decade side by side reveals that consistency across some of the technologies such as engineering biology or quantum technology exists – both being explored in more detail in the Handbook (see Section 4).

A reflection by the former Science Minister, Lord David Willetts,[20] comments on his '*Eight Great Technologies*' initiative as well as on the history and role of industrial policy in the UK. He suggests that industrial strategy in the UK has faced substantial scepticism, largely due to past failures such as the Concorde, the civil nuclear power programmes, and the decline of the British car industry. These examples fuelled critiques, most notably from figures like David Henderson and Margaret Thatcher, who argued that such strategies wasted money and supported failing industries. He also argues that this scepticism has permeated the Treasury and Whitehall, fostering a preference for 'horizontal' policies that promote general economic conditions rather than 'vertical' ones targeting specific sectors or technologies. The belief is that government intervention often fails to pick winners and instead drains taxpayer resources on unsuccessful ventures. There is thus a tendency to avoid specific interventions, focusing instead on general support like funding for basic research, effective intellectual property regimes, and tax incentives for R&D.

However, he argues that despite this prevailing scepticism, there is a recognition that some level of strategic intervention is necessary, especially in promoting innovation. Successful industrial policies often occur in the 'messy' space between laissez-faire detachment and active government intervention. Examples include Margaret Thatcher's successful efforts to attract Japanese car manufacturers to the UK and the strategic promotion of mobile phone standards that benefited companies like Vodafone. The development of FinTech through regulatory sandboxes also illustrates effective government involvement. Therefore, the government must balance its role, bearing some risks to stimulate private investment in

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[19] Jones (2024). The shifting sands of UK Government technology prioritisation.

[20] Willetts (2023). The Eight Great Technologies 10 years on.

innovation and supporting the transition of new technologies from research to market. This aligns closely with the global trend of bringing industrial policies to the forefront once again.

The following section briefly summarizes UK's technology policies of the past decade:

The Eight Great Technologies Initiative (2012)[21]

A significant milestone in the UK's technology policy was marked in the Autumn Statement of 2012 when Chancellor George Osborne announced a substantial investment of £600 million in the *'8 Great Technologies'*. A pamphlet by the then Science Minister, Lord David Willetts, expanded on the rationale for choosing these particular eight technologies. It was built upon evidence from Research Council impact reports, Technology Strategy Board (newly Innovate UK), and foresight exercises conducted by the Government Office for Science (GO-Science). The pamphlet provided a compelling narrative for why the UK should invest in these technologies referring to UK's competitive advantage on several occasions. The **eight great technologies** include:

1. Big Data and Energy-Efficient Computing
2. Satellites and Commercial Applications of Space
3. Robotics and Autonomous Systems
4. Life Sciences, Genomics and Synthetic Biology
5. Regenerative Medicine
6. Agri-Science
7. Advanced Materials and Nanotechnology
8. Energy and its Storage

The Eight Great Technologies reinforced and expanded under the *Our Plan for Growth* (2014)[22]

The commitment to the *8 Great Technologies* was reaffirmed and expanded upon in the (Conservative & Liberal Democrats) coalition government's '*Our Plan for Growth*' in 2014. This plan not only reinforced the initial £600 million investment into the 8 technologies but also introduced additional funding to bolster the UK's research capabilities. Notably, it included:

- £90 million investment in **graphene** research, which led to the establishment of three new graphene centres and two centres for doctoral training
- £270 million investment in **quantum technologies**, aimed at developing a network of research hubs focused on postgraduate skills, research infrastructure, and an innovation program worth £50 million to support business-led feasibility and demonstrator projects in quantum technologies

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[21] BIS (2013). Eight Great Technologies: Speech.; Willetts (2023). The Eight Great Technologies 10 years on.

[22] HMT & BIS (2014). Our plan for growth: Science and innovation.

Despite the re-election of a majority Conservative government and continuity in the office of the Prime Minister, there was a short period in which industrial strategy was not endorsed under the new Secretary of State in the Department of Business, Innovation and Skills (BIS), Sajid Javid.

New Four Grand Challenges under the *UK Industrial Strategy* (2017)[23]

After the Brexit referendum and change in the office of the Prime Minister, a renewed interest in industrial strategy led to the publication of the '*UK Industrial Strategy'* in 2017. This was at a time when BIS was renamed and merged with the Department of Energy and Climate Change (DECC) into the Department of Business, Energy and Industrial Strategy (BEIS). While the new industrial strategy acknowledged the importance of emerging technologies, it focused on **four grand challenges**:

1. Growing the Artificial Intelligence (AI) & Data-Driven Economy
2. Clean Growth
3. The Future of Mobility
4. Ageing Society

It also brought about the establishment of the *Industrial Strategy Challenge Fund* that is used to support emerging technologies to this date.

New Seven Technology Families under the *UK Innovation Strategy* (2021)[24]

Another election with another Conservative government led to the publishing of the '*Plan for Growth'* accompanied by the '*UK Innovation Strategy'.* Its key vision was to make the UK a global hub for innovation by 2035 through 4 key actions, including business support, talent support, institutions & places, and missions & technologies. The strategy identified a set of **seven technology families**:

1. Advanced Materials and Manufacturing
2. AI, Digital and Advanced Computing
3. Bioinformatics and Genomics
4. Engineering Biology
5. Electronics, Photonics and Quantum
6. Energy and Environment Technologies
7. Robotics and Smart Machines

New Five Critical Technologies under the *UK Science & Technology Framework* (2023)[25]

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[23] HMG (2017). Industrial Strategy: Building a Britain fit for the future.

[24] BEIS (2021). UK Innovation Strategy.

[25] DSIT (2023). UK Science and Technology Framework.

In 2023, as the new Department for Science, Innovation and Technology (DSIT) was formed, the UK's strategic focus shifted to **five critical technologies** published in the *'UK Science & Technology Framework'*. These for the first time included semiconductors and future telecommunications that did not appear in earlier strategies, and includes:

1. Artificial Intelligence
2. Engineering Biology
3. Future Telecommunications
4. Semiconductors
5. Quantum Technologies

The rest of the document focuses on more cross-cutting (or 'horizontal') actions to support these technologies and create an environment enabling innovation. More importantly, it makes a reference to the *'own-collaborate-access (OCA) framework'* which emphasizes the need to understand whether end-to-end capabilities to support an emerging technology are available domestically or should be developed domestically, or whether collaboration and/or access are strategically a better choice. The OCA framework was developed in the *'2021 Integrated Review,'*[26] which attempted to create a unified vision across security, defence, development and foreign policy. The Integrated Review put science and technology at the centre of UK's overarching national and international strategy to sustain its strategic advantage – and gain economic, political and security advantages.

The Eight Growth-Driving Sectors under *The UK's Modern Industrial Strategy* (2025) [27]

In 2024, with the election of the Labour government, a consultation was published putting a new industrial strategy at the centre of its mission with eight growth-driving sector priorities. Not long after, in 2025, *The UK's Modern Industrial Strategy*[28] was published providing further detail on the eight growth-driving sectors and their subsectors accompanied by sector plans:

1. Advanced Manufacturing
2. Clean Energy Industries
3. Creative Industries
4. Defence
5. Digital and Technologies
6. Financial Services
7. Life Sciences
8. Professional and Business Services

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[26] HMG (2021). Global Britain in a Competitive Age.
[27] DBT (2025). The UK's Modern Industrial Strategy.
[28] Ibid.

While the newest strategy focuses on growth-driving sectors and subsectors, it acknowledges that these will depend on UK's current and emerging strengths, including emerging technologies, processes and ideas.

The Digital and Technologies Sector Plan[29] specifically focuses on emerging technologies identifying six frontier technologies of particular interest to the UK:

1. Advanced Connectivity Technologies
2. Artificial Intelligence
3. Cyber Security
4. Engineering Biology
5. Quantum Technologies
6. Semiconductors

Conclusions

Despite shifting priorities, the focus on the eight great technologies and subsequent strategic investments in grand challenges, technology families, critical technologies, and frontier technologies have yielded significant advancements. For instance, the UK has made notable progress in fields like quantum technologies and engineering biology, positioning itself as a global leader. However, challenges remain. Maintaining a competitive edge in an increasingly globalized and fast-paced technological environment requires sustained investment, consistency and coherence across priorities, strategic decisions and agile policymaking **underpinned by a strong evidence base. This latter point is indeed what this Handbook attempts to cover.**

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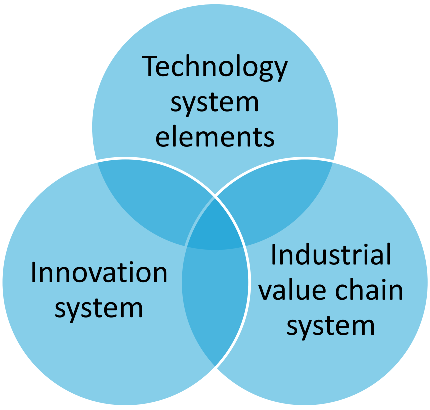
[29] DSIT (2025). Digital and Technologies Sector Plan.

2 Conceptual systems frameworks guiding strategic analysis

The aim of this section is twofold. First, it aims to **define emerging technologies**, as the core unit of analysis in this Handbook, while also making a case for the need to have unified definitions. However, rather than providing a ready-made definition, which would be highly dependent on the 'exam question' and 'who is asking', key elements that make a technology emerging are highlighted instead.

Second, this section aims to introduce a handful of **conceptual systems frameworks as mental shortcuts to organizing the complex landscape of emerging technologies in a more systematic and holistic manner,** drawing on academic understanding of innovation and industrial policy**.** They can help to assist in integrating systems thinking into practice to enable better handling complex problems by providing structure to the process. Three key frameworks are presented each capturing a different aspect of emerging technologies – technology elements, innovation actors and their interactions, and industrial capabilities:



1. **Technology system elements framework**
    - What are the different types of technologies that we need to think about?
    - What technologies and capabilities do we need to accelerate development and capture value?
    - How will the availability of one technology influence the development of another technology?
    - What are the innovation economics of each technology group and how does this affect government (and in turn private) funding?
    - Which stakeholders should we engage with for the development of different technologies?

2. **Innovation system framework**
    - Who are the different actors involved in innovation?
    - How do they interact and what types of linkages exist between them?
    - How do these actors generate, share and use knowledge?

- Which innovation stages do they take part in (e.g., knowledge generation, knowledge diffusion or knowledge absorption)?
- What capabilities and resources do they have or could potentially develop?

3. **Industrial value chain framework**
    - What industrial capabilities and resources are currently available to support an emerging technology and what capabilities and resources will need to be developed?
    - What is the division of labour across the value chain? What are the key actors in the system possessing what capabilities and resources?
    - What parts of the industrial value chain may potentially have the highest value added?

The frameworks are some of the most prominent conceptualizations of innovation policy, innovation economics and innovation management grounded in practical observations. But also, the ones that are deemed most relevant for emerging technology policy as agreed by the authors and suggested during consultations with policy stakeholders.

The selected frameworks complement each other by describing different system components and linkages between them. Once these system components are understood and accounted for; systems-based methods can be used to analyse them.

There are several systems-based methods, approaches and tools as summarized by the Government Office for Science or the European Commission[30] – a number of these are presented and exemplified through use cases in Section 3.

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[30] Several systems-based methods exist that are worth exploring and best used in combination when feasible. European Commission (2023). Systems-based methods for research & innovation policy.; GO-Science (2023). An introductory systems thinking toolkit for civil servants.

2.1 Defining emerging technology

Emerging technologies can most usefully be defined relative to their stage of development. **Their key defining feature is that their knowledge, technology, and/or application base needed for their R&D, production, and diffusion are not well established.** This means that there is no universally used and agreed core technology platform, standard configuration, dominant product design, set of materials, components, science & engineering tools, etc. and thus clear supply and demand. Emerging technologies therefore require the:

1. development of novel research and engineering innovations, including related knowledge and infrastructure[31,32]
2. establishment of new and reconfiguration of old supply chains and industrial capabilities
3. exploration of potential market applications and formation of a user base

The fact that the knowledge, technology, and application base is still emerging entails several issues that require support and attention enabling the acceleration of technology development. For example, the lack of knowledge and infrastructure base presents significant challenges. There is a need to support foundational research, which can be both time-consuming and resource intensive. Moreover, without a clear understanding of the most effective methodologies, there is a higher risk of failure or inefficiency in early R&D stages, but there is a need to allow for risk and failure. Establishing new infrastructure, including demonstrators all the way from technology demonstrators, though pilot lines and testbeds to living labs, also demands substantial support.

Another common issue resembles the chicken and egg dilemma: "Suppliers are reluctant to invest in new technology until their customers [e.g., quantum system developers] are willing to commit to large sales volumes, but customers are reluctant to commit to significant purchases until they see the technology they need from suppliers and until the demand for their own products is clearer. A large share of the discussion across many of the [quantum technology-related] industry needs reflected this dilemma. These challenges typically resolve themselves as tipping points are reached, official and de facto standards are created, and dominant approaches emerge and refine the marketplace."[33] This phenomenon has been observed in several emerging technologies, including in a quantum technology manufacturing roadmap by the US[34] but also in a roadmapping exercise on quantum technology in the UK.

The supplier-customer dilemma thus highlights that there is inherent uncertainty about the viability and demand for new products. There are also wider technology adoption and

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[31] RAEng (2023). State of UK deep tech.

[32] Nanda (2020). Financing "tough tech" innovation. Global Innovation Index 2020: Who will finance innovation?

[33] SRI International Center for Innovation Strategy and Policy (2023). Quantum technology manufacturing roadmap.

[34] Ibid.

diffusion related challenges concerning regulation, social/market acceptance, availability of external infrastructure, and ethical considerations.

Emerging technologies can lead to different levels of economy-wide impact which are difficult to assess at early stages of emergence and growth. This is often referred to in terms of disruption, with different degrees of disruption starting from sustaining innovations that affect only a single technology with no major changes to markets all the way to disruptive innovations that affect all technologies leading to the reorganization of the whole economy.[35] Examples of core (platform) technologies that have led to large-scale changes in the organization of the whole economy are the steam engine, electric generator, electric motor, transistor, and the internet. These can also be referred as general-purpose technologies as assessed retrospectively. [36]

Given the novel, fast-growing and uncertain nature of emerging technologies, it is this knowledge, technology and application base that requires systematic understanding and continuous upgrading to enable gaining competitive advantage.

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[35] Bower & Christensen (1995). Disruptive technologies: Catching the wave.

[36] Teece (2018). Profiting from innovation in the digital economy.

BOX 1: Definitions of emerging, deep, tough technology

"There is no universal definition of deep tech, and other terms like hard tech and tough tech are also in the mix. By its very nature, the term encompasses a broad and evolving spectrum of innovative technologies, and what constitutes deep tech may vary based on the perspectives and metrics of different stakeholders. What does appear to be common in the definition of deep tech companies is that the **technologies are grounded in innovative engineering and cutting-edge scientific advances** and the companies are recognised as being **capital, time and R&D intensive**."

(State of UK deep tech, RAEng)

"Many of the world's most pressing problems — from addressing climate change, developing sustainable food and water systems, and improving human health and wellbeing — depend critically on the successful **commercialisation of fundamental science and engineering innovations** that are often referred to collectively as 'Deep Tech'. Deep tech is a cornerstone of continued advances in new technological paradigms such as quantum computing, advanced materials, synthetic biology, and numerous other innovations that arise from fundamental science and tangible innovation."

(Institute for Deep Tech Entrepreneurship, Imperial College London)

"The result is the delineation of five key attributes that qualify a technology as emerging. These are: (i) radical novelty, (ii) relatively fast growth, (iii) coherence, (iv) prominent impact, and (v) uncertainty and ambiguity. Specifically, we conceive of an emerging technology as a radically novel and relatively fast growing technology characterised by a **certain degree of coherence persisting over time** and with the potential to exert a considerable impact on the socio-economic domain(s) which is **observed in terms of the composition of actors, institutions and patterns of interactions among those, along with the associated knowledge production processes.** Its most prominent impact, however, lies in the future and so in the emergence phase is still somewhat uncertain and ambiguous."

(Academic literature review in Rotolo et al., 2015)

2.2 Technology system elements framework

Summary

- This section addresses the need for a clear and structured approach to understanding and distinguishing a set of technologies that make up a group of emerging technologies – ‘a technology family’.
- Distinguishing technologies is crucial for strategising beyond core platform technologies and final products or services. Less often considered groups, but potentially rate-enhancing or -limiting factors, include R&D tools, engineering tools, manufacturing technologies, external infrastructural technologies or demonstration environments.
- Sources of high value and competitive advantage can come from any of these other groups of technologies and are essential for unlocking the trajectories of core platform technologies and final products or services.

Technology system and its key elements

The term ‘technology’ often conflates various technological entities. Yet, they may have different innovation economics and require the attention of different stakeholders, which has significant implications in terms of who funds what (and the role of government). The Technology Strata Framework[37] proposes a systematic way that can be adapted for any emerging technology to differentiate between various types of technological entities based on their evolutionary stages and interdependencies.

As shown Figure 2, every technological entity evolves through and can be classified across different technology strata starting from **1) its underpinning scientific principles, through the application of this principle into 2) a core technology, and integration into a larger system forming 3) an integrated technology.**

Some technologies then become 4) final solutions products or services – e.g., a smartphone or an ultra-responsive hearing aid. Others continue to serve the development and production of these. They include: 5) R&D tools, 6) engineering tools, 7) demonstration environments, 8) production technologies, 9) external infrastructural technologies – all playing a vital role in other technology lifecycles despite often being neglected during strategic development.

Section 3 Step 1 provides details on the process of identifying these different systems elements and gives an example (see Use Case 3). Section 3 Step 2 then builds on this and

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[37] Döme & O’Sullivan (2026). Technology ‘strata’ system framework (version 2, forthcoming). Link to version 1.

suggests how technology pathways (and technology combinations) from research to market applications can be identified.

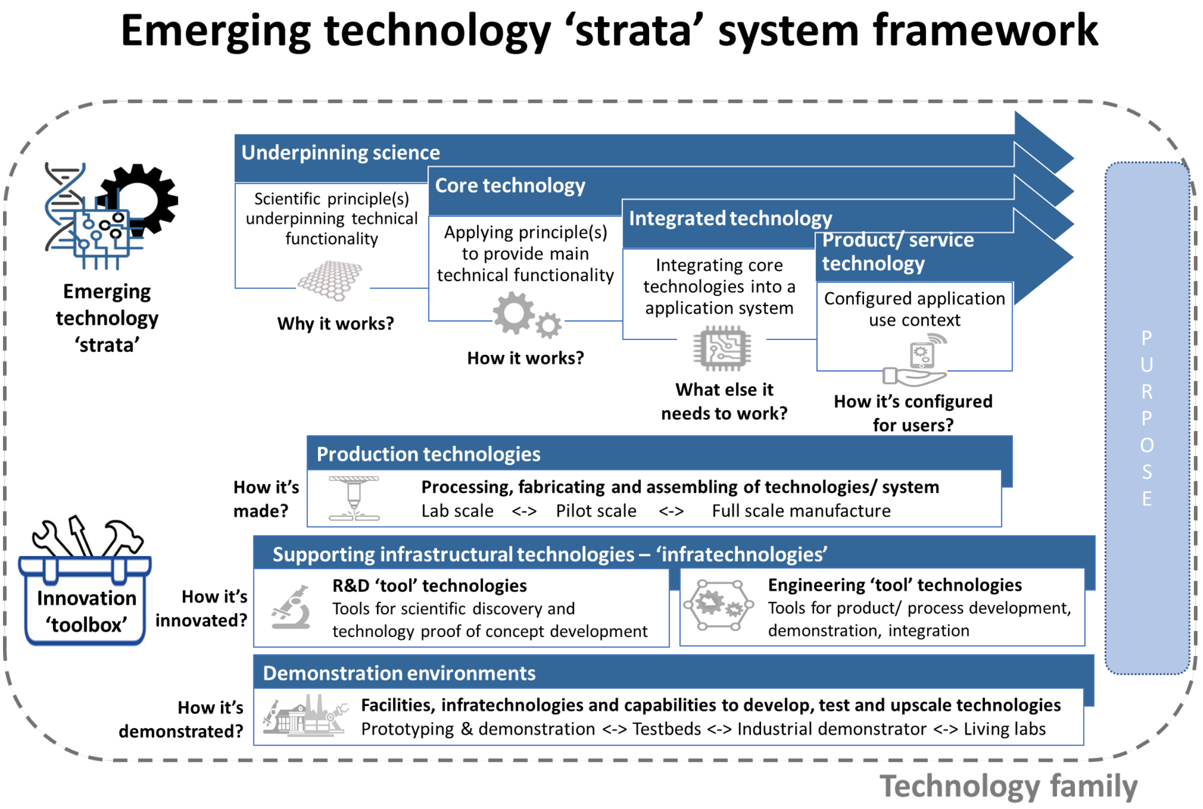

Figure 2 Simplified framework distinguishing between technology strata and other key technology system elements.[38] *Source: Döme & O’Sullivan, 2025.*

In practical terms, distinguishing between technologies enables…

Developing comprehensive lists of ‘enabling’ technologies that constitute and support emerging technologies—such as innovation infrastructure, standards, engineering tools, manufacturing technologies, components, related capabilities, etc. — which can provide valuable insights to:

- **Inform the next stage of strategic analysis** essentially mapping these technologies and their expected combinations over time towards application sectors
- Strategize for **‘enabling’ technologies that cut across several emerging technologies** within the same group (e.g., quantum sensors and quantum computing) or adjacent technologies and applications – e.g., semiconductor technology leading to more scalable and stable quantum computers, and vice versa, quantum computers solving complex semiconductor design problems.

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[38] *Note: The number of technology strata, core technologies, and external infrastructural technologies increases with complexity of the final solutions technology. Demonstration environments play an important role here as they combine a number of these technology strata – they are also important for strategic analysis.*

- Identify technologies that may have different innovation economics (i.e., public good nature of technologies such as precompetitive R&D for tool technologies vs. proprietary technology), with significant implications in terms of who funds what (and the role of government)
- Think about which parts of the supply chain the UK has or could have and get economic value from
- Think about national security vulnerabilities in the supply chain
- Anticipate which technologies are most resilient to uncertainty about which core platform technology wins and therefore make better industrial bets
- Anticipate which technologies would have an out-sized impact if they became monopolised. For example, if a production technology underpins multiple quantum sensors but will also support technologies in quantum compute and other photonics applications, a single country controlling that production technology would have significant influence over multiple critical technologies

Technology family as a unit of analysis of policy

These different sets of technologies then belong to the '*technology family'* (or a bucket of technologies) as they share a common and evolving knowledge and technology base due to a common feature. The common feature can come from underpinning science and engineering (e.g., nanotechnology, biotechnology, advanced materials) or an application area (e.g., renewable energy generation, medical imaging, advanced manufacturing) depending on the direction from which innovation is stimulated.

The technology family (or other similar umbrella terms used to group and strategize for a set of emerging technologies) thus forms a *useful unit of analysis for emerging technology policy*. Setting out boundaries in terms of what belong in a technology family depends on the policy motivation and could be considered at different levels (e.g., quantum technologies as a larger group, as quantum computing at a lower level, or superconducting technologies at an even lower level). If comparisons are made across different technologies, it is important for emerging technology families to be conceptualized at the same level. See one example applying the framework on a multifunctional product technology presented in Figure 3.

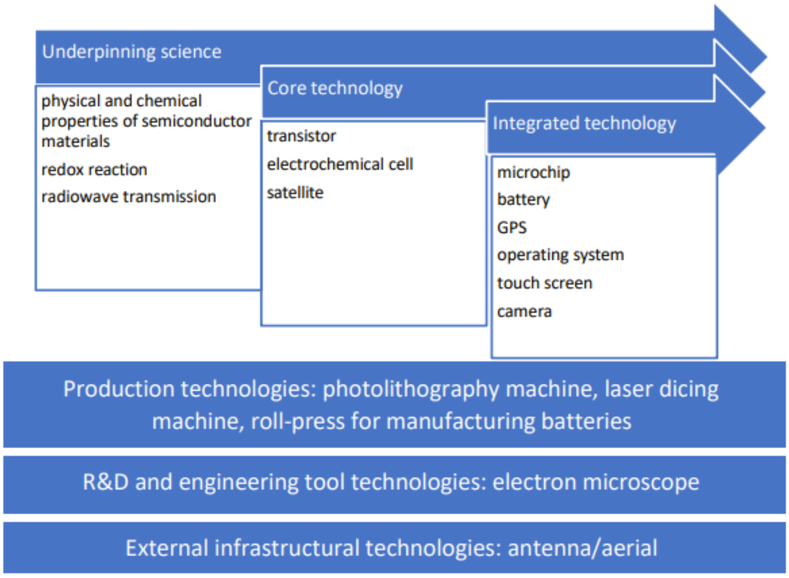

Figure 3 An example of mapping the technology system elements of a multifunctional product technology – a smartphone.[39] *Source: Döme & O'Sullivan, 2025.*

What about demonstration environments?

Demonstration environments are crucial for emerging technologies because they provide structured stages of validation, development, and adoption, ensuring that the technology products are viable, manufacturable, integrable, and beneficial for end-users. They essentially mitigate risks associated with technological innovation, from initial concept to market adoption. Demonstration environments are a technology in and of itself, but also a system that wires up different technologies in a variety of configurations. They can be usefully grouped as:

- **Demonstrating that the technology works** (e.g., technology demonstration, prototyping)
- **Demonstrating that the technology can be manufactured** (e.g., low volume production pilot lines)
- **Demonstrating compatibility and interoperability with other systems** (e.g., testbeds)
- **Demonstrating tangible benefits to end-users** (e.g., living labs)
- **Hybrids of the above.** Usually come in at certain points in the technology development lifecycle. For example, both MOCVD (Metal-Organic Chemical Vapor Deposition) and MBE (Molecular Beam Epitaxy) are techniques used to manufacture semiconductors, but require entirely different environments, or technologies and configurations of technologies to grow thin films and epitaxial layers of materials. This has implications in terms of when in the technology innovation lifecycle they are used – the former

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[39] *Note: This highlights the importance of tool technologies and manufacturing technologies that indeed form some of the most complex and expensive technologies in the world that are heavily monopolized (e.g., extreme ultraviolet lithography machine used to produce the most advanced semiconductors).*

being more scalable and cost-effective and thus suitable for industrial-scale manufacturing and the latter providing higher precision and thus invaluable for research and experimental semiconductor devices.

Technology Demonstration – represented by the technology readiness level (TRL) concept

Technology Readiness Levels (TRLs)[40] are a framework for assessing the maturity of a particular technology. Technology demonstration focuses on showcasing applied science and technology in controlled settings to validate technology functionality and performance. Technology demonstration is vital for moving a technology from theoretical research to practical application. It typically involves prototypes or early models tested in environments that simulate real-world conditions.

Demonstration of Manufacturability – related concept of manufacturing readiness level (MRL)

Manufacturing Readiness Levels (MRLs)[41] are used to gauge the manufacturability of a technology, assessing how ready it is to be produced at scale. Pilot lines are essential demonstration environments at this stage, where the focus shifts to testing and refining the manufacturing process. These lines are smaller-scale versions of full production lines, allowing engineers to identify and resolve issues related to materials, processes, and quality control before committing to large-scale production. Pilot lines help in verifying that the technology can be manufactured efficiently, reliably, and cost-effectively, ensuring a smoother transition to full production and reducing risks associated with scaling up.

Demonstration of Interoperability – related to the system readiness level (SRL) concept

System Readiness Levels (SRLs) evaluate the integration of new technologies within larger systems. Testbeds serve as critical demonstration environments, providing a controlled yet realistic setting where different components and subsystems can be tested together. These environments are designed to simulate the actual conditions in which the integrated system will operate, allowing for thorough testing of interoperability, performance, and reliability. This step is crucial for complex systems where the failure of one component can affect the entire system's functionality.

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[40] Mankins (1995). Technology Readiness Levels.

[41] Department of Defense (2003). Technology Readiness Assessment (TRA) Deskbook.

Demonstration of value to user – related to the user readiness level (URL)

User Readiness Levels (URLs) focus on demonstrating the benefits of a technology to its end-users or adopters. Living labs are essential environments for this stage, where technologies are tested in real-world settings with actual users. They provide invaluable feedback on user experience, usability, and the overall impact of the technology on daily life. They are crucial for ensuring that the technology meets user needs and delivers tangible benefits, thereby increasing the likelihood of successful adoption and market acceptance.

These readiness levels are further explained in Section 2.5.

2.3 Innovation system framework

Summary

- Innovation systems emphasize the importance of interactions between innovation actors shaped by an institutional framework, underlining that innovation is far from being linear.
- The structure of interactions differs across countries, regions, technologies and sectors due to their distinct knowledge networks, industrial structures and institutional frameworks. This has implications for their innovation performance.
- Mapping innovation systems can help to understand the factors that enable or hinder innovation performance.

Innovation system and its key elements

Innovation is not a linear process. Instead, innovation emerges as part of complex interactions among innovation actors, including firms, customers, research centres, governments, national laboratories, standards institutions, etc. The interactions between these actors are shaped and often constrained by institutions like policies, laws, regulations, norms and routines. Therefore, the so-called **'innovation system' can be described as having three key elements as presented in Figure 4: 1) innovation actors, 2) their interactions, and 3) the institutional framework in which they occur.**

Section 3 Step 4 describes in more detail how innovation systems can be mapped and provides two examples tested with UK civil servants – one example mapping UK's national innovation system (see Use Case 6) and one its quantum innovation system (see Use Case 7).[42]

The **structure of interactions** differs across countries, regions, sectors and technologies, which has **implications in terms of innovation performance**. This has to do with their distinct institutional frameworks, industrial structures and cultural conditions, which are naturally most predominant at the country level. [43] There are also differences in terms of the resources (e.g., knowledge base, infrastructure, education, workforce) and capabilities (or unique combinations of resources such as technological capabilities or absorptive capacity) available to different actors in various innovation and industrial systems and across the disparate stages of these systems. Some examples of potential differences include the different roles of the main actors in innovation processes, and the forms, quality and intensity of their relationships;

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[42] The two exercises make use of a method referred to as 'systems mapping' as it enables enough flexibility to be adopted to specific policy questions and enables drawing linkages between actors. However, there are several systems-based methods that are worth exploring. They are best used in combination when feasible. European Commission JRC (2023). Technology foresight for public funding of innovation: Methods and best practices.; GO-Science (2023). An introductory systems thinking toolkit for civil servants.

[43] OECD (1999). Managing national innovation systems.

structure of R&D financing (public/private/etc.); orientation of public R&D funding; etc.[44] **Therefore, mapping an innovation system of interest can help to understand the factors that enable or hinder innovation performance, guiding strategic analysis and policy decisions.**

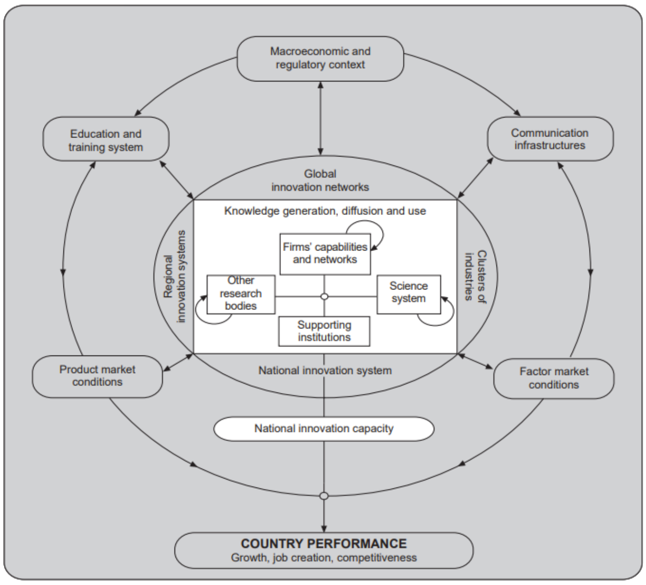

Figure 4 Actors and linkages in an innovation system embedded in the wider institutional framework. Source: OECD, 1999.

The innovation system concept was first conceptualized at the national level as a network of "public and private sectors whose activities and interactions initiate, import, and diffuse new technologies" within national boundaries.[45] However, different geographical boundaries and units of analysis have been suggested to answer different questions: global,[46] regional,[47] technological,[48] and sectoral[49] innovation systems.

The national and technological innovation system concepts are likely to be the most useful for analysing and mapping emerging technology innovation systems. As shown in Figure 5, the two systems overlap.[50] The technological innovation system reaches beyond national boundaries and may require the consideration of international actors that are involved in innovation activities of the given technology.

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[44] OECD (1999). Managing National Innovation Systems.
[45] Freeman (1987). Technology and Economic Performance: Lessons from Japan.
[46] Binz & Truffer (2017). Global innovation systems: A conceptual framework for innovation dynamics in transnational contexts.
[47] Asheim & Gertler (2005). The geography of innovation: Regional innovation systems.
[48] Carlsson & Stankiewicz (1991). On the nature, function and composition of technological systems.
[49] Malerba (2005). Sectoral systems: How and why innovation differs across sectors.
[50] Hekkert et al. (2007). Functions of innovation systems: A new approach for analysing technological change.

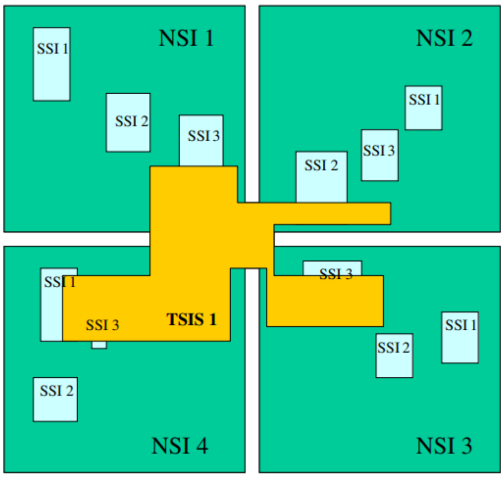

Figure 5 Boundary relations between national, technological and sectoral innovation systems. Note: NSI refers to National Systems of Innovation, SSI refers to Sectoral Systems of Innovation, and TSIS refers to Technological Systems of Innovation. Source: Hekkert et al. (2007).

Innovation dynamics through innovation functions

Each actor in the innovation system has a different function as presented in Figure 6. These can be summarized as:[51]

1. Knowledge generation – this is one end of the innovation spectrum, where knowledge is generated by innovation actors. This includes R&D activities conducted by universities, public research centres, and private research centres. Feasibility (proof of concept); development (proof of viability); demonstration (proof of prototypes in a realistic environment); and deployment (demonstration in the real world) would be some examples of activities that are included.
2. Knowledge diffusion – in between the first and last function serves to mediate between these two and enable knowledge exchange. There are three intertwined activities that facilitate the efficient diffusion of knowledge: development of network linkages (e.g. industrial dialogue); performing system intelligence activities (e.g. data analytics, benchmarking and foresight); and the development and strengthening of formal and informal institutions (e.g. standards and regulation).
3. Knowledge absorption – on the far end of the innovation process, refers to the development of capabilities to access and use new technological knowledge. This includes skills enhancement and education activities; enabling access to expertise and facilities; and providing incubation support, such as access to business space, mentoring and early venture assistance.

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[51] Cambridge Industrial Innovation Policy (forthcoming). Industrial innovation policy handbook: A primer for practitioners.

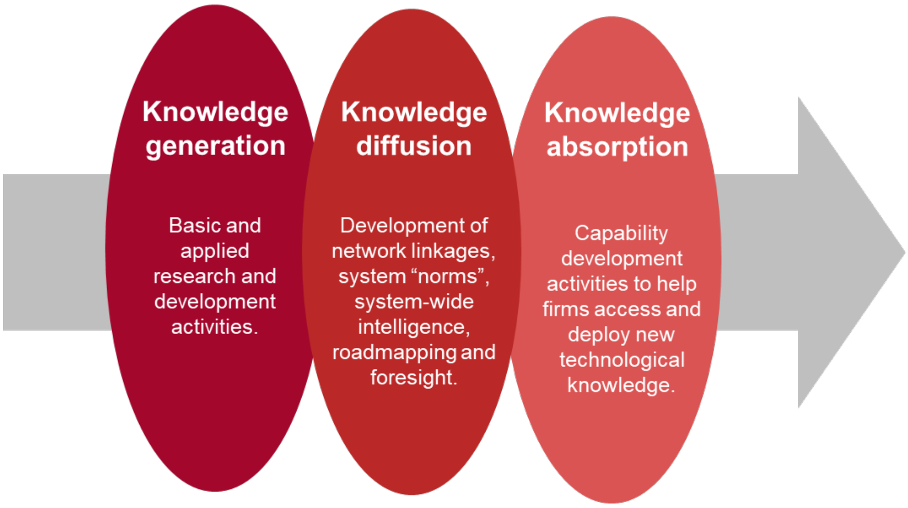

Figure 6 Simplified version of innovation functions. Source: Cambridge Industrial Innovation Policy, forthcoming.

Another way of viewing innovation functions can be summarized as:[52]

a. Entrepreneurial activities
b. Knowledge development
c. Knowledge diffusion through networks
d. Guidance of the search
e. Market formation
f. Resource mobilization
g. Creation of legitimacy/counteract resistance to change

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[52] Hekkert et al. (2007). Functions of innovation systems: A new approach for analysing technological change.

2.4 Industrial value chain framework

Summary

- Globalization has led to the fragmentation of industries with stages of production (and production services) spread across different countries interlinked in complex industrial value chain systems.
- High added value and competitiveness can come from any stage of industrial value chains, including pre- and post-production services, or their combinations. This is especially important in the case of emerging technologies as (supply and) value chains are not yet established, opening future opportunities.
- Systems mapping of industrial value chains can help to identify current industrial capabilities across the value chain and anticipate potential high added value opportunities.
- **There is a difference between supply and value chains making the former more suitable to analyse supply chain resilience and risk and the latter to analyse competitive advantage and anticipate future opportunities.**

Industrial value chain systems

Due to globalization, industries have become increasingly fragmented and interdependent at the same time. Industrial value chain systems are thus global, with value-added processes spanning multiple countries. They are not only composed of production but also include pre- and post-production manufacturing services, which often also comprise high value-added activities.

Understanding industrial systems and capabilities is a complex task, especially in the realm of emerging technologies. Just to exemplify this point: in early years, enabling Apple's manufacturing operations in China required that the design of production processes is co-located with manufacturing in China. This has essentially led over time to the building up of local technological capabilities and the development of an entire semiconductor manufacturing ecosystem, often with specialty subcontractors and suppliers that today can only be found in China. Today, this makes it extremely difficult for Apple to disentangle its value chain.[53] Likewise, in recent years, Taiwan Semiconductor Manufacturing Company (TSMC) has faced several challenges constructing and opening new semiconductor manufacturing plants in Arizona, underlining how the loss of a production base can lead to diminishing technological capabilities in the long-term.[54] Complex industrial systems and capabilities thus require careful and detailed analysis.

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[53] Financial Times (2023). How Apple tied its fortunes to China.

[54] Financial Times (2023). TSMC in the US: can Taiwan's chip giant overcome a culture clash?

Given that emerging technologies, by definition, require establishing new or reconfiguring old supply and value chains, analysing and anticipating industrial value chain systems can help to identify high-value markets and leverage competitive advantage. **It requires the identification of 1) global value chain activities (from R&D, design, etc. all the way to post-production services), and 2) companies across the different activities, which then enables understanding 3) current industrial capabilities within global value chains, and 4) potential high value-added activities and future opportunities.**[55]

Section 3 Step 4 provides more details on how industrial value chain systems and industrial capabilities can be analysed. It also provides a couple of national and international examples.

Supply chains

Supply chains represent the sequence of processes involved in the production and distribution of a product or service, starting with the supply of raw materials and ending with the delivery of a finished commodity. In essence, it enables tracking the flow of inputs and outputs through firms. Its key steps include raw material supply, logistics, production, assembly, marketing, distribution, delivery, procurement, customer support, etc. as presented by a generic supply chain in Figure 7. It is a useful strategic planning tool for assessing supply chain resilience and risk; however, it is not the main concept to strategize for competitive advantage and market opportunities.

Figure 7 Generic supply chain. Source: Corporate Finance Institute, n.d.

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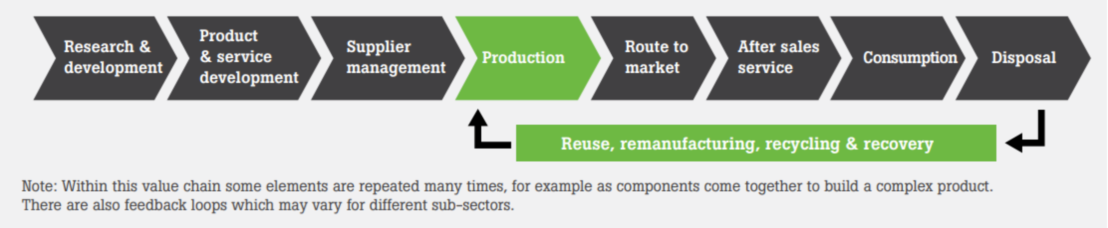
[55] Gereffi & Fernandez-Stark (2016). Global value chain analysis: A primer.

Value chains

The concept of the value chain complements that of supply chains by **placing an emphasis on the processes of value addition** alongside the set of activities involved in creating a product or service.[56] A broad definition of a value chain would be “the interconnected set of firms and wider activities that together create the value added of the product”.[57] Each step in the sequence contributes to the overall value creation within the chain. Such a cumulative effect is particularly important to consider as it highlights that a rate-limiting factor in one step can lead to large losses in later steps, diminishing the overall value of earlier efforts. This perspective can thus help to identify activities that underpin the competitive advantage of firms and industries.

Depending on the industry, value chains could include R&D, design, raw materials processing, production, distribution, marketing, sales, after-sales services, recycling of products after use, etc. In the case of products, value chains often resemble a sequential (though not linear) process as each step builds on the next, while in the case of services, this can be conceived of as a network of processes. Figure 8, Figure 9 and Figure 10 provide use cases of different value chain analyses for manufacturing, materials innovation, and the textile industry.



Note: Within this value chain some elements are repeated many times, for example as components come together to build a complex product. There are also feedback loops which may vary for different sub-sectors.

Figure 8 Simplified model of the manufacturing value chain as presented in ‘The Future of Manufacturing’ report. Source: GO-Science, 2013.

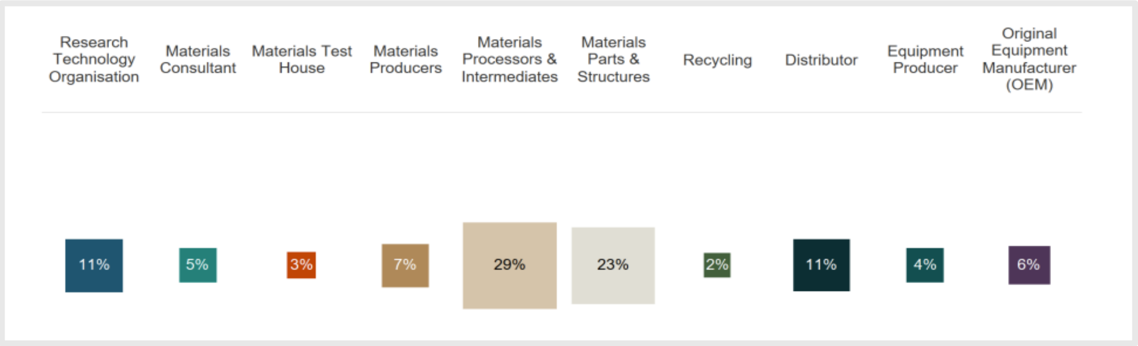


Figure 9 Value chain analysis of UK companies active in materials innovation as a share of all materials innovation companies in the UK. Source: Henry Royce Institute, 2024. [58]

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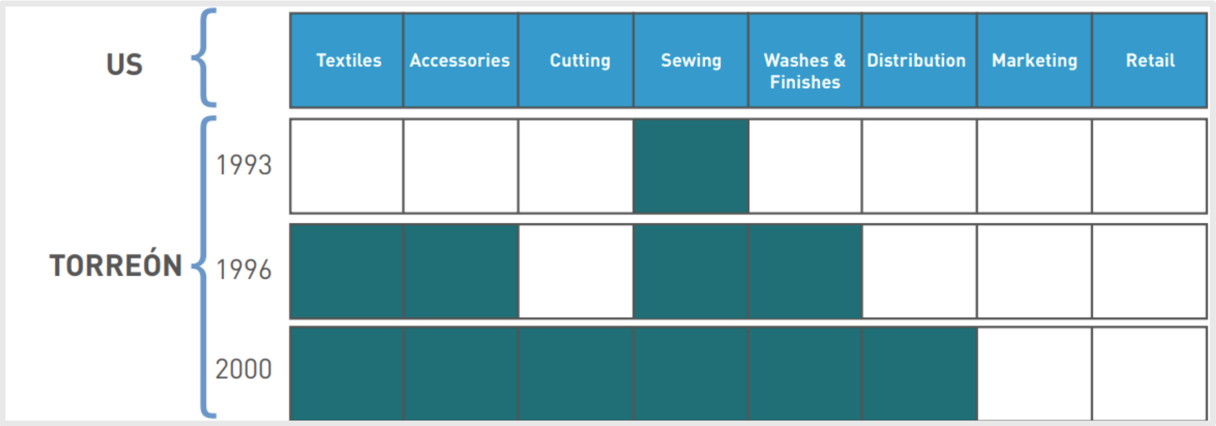
[56] Cambridge Industrial Innovation Policy (forthcoming). Industrial innovation policy handbook: A primer for practitioners.

[57] UNIDO (2009). Value Chain Diagnostics for Industrial Development.

[58] Henry Royce Institute (2024). National Materials Innovation Strategy Interim Report.



US		Textiles	Accessories	Cutting	Sewing	Washes & Finishes	Distribution	Marketing	Retail
TORREÓN	1993				🟩				
	1996	🟩	🟩		🟩	🟩			
	2000	🟩	🟩	🟩	🟩	🟩	🟩		

Figure 10 U.S.- Torreon, Mexico apparel value chain and its evolution over time in Torreon highlighted by green coloured blocks. Source: Gereffi & Fernandez-Stark, 2016.

Supply chains vs. value chains

There is an **important distinction between supply chains and value chains**, depending on the problem being addressed. Supply chains focus on the flow of inputs and outputs through firms as a useful tool for trade data analysis or understanding supply chain resilience and security concerns. In contrast, value chain analysis is essential for understanding where value is generated within the economy, which is crucial for examining emerging technologies and determining where economic value can be created. Policymakers and analysts must recognize this distinction and tailor their strategies and analysis, accordingly, aligning interventions with specific objectives, whether addressing supply chain resilience or strengthening value creation.

Global value chains

Steps of the value chain are nested within specific contexts, which can be at the local, regional, national, or international level. Over the past half a century, **the concept of global value chain** has emerged to describe the fragmentation of value chain activities (or steps) across different parts of the world.

A global value chain "includes *all* the activities and inputs used to create a final good or service. The term refers to the economic phenomenon in which *different stages of the production process are spread across multiple countries.* Multinational corporations use offshoring and outsourcing to exploit a region's comparative advantage, such as raw material abundance, technical expertise, cheap labour, a favourable regulatory and tax environment, or proximity to consumers. It is common for design, marketing, production, and distribution functions to be entirely separate in a firm's operation. Each step in this chain adds value to the finished product."[59]

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[59] Gereffi & Fernandez-Stark (2016). Global value chain analysis: A primer.

The globalization of value chains has significant implications for policymakers, as it necessitates understanding not only domestic industrial dynamics but also international trade relationships and global market trends. Policymakers should aim to enhance the competitiveness of domestic industries by identifying opportunities for value addition, upgrading capabilities along the value chain, and fostering collaboration between firms and suppliers. Identifying national firms active across different stages of the value chain can provide a good starting point to understanding current capabilities and future market opportunities (see Figure 11 for such an analysis).

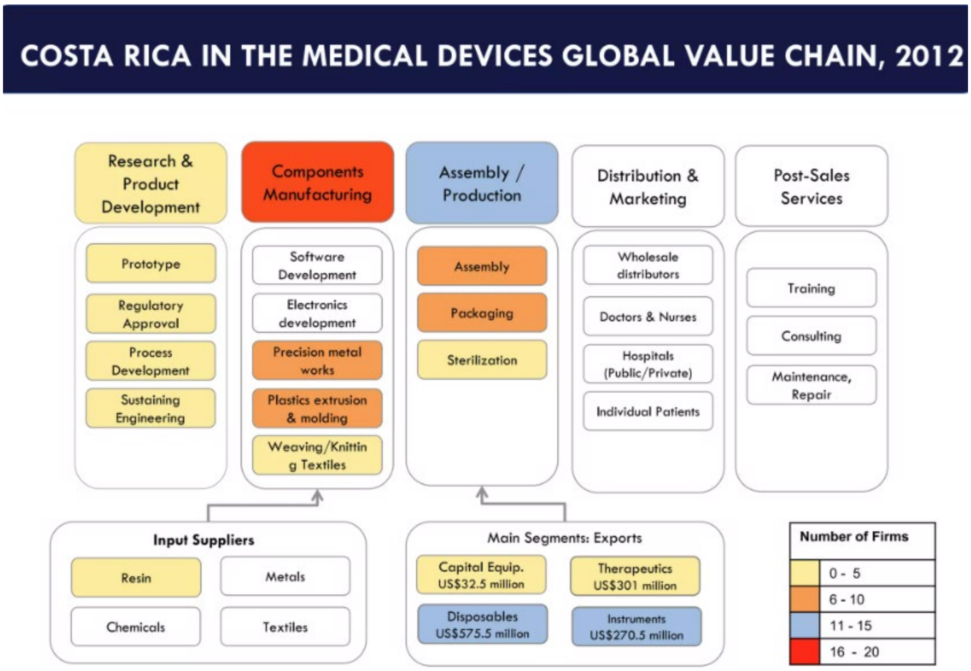

Figure 11 Mapping value chain activities in the medical devices industry and identifying industrial capabilities in Costa Rica. Source: Gereffi & Fernandez-Stark, 2016.

BOX 2: How the Australian Silicon Quantum Computing (SQC) worked with domestic firms to help build a quantum value chain

“To feed the manufacturing underway, SQC secures raw materials from a local provider Silex Systems. With the support of the Department of Industry, Science and Resources’ CRC [Cooperative Research Centres Grants] program, Silex expanded its operations to include the production of isotopically pure silicon at its facilities in Lucas Heights, NSW.

Down-stream of the hardware, SQC procures services from quantum software company Aqacia, which helps develop machine learning tools focused on accelerating quantum computing chip development and insights. While SQC is one of their local ‘anchors’, the digital nature of the company means that Aqacia can provide services to, and earn revenue from, all over the world.

At the other end of the local value chain, SQC has had a long-standing relationship with the Commonwealth Bank and Telstra, its co-development partners who recognised early the transformational nature of quantum computing to their business. As the technology continues to mature, these essential partnerships have informed the company of the valuable use cases and accelerated the development of the full quantum computing stack in SQC to meet these requirements.”

Source: Australian Government (2023). National Quantum Strategy.

2.5 Lifecycles and readiness levels

Economic historians have observed several historical instances in which the absence of complementary technologies hindered and postponed the development of technologies – including some that have had economy-wide impacts and wide-ranging applications once complementary technologies emerged.

Emerging technologies often involve multiple, interdependent innovation lifecycles that span across different readiness levels. For example, a breakthrough in a core technology, such as optically-pumped magnetometers (OPM) for brain imaging, may lead to new applications, like portable brain scanners. However, the successful commercialization of these scanners requires innovation and advancement in materials, miniaturization and integration technologies, shielding, advanced algorithms, machine learning models, software for visualization and analysis, etc. The dynamic and evolving nature of emerging technologies may thus require attention to different, nested and interdependent innovation lifecycles and readiness levels as shown in Figure 12.

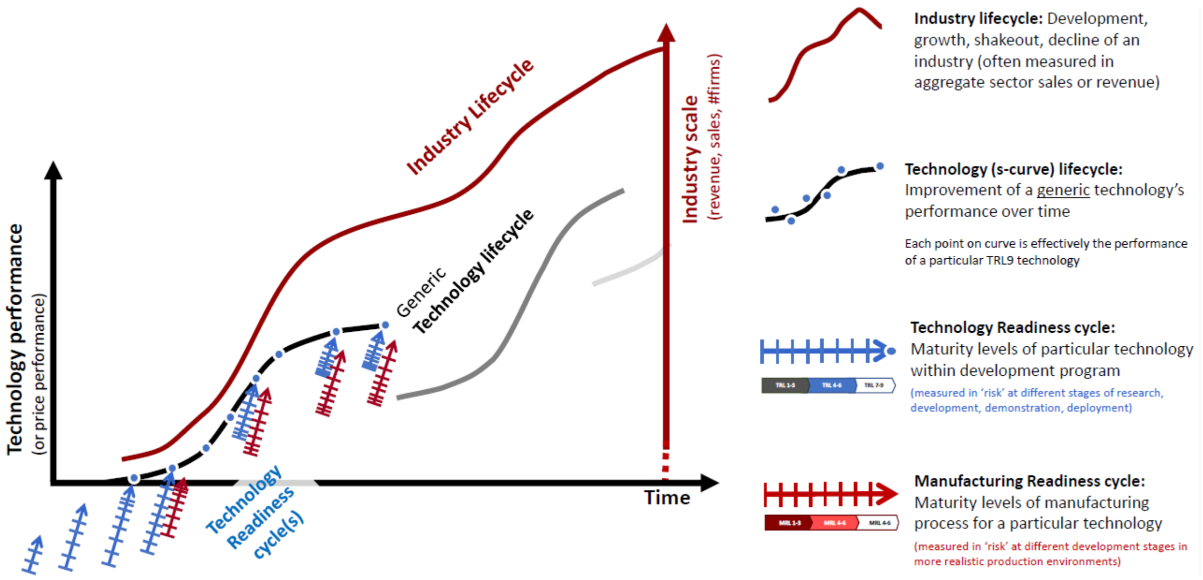

Figure 12 Nested innovation cycles (R&D program/TRL, technology lifecycle, industry lifecycle) with implications for strategic analysis and its sequencing. Source: NETS Handbook Project Team.

Various management tools and theoretical frameworks have attempted to capture such dynamics while focusing on different aspects of innovation. The most widely known is the **technology readiness level (TRL)**. It is a project management tool that has been developed by NASA to enhance communication about the stage of technology maturity.[60] While this concept has proven useful for complex capital-intensive, and usually concrete, technologies such as those developed by NASA, it is only applicable at the level of a project or a technology as its unit of analysis. **Government strategies and funding agencies have (sometimes less**

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[60] Mankins (1995). Technology readiness levels: NASA White Paper.

appropriately) used the TRL to allocate R&D budgets across large portfolios of technologies. This can however lead to overlooking important intersections such as the need to develop and update production technologies or tools among others.

To address this challenge, the concept of technology readiness levels has been adapted to various contexts – forming the systems readiness levels (SRL), manufacturing readiness levels (MRL), user readiness levels (URL), etc. Thinking about these different readiness levels helps to avoid gaps and associated risks when transitioning between technology development, its integration into a system, manufacturing and adoption by users. [61] Figure 13 depicts that a height difference between current and desired level of knowledge along both TRL and MRL can pose risks in the development process of technologies. It suggests that management tools such as MRL enable the assessment of the state of current and desired knowledge easing transition at specific inflection points.

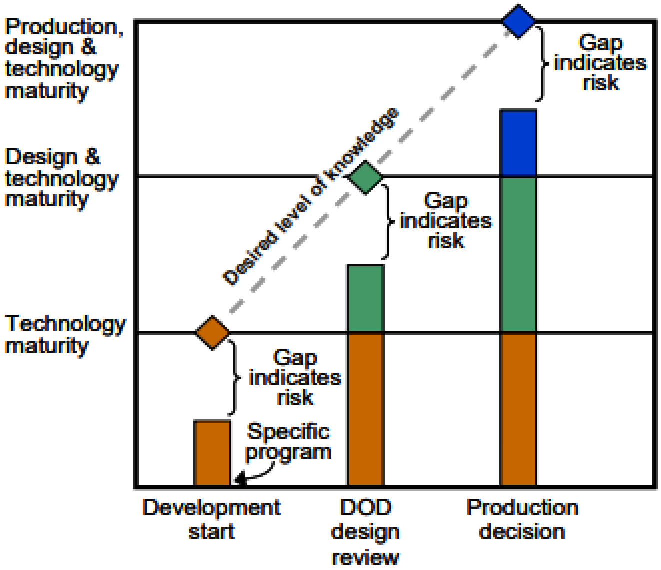

Figure 13 Gaps and associated risks of strategising for technology only as opposed to thinking about system parts and production. Source: Defense Contract Management Agency, 2016.

System readiness levels (SRLs)

SRLs expand upon TRLs by considering the integration of multiple technologies into a coherent system. This is critical when dealing with complex technologies that must work together seamlessly, such as in aerospace, defence, and healthcare. SRLs provide a broader perspective on the challenges of system integration and the interdependencies between different components. This understanding is crucial for fostering collaborations and fast feedback loops between various stakeholders, including researchers, manufacturers, and end-users, to

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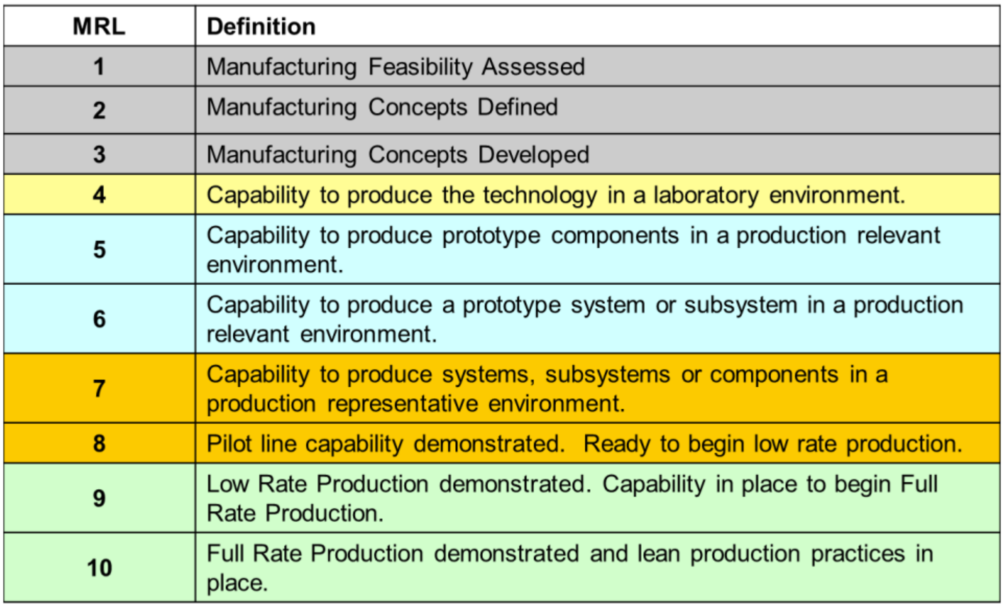
[61] Defense Contract Management Agency (2016). Introduction to manufacturing readiness levels (MRL).

ensure that systems can be developed, tested, and deployed effectively. Quick feedback loops and learning curves between technology developers and system integrators are an important aspect here.

Manufacturing readiness levels (MRLs)

Developed by the U.S. Department of Defense,[62] MRLs focus on the production aspects of technology development, assessing the maturity of manufacturing processes and the ability to scale up production and related capabilities. They help to assess the availability of small- and mid-scale pilot lines, testbeds, materials, prototype components, prototype systems, workforce, and supply chains as presented in Figure 14.

One emerging technology example that has adapted this concept in the form of a 'manufacturing roadmap' assesses the capabilities, and materials, devices, structures and systems that can be manufactured at scale to realize the full potential of quantum information science technologies (QIST).[63]



MRL	Definition
1	Manufacturing Feasibility Assessed
2	Manufacturing Concepts Defined
3	Manufacturing Concepts Developed
4	Capability to produce the technology in a laboratory environment.
5	Capability to produce prototype components in a production relevant environment.
6	Capability to produce a prototype system or subsystem in a production relevant environment.
7	Capability to produce systems, subsystems or components in a production representative environment.
8	Pilot line capability demonstrated. Ready to begin low rate production.
9	Low Rate Production demonstrated. Capability in place to begin Full Rate Production.
10	Full Rate Production demonstrated and lean production practices in place.

Figure 14 Manufacturing readiness levels explained. Source: Defense Contract Management Agency, 2016.

User readiness levels (URLs)

URLs assess the readiness of the market and users to adopt new technologies. This includes factors such as user awareness, market demand, regulatory environment, and the availability

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[62] Department of Defense (2011). Manufacturing readiness level (MRL) deskbook.

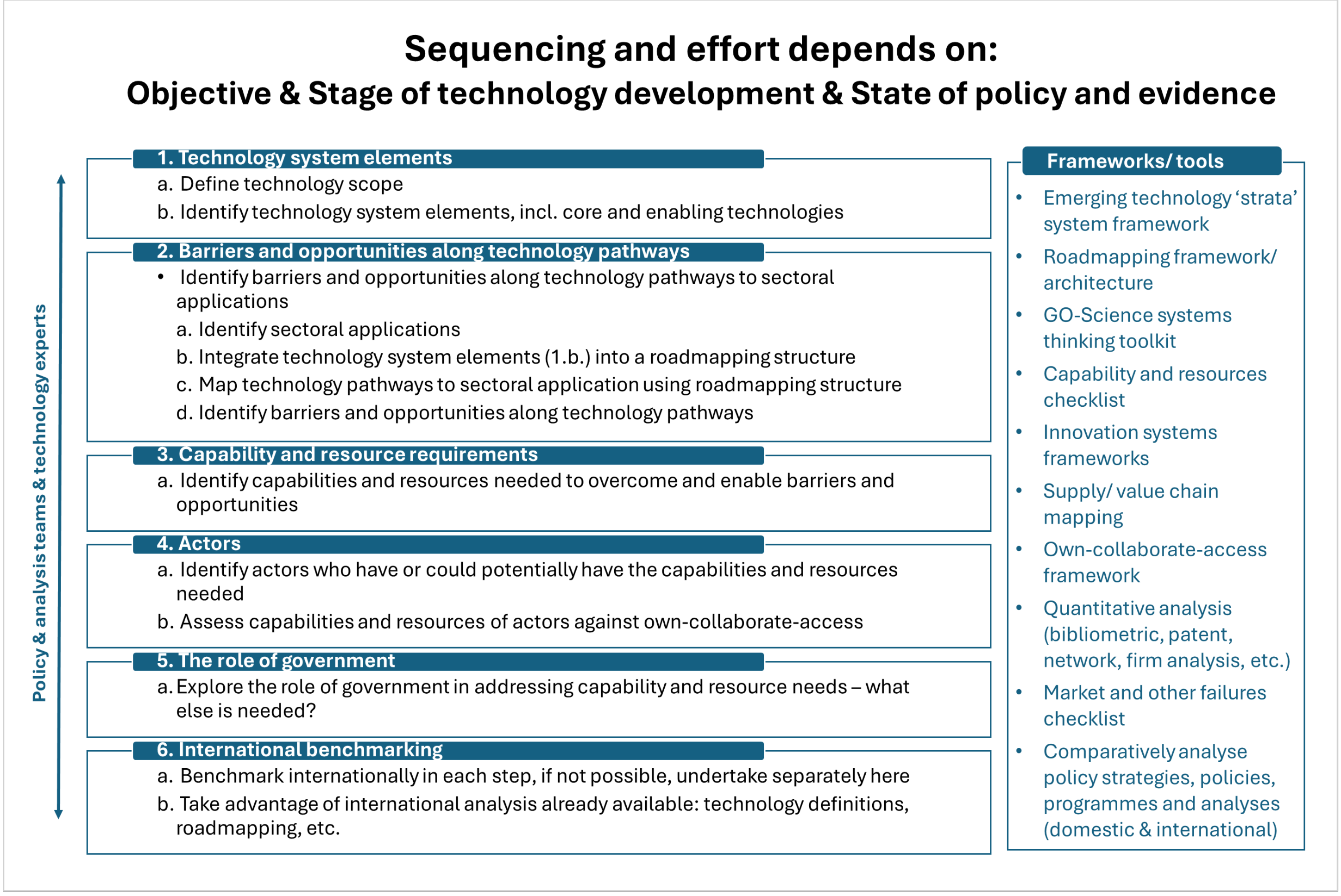
[63] SRI International Center for Innovation Strategy and Policy (2023). Quantum Technology Manufacturing Roadmap.

of living labs for testing and adopting new technologies. Policymakers must consider user readiness to ensure that technologies not only reach the market but are also embraced by consumers and businesses. By understanding URLs, policymakers can design incentives, regulations, and support programs that encourage the uptake of new technologies, facilitating their integration into society and the economy.

3 A process guiding strategic analysis of emerging technologies for policy

This section presents a guide to strategic analysis of emerging technologies for policy. It outlines a flexible yet systematic approach by breaking down the complex task of strategic analysis and evidence gathering into several manageable steps and presenting frameworks and tools that provide structure to the analysis, as presented in Figure 15.

The proposed process is built based on international and national best practice, and conceptual frameworks and tools introduced in Section 2. Several templates and use cases are also provided to illustrate these steps and their applications. For example, Use Case 1 below shows how the EU incorporated several different steps of the process proposed here in a single pilot project on quantum information science and technology in its early year of development, in 2025.



Sequencing and effort depends on:
Objective & Stage of technology development & State of policy and evidence

1. Technology system elements
a. Define technology scope
b. Identify technology system elements, incl. core and enabling technologies

2. Barriers and opportunities along technology pathways
- Identify barriers and opportunities along technology pathways to sectoral applications
  a. Identify sectoral applications
  b. Integrate technology system elements (1.b.) into a roadmapping structure
  c. Map technology pathways to sectoral application using roadmapping structure
  d. Identify barriers and opportunities along technology pathways

3. Capability and resource requirements
a. Identify capabilities and resources needed to overcome and enable barriers and opportunities

4. Actors
a. Identify actors who have or could potentially have the capabilities and resources needed
b. Assess capabilities and resources of actors against own-collaborate-access

5. The role of government
a. Explore the role of government in addressing capability and resource needs – what else is needed?

6. International benchmarking
a. Benchmark internationally in each step, if not possible, undertake separately here
b. Take advantage of international analysis already available: technology definitions, roadmapping, etc.

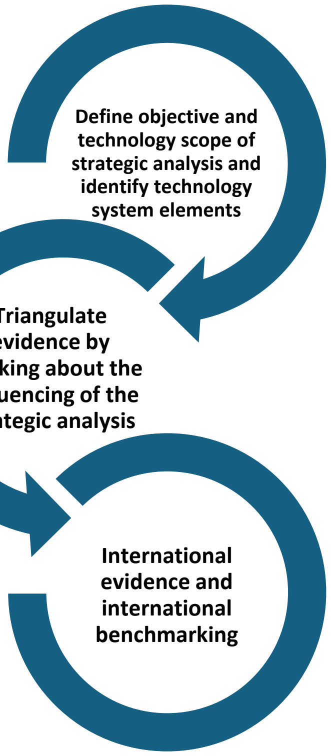
Frameworks/ tools
- Emerging technology 'strata' system framework
- Roadmapping framework/ architecture
- GO-Science systems thinking toolkit
- Capability and resources checklist
- Innovation systems frameworks
- Supply/ value chain mapping
- Own-collaborate-access framework
- Quantitative analysis (bibliometric, patent, network, firm analysis, etc.)
- Market and other failures checklist
- Comparatively analyse policy strategies, policies, programmes and analyses (domestic & international)

Figure 15 A flexible and adaptable process guiding emerging technology analysis for policy. Source: NETS Handbook Project Team.

The process does not intend to prescribe a set of instructions to be strictly followed but instead, it intends to serve as a flexible guide that can be easily adapted according to policy needs and cycles, and availability of resources and time. For example, the process is designed to allow entry at any point, and each step includes options (referred to as 'tasks') requiring varying levels of effort, balancing depth with practicality. Summary of the process can be found in the Short Guide.

High level recommendations

1. Define objective and technology scope of strategic analysis and identify technology system elements



Undertaking this step early on enables clear communication between stakeholders and consistency across the steps of the process of strategic analysis.

Clarifying system boundaries and identifying system parts in detail (e.g., technologies, capabilities, resources, actors, etc.) enables focused analysis, revealing parts that would otherwise be left out leading to missed opportunities, and carrying over evidence and analysis that is consistent in terminology and detail across different steps. This could sharpen the process of strategic analysis as well as enable more strategic decisions.

There is an early mover advantage in properly defining and categorizing technologies based on one's interest, which could then be picked up by others almost as a standard. However, there are cases in which it is most time and cost efficient to follow the definitions of others, especially when they have already been well defined and are of good quality in terms of incorporating system elements.

2. Triangulate evidence by thinking about the sequencing of the strategic analysis

Synthesizing data and evidence into a coherent story and/or business case can be challenging. This is especially the case when evidence comes from a variety of sources each with their own limitations and when these are gathered without prior consideration of their sequence. Whenever possible, sequencing data collection and analysis in a somewhat logical order can enable triangulation of evidence and significantly improve the process of strategic analysis. Findings from one step can then inform the next step. This is because key technology terms, barriers and opportunities, capability and resource needs, actors, etc. identified in one step of the analysis can lead to an interesting inquiry within the next step of the analysis.

The sequencing of the analytical process is likely to be based on the 1) key objective set out, 2) stage of the emerging technology development, i.e., the lifecycle stage of the emerging technology being analysed related to 3) the state of policy and evidence available. For example, for an early stage emerging technology, just emerging from the science base and being explored by companies and governments, it is likely that following the current order of Steps from 1 to 6 (Figure 15) would be most useful, as not much evidence may be available yet and understanding the current and future system is necessary.

For a mid-stage emerging technology with some early applications that is already receiving significant government and private sector interest or investment, it is likely that several evidence gathering exercises have been undertaken already – often signalled in government policies. Therefore, evidence on capability and resource needs (Step 3) and key actors (Step 4) may already be available domestically or internationally, and therefore, enable narrowing down the number of technology pathways and related barriers and opportunities using roadmapping (Step 2) (Figure 15).

The strategic analysis needs to reflect the dynamic and evolving nature of emerging technologies, products and industries and related policies. Attention needs to be paid to different, nested and interdependent innovation lifecycles and readiness levels as explained in Figure 12 and Section 2.5.

3. International evidence and international benchmarking

Analytically, scanning the international landscape throughout each step of the process can help to understand whether there is already existing evidence and analysis that can be used (e.g., technology definitions and hierarchies, technology roadmaps, etc.), especially produced by countries that are at a more advanced stage of strategic analysis. This can help avoid duplication of effort and speed up the process across each step of the analysis. If such evidence or data is already available at sufficient level of detail, further contextualisation can be achieved through smaller sized workshops or consultations.

To understand comparative advantage, international benchmarking needs to be undertaken for each step of the process at a sufficient level of detail. There is a need to understand how other countries are approaching technology definitions and classifications; how they are identifying key barriers and opportunities; what they think the key capabilities and resources required are; who their current and future key actors are; what policies and programmes they use and plan to use.

USE CASE 1: EU pilot project structuring European research area of quantum information by defining key terms, roadmapping, mapping domestic and international innovation capabilities, and setting up a coordination activity

The ERA-Pilot Quantum Information Science and Technology (QIST) project was commissioned in 2005 and lasted until 2008 with an aim to map EU research activities in this area and to create a vision. UK stakeholder from EPSRC and Oxford University also took part along with other EU stakeholders. Key objectives and tasks achieved:

- QIST classification (QISTC) scheme was developed and iteratively updated over time, based on community input. It was submitted to and adopted by the academic European Physical Journal D, which encouraged authors publishing in the field to use these codes to identify their research.
- **A common QIST-vision named 'QIPC: Strategic Report on current status, visions and goals for research in Europe'** was developed and continuously updated, based on input from most relevant EU research groups and international roadmaps. While the report does not follow the roadmapping structure advised here, it does cover several important **aspects of a roadmapping exercise**. It divides QIPC technologies into quantum computing, communications, and theory. Each of these is further broken down into underpinning science/core technology, with further details on each including current state of the art, strengths and weaknesses, short- and long-term goals, key challenges, key research groups or companies active. E.g., Quantum computing > One of underpinning science/core technologies: trapped ions > State of the art: strings up to eight trapped ions, …
- Both QISTC and the QIPC Strategic Report were made available as **free-content web resources** for anyone to be edited, which was constantly monitored leading to updated versions over time. This was then taken over by the newly established coordination action QUROPE (funding of EUR1 million).
- **Overview of EU and international research groups** based on web data and surveys. Surveys were sent to research groups asking for number of staff, funding amount, funding source, salaries, projects, project topics etc. The first survey did not work well as researchers did not want to reveal confidential information. Estimates of funding amounts were calculated based on salaries, equipment and overheads. The second survey was designed to help corroborate estimates more precisely, as opposed to getting confidential information.
- **Overview of nationally and EU funded QIST projects** based on surveys of research groups (their funders, but also their websites, their publication acknowledgements), followed by a workshop and a questionnaire sent to funding agencies asking about: type of organization, mission, link to national research strategy, strategic focus concerning QIST, details of funding programs, overall budget, QIST budget, link to other actors, etc.

Source: Austrian Research Centres GmbH - ARC (2008). ERA-Pilot QIST. European Commission (2010). Structuring the

Step 1. Technology scope and technology system elements

This first step focuses on clarifying and defining the technology scope of the strategic analysis followed by breaking down the complex technology according to the different technology system elements it comprises.

a. Define the technology scope of the strategic analysis

The technology scope can be at the highest level of technology classification (e.g., quantum technologies) or any level below (e.g., quantum sensors or lower). This becomes the boundary object, which can be referred to as the ***'technology family'***[64] as it consists of several technologies (see Section 2.2 for more details).

b. Break down the complex technology family and identify its system elements

As more detailed classification and hierarchical understanding can significantly improve analysis, this is then followed by identifying the different technologies that comprise the chosen technology family. To help guide this complexity, the ***Technology 'strata' system framework***[65] can be used to provide a structure for analysis as shown in Figure 2 and presented in Section 2.2.

The framework suggests that every technological entity evolves through and can be classified across different technology strata starting from 1) its underpinning scientific principles, through the application of this principle into 2) a core technology, and its integration into a larger system forming 3) an integrated technology.

Some technologies then become 4) final solutions products or services – e.g., a smartphone or an ultra-responsive hearing aid. Others continue to serve the development and production of these. They include: 5) R&D tools, 6) engineering tools, 7) demonstration environments, 8) production technologies, 9) external infrastructural technologies – all playing a vital role in other technology lifecycles despite often being neglected during strategic development.

Methodology in more detail:

In practice, the output of this exercise resembles checklists of sets of different technologies required for development and commercialization of, for example, underpinning science or core platform technologies. This includes both technologies that are currently available and those that will be required in the future. This may require the identification of final products and services or application markets, industries or sectors to enable foresight.

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[64] 'Technology family' is an umbrella term encompassing related and complementary technologies that share a common and evolving knowledge and technology base. It is different from 'technology', which is a single unit of technology, suggesting that technology families are made up of several technologies as presented by the Technology Strata Framework.

[65] Döme & O'Sullivan (2026). Technology 'strata' system framework (version 2, forthcoming). Link to version 1.

This could then feed into the next step of the process – roadmapping in Step 2 – which enables mapping these sets of different technologies and their combinations as required over time towards certain application markets or sectors. This enables understanding domestic capabilities and opportunities (‘own’) and bottlenecks where ‘collaborate’ and/or ‘access’ will be needed (Steps 3 and 4).

Briefly scanning the international landscape can help reveal whether there are already existing definitions and classifications used by other countries. If available, international evidence then needs to be analysed for suitability in terms of level of detail, context, stakeholders taking part in evidence gathering etc. as presented under Task A. If more evidence, context or different technology scope is needed, holding a workshop or consultations with technology experts can be undertaken as presented in Task B. If resources allow a mix of the two would enable the most comprehensive coverage of related issues:

Task A. Scan international landscape for existing definitions and classifications (see Use Case 2 for an example)

1. **Clarify the technology scope of the strategic analysis** (and overall objective if possible) as this is going to guide the analysis.
2. **Scan the international landscape for definitions, technology breakdowns, technology system elements** by considering workshop reports, landscape assessment reports, technical reports, early roadmapping activity, pilot projects, etc. These are often undertaken by national research agencies, newly established technology councils, technology expert groups, technology advisory boards, the community or commissioned to consultancies and research institutes. The best place to search for these is in countries that have shown an early interest in the technology. A web search of related terms is likely to return key documents.
3. **Ensure evidence comes from participants with wide range of expertise** including systems engineers and integrators, manufacturing companies, materials and component suppliers in addition to scientists and engineers from both academia and industry.
4. **Ensure consistency or classification so that important technoloigy system elements are captured** when scanning international work and that definitions and terms are relevant and adapted to domestic needs, capabilities and thinking. This could be done through using the Technology Strata Framework as exemplified in **Template 1**. This may lead to a workshop or consultation of a smaller scale if needed.

Task B. Organize workshop or consultations with technology experts to identify technology system elements (see Use Case 3 for an example)

1. **Clarify the technology scope of the strategic analysis** as this is going to guide the analysis

2. **Clarify the objective of the workshop or consultation.** This could be a variety of things, for example, scaling up of technology X, manufacturing technology X, etc.
3. **Provide a structure to the workshop to ensure that important system elements are identified** and that key questions of interest. This could be done through using the Technology Strata Framework as exemplified in **Template 1**.
1. **Ask experts to identify application markets or sectors (also in Step 2)** when thinking about emerging technologies as this will enable thinking about the pathway from technology to application. This helps thinking about current and future challenges and opportunities along the way - materials, tools, manufacturing technologies, demonstration environments, skills, capabilities, supply chain, etc. Ranking sectoral applications based on factors of interest can be used to achieve consensus. Avoid selecting based on personal interest or hype.
4. **Ensure good representation of experts** including scientists, engineers, product developers, but also systems engineers and integrators, manufacturing companies, materials and component suppliers. The latter are particularly important when it comes to emerging technologies that are of high complexity, requiring the development of new science and engineering tools, and manufacturing technologies.
5. **Engage with a technology expert who can help distil output** for non-technical audience and help with policy recommendations given the highly technical nature of such exercises. Clearly defined analytical and policy questions could help communication.

TEMPLATE 1

OBJECTIVE:

TECHNOLOGY SCOPE:

Underpinning science	Core technology	Integrated technology	Final use technologies/ application markets	R&D and engineering tool technologies	Demonstration environments	Production technologies	External infrastructural technologies

Note: Template is based on the ***Technology 'strata' system framework***[66] concept as presented in Figure 2.

TEMPLATE 1 with an example

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[66] Döme & O'Sullivan (2026). Technology 'strata' system framework (version 2, forthcoming). Link to version 1.

OBJECTIVE: IDENTIFY TECHNOLOGY SYSTEM ELEMENTS OF 5 CHOSEN CORE TECHNOLOGIES FROM THE NANOTECHNOLOGY FAMILY

TECHNOLOGY SCOPE: 5 CHOSEN CORE TECHNOLOGIES WITHIN THE NANOTECHNOLOGY FAMILY

Underpinning science	Core technology	Integrated technology	Final use technologies/ application markets	R&D and engineering tool technologies	Demonstration environments	Production technologies	External infrastructural technologies
physical and chemical properties of semiconductor materials	**transistor**	integrated circuit (could be divided into memory, logic, analogue, power semiconductors)	Can include concrete tech applications such as computer memory, computer central processing unit (CPU) Can include less concrete markets/ sectors such as automotive, renewables, medical equipment …	scanning tunnelling microscope atomic force microscope electronic design automation (EDA) tools simulation software material characterization tools precision instruments for metrology …	automated test equipment (ATE) small-scale production facilities environmental chambers for testing field-programmable gate array (FPGA) development boards cleanrooms …	photolithography machine laser dicing machine chemical and physical vapor deposition (PVD) etching equipment …	Antenna high-speed reliable network infrastructure advanced systems for producing ultra-pure water (UPW) robust power infrastructure …
chemical modification of cellulose nanomaterials	**modified cellulosic nanomaterials**	…	drug delivery biosensing biocomposites coatings and films …	scanning electron microscope transmission electron microscope standards set by bodies like the FDA or EPA …	thermal and mechanical testing …	free radical polymerization atom transfer radical polymerization (ATRP) click chemistry composite fabrication (extrusion, injection molding, 3D printing) …	…
	core tech 3						
	core tech 4						
	core tech 5						

Note: Template is based on the ***Technology 'strata' system framework***[67] concept as presented in Figure 2. Examples are shown in blue; they do not provide a comprehensive list of all technologies as represented by three dots.

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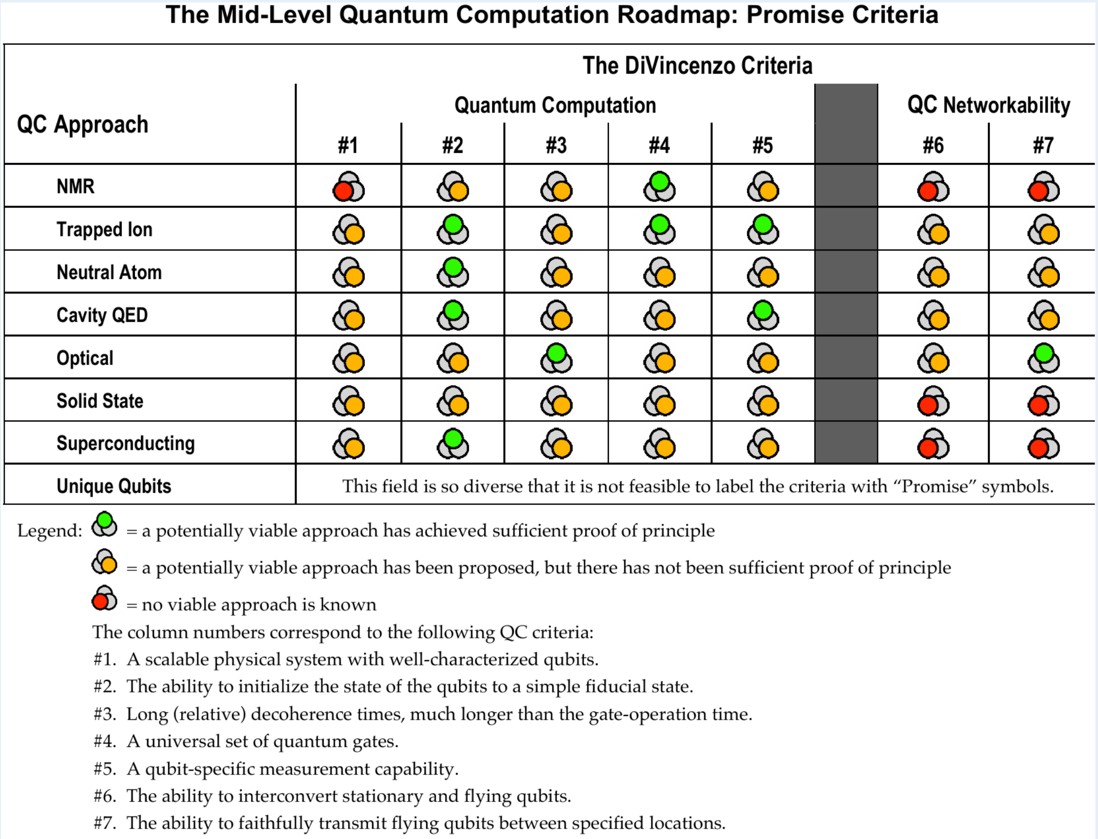
[67] Döme & O'Sullivan (2026). Technology 'strata' system framework (version 2, forthcoming). Link to version 1.

USE CASE 2: US expert panel commissioned to classify experimental approaches to quantum computers, highlighting their differences and similarities

In 2004, the US Advanced Research and Development Activity (ARDA) commissioned an experts panel that classified the different experimental approaches to quantum computers based on their underlying experimental physics as shown in figure below. They assessed each of these against a set of criteria and time (years of 2007 and 2012). Such distinctions led to highlighting important differences and similarities in terms of their stage of development, knowledge and technology base. One such example is that solid state and superconducting approaches share a common production technology base and can draw on existing investments in fabrication technologies, while atomic, optical and NMR approaches are built on experimental capabilities to control quantum properties, which are reasonably well-developed. If we then consider these different experimental approaches to quantum computers when analysing innovation and industrial capabilities in the next steps, we can synthesize knowledge that can enable more strategic and systematic choices.



The Mid-Level Quantum Computation Roadmap: Promise Criteria

QC Approach	The DiVincenzo Criteria						
	Quantum Computation					QC Networkability	
	#1	#2	#3	#4	#5	#6	#7
NMR	🔴	🟠	🟠	🟢	🟠	🔴	🔴
Trapped Ion	🟠	🟢	🟠	🟢	🟢	🟠	🟠
Neutral Atom	🟠	🟢	🟠	🟠	🟠	🟠	🟠
Cavity QED	🟠	🟢	🟠	🟠	🟢	🟠	🟠
Optical	🟠	🟠	🟢	🟠	🟠	🟠	🟢
Solid State	🟠	🟠	🟠	🟠	🟠	🔴	🔴
Superconducting	🟠	🟢	🟠	🟠	🟠	🔴	🔴
Unique Qubits	This field is so diverse that it is not feasible to label the criteria with “Promise” symbols.						

Legend: 🟢 = a potentially viable approach has achieved sufficient proof of principle

🟠 = a potentially viable approach has been proposed, but there has not been sufficient proof of principle

🔴 = no viable approach is known

The column numbers correspond to the following QC criteria:

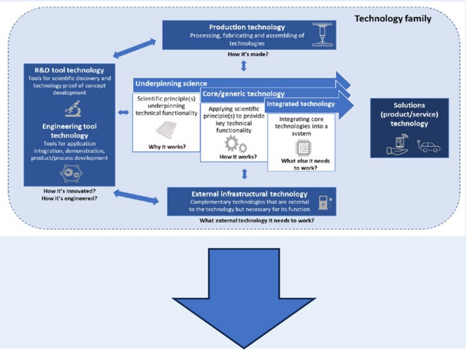
#1. A scalable physical system with well-characterized qubits.
#2. The ability to initialize the state of the qubits to a simple fiducial state.
#3. Long (relative) decoherence times, much longer than the gate-operation time.
#4. A universal set of quantum gates.
#5. A qubit-specific measurement capability.
#6. The ability to interconvert stationary and flying qubits.
#7. The ability to faithfully transmit flying qubits between specified locations.

Source: ARDA (2004). A Quantum Information Science and Technology Roadmap.

USE CASE 3: A workshop held by the Government Office for Science identifying technology system elements of quantum sensor technologies

The workshop started out by laying out 5 prepopulated templates for 5 quantum sensor core technologies of interest, detailing their underpinning science, core technology and integrated technology. Each group of workshop participants working on one of the quantum sensor core technologies was tasked first to identify potential application sectors through collective thinking and imagination and then to narrow this down to the most promising application sector for further analysis. This was then followed by filing out all the other sections of the template, including production technologies, tool technologies, etc. See figure with the results below for 1 of the quantum sensor technologies.

The workshop enabled a more detailed understanding and classifying of each technology and its stages of technological development, as well as identifying the components, production technologies, external infrastructural technologies and capabilities that each technology requires now, in 5 and in 10 years. Comparing these 'supporting' technologies across the 5 quantum sensors highlighted which of these are cross-cutting justifying government support.



Underpinning science	Core technology	Integrated technology	Final use case
Solid state spin defects	Ensemble of NV defects in diamond	NV magnetometer Hybrid devices (e.g. magnetometer + graviometer) Sensor integrated in battery	Battery monitoring Navigation Navigation Avs & drones Mapping magnetic contours

Current requirements
+
5-year requirements
+
10-year requirements

Components

Now	5-year needs	10-year needs
High power laser Visible laser Photodiode Photomultiplier tube Visible detector Microwave source Quantum grade diamond Microprocessor chips Free space optical components (visible) Optomechanical components Electrical cabling	Low power laser Narrow line laser Near IR laser Low noise photon amp Magnetic shielding RF signal generator	Single photon detector

Production Technology

Now	5-year needs	10-year needs
Plasma enhanced CVD synthesis Laser sawing & cutting Chemical mechanical polishing Wet chemical etching Reactive ion etching Vacuum tube furnace Doping & ion implantation Optoelectronics packaging Castings of housing CNC fabrication	Photolithography (UV) Photolithography (Deep UV) Miniature integrated photonics (Vis) Magnetic shielding Additive manufacturing of photonics Additive manufacturing of housings	Photonic integrated circuit (PIC) fabrication PIC packaging and assembly Pick & Place component assembly MEMs manufacturing

External infrastructure

Now	5-year needs	10-year needs
Large scale plasma CVD facility Test beds for civil infrastructure Semiconductor/photonics clean rooms	Semiconductor foundry Deep UV photolithography facility Electron beam lithography facility Test beds for defence applications Test beds for clinical applications	Photonics foundry Cryogenic environments Magnetic shielding within building infrastructure

Supporting capability

Now	Quantum start ups 5-year needs	10-year needs
Firmware development User interface development User data visualisation tools Data analysis tools Data sets for validation Data processes for QA Contract electronic engineering Systems integrators Testing integrated photonics QA inspection tools Device regulation Standardisation Computer aided design	Cloud &/or high-performance computing Cloud &/or network data storage Deskilling needs of end users Technicians for quantum tech Professional services in quantum tech. Medically compliant software Data sets for clinical evidence Allied diagnostic tools	Fraunhofer style institutes Deskilling production processes PIC design services Technical skills in adjacent technologies Clinical approval Apprenticeships in quantum tech

Source: One-day workshop with key quantum stakeholders (academia, industry, policy), held by GO-Science.

Step 2. Barriers and opportunities along technology pathways

This step focuses on **identifying key barriers and value adding opportunities that may arise along emerging technology pathways from technology to sectoral applications**. This can be achieved through:

a. **Identifying and selecting sectoral applications**
b. **Integrating technology system elements (identified in Step 1.) into a roadmapping structure and adding other 'layers' that may be of interest given the objective of the analysis**
c. **Mapping technology pathways to sectoral application using roadmapping structure**
d. **Identifying barriers and opportunities along these technology pathways**

Roadmapping

Collective knowledge and imagination serve as the best estimate of the near-, mid- and long-term future of emerging technologies. While there are several tools and methods that exist for these purposes, ***roadmapping*** is presented here as it is among the more structured approaches to the process of collective scanning and pathfinding.[68]

Roadmapping can refer to several things including: (1) the roadmapping framework structure; (2) the foresight evidence captured on the canvas; (3) the process of generating the evidence; and (4) any final strategic plan developed using that evidence (with goals, milestones, actions, etc).[69]

Roadmapping structure

The roadmapping framework structure is particularly useful as it enables breaking down complex strategic problems of multiple interacting layers and promoting the unfolding of interdependencies between these layers in a structured manner, as presented in Figure 16 and Figure 17.[70]

Its structure is highly adaptable, and its layers can be modified according to the objective of the strategic analysis. For example, it can enable assessing the level of strategic advantage of a country and its choices in terms of sourcing required capabilities and resources by adding own-collaborate-access as a layer within the structure (OCA, further explained in Section 3, Step 4: Actors with capabilities and resources).

Furthermore, its structure with time presented along its x-axis enables scanning for future opportunities in terms of sectoral applications, which then enables mapping out technology

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[68] European Commission JRC (2023). Technology foresight for public funding of innovation: Methods and best practices. Tool 4, 5 and 6 could also be potentially used for identifying sectoral applications and enablers/ inhibitors, respectively: GO-Science (2023). An introductory systems thinking toolkit for civil servants.
[69] O'Sullivan et al. (2021). Agile roadmapping.
[70] Phaal & Muller (2009). An architectural framework for roadmapping: Towards visual strategy.

pathways towards these sectoral applications. A summary of its key functions is presented in Figure 18.

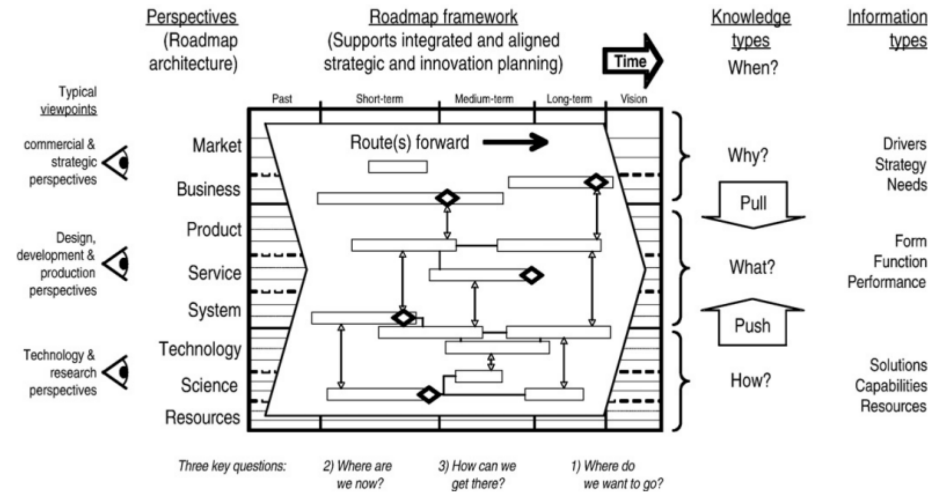

Figure 16 Schematic multi-layered roadmap. Source: Phaal & Muller, 2009.

Roadmapping process

Roadmapping as a process enables capturing foresight evidence by mapping out technology pathways from technology to application/sectoral markets, while relying on collective imagination. It can be useful as a standalone tool, but if used in combination with Step 1 (or similar evidence), it can be used to identify and map combinations of technology system elements – both those that are currently available and those that will be needed in the future – to reach application markets. The mapping of technology combinations towards application markets can reveal key bottlenecks and opportunities.

Given the yet unestablished knowledge and technology base and supply chain of emerging technologies, there are also opportunities to strategize for technologies that cut across several emerging technologies within the 'same' group (e.g., quantum sensors and quantum computing) or adjacent technologies and applications – e.g., semiconductor technology leading to more scalable and stable quantum computers, and vice versa, quantum computers solving complex semiconductor design problems.

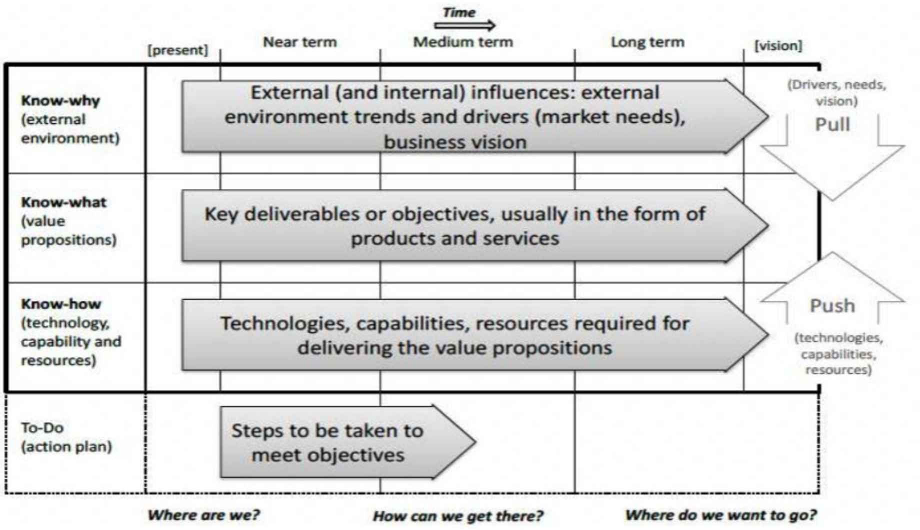

Figure 17 Schematic simplified roadmap. Source: European Commission JRC, 2023.

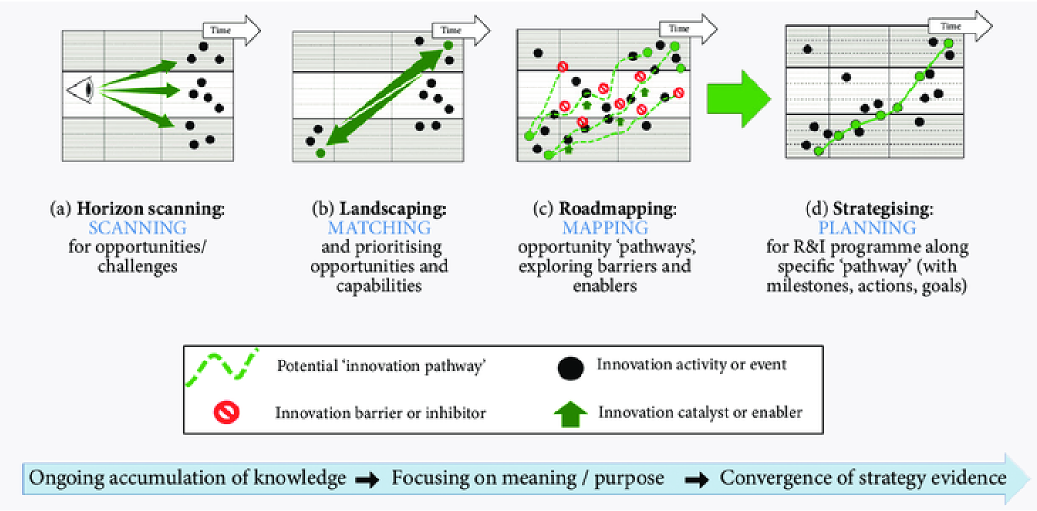

Figure 18 Summary of roadmapping functions. Source: O'Sullivan et al., 2021.

Methodology in more detail:

There are several examples of emerging technology roadmaps relying on robust roadmapping processes, especially by industry (often not in the public domain), but also by governments or as part of joint undertakings by interested communities and consortia, which tend to be available publicly (see Use Case 4 and 5 for examples).

Therefore, briefly scanning the international landscape for roadmaps is a great initial step as roadmaps often have enough detail that is relevant across different countries without needing to redo these. If a roadmap that is up to date and of sufficient quality is available steps in Task A can be followed. If more contextualisation or timely evidence is needed, or specific objective needs to be answered, a roadmapping workshop can be undertaken following steps in Task B. Deep dives into specific barriers and opportunities are also highly recommended.

Task A. Scan international landscape for existing roadmaps relying on a robust roadmapping process

1. **Scan the international landscape** for workshop reports, landscape assessment reports, technical reports, early roadmapping activity, pilot projects, etc. These are often undertaken by national research agencies, newly established technology councils, technology expert groups, technology advisory boards, the community or commissioned to consultancies and research institutes or technology companies. The best place to search for these is in countries that have shown an early interest in the technology. A web search of related terms is likely to return key documents.
2. **Ensure that the process of data collection relies on a robust process and answers key questions posed in this step** (regardless of the tool being used for analysis).
3. **Ensure evidence comes from participants with wide range of expertise** including systems engineers and integrators, manufacturing companies, materials and component suppliers in addition to scientists and engineers from both academia and industry, and policy.
4. **Explore key sectoral applications proposed in the evidence document and technology pathways towards these sectoral applications.**
5. **Explore barriers and opportunities highlighted in the document.**
6. **Ensure coverage in terms of other sectoral applications, barriers and opportunities, and technology system elements** (e.g., production technologies, tool technologies, standards, etc.), which might not have been explored but might be of importance.

Task B. Organize roadmapping workshop with technology experts[71]

2. **Clarify the technology scope of roadmapping workshop**, which can be the highest level of technology classification (e.g., quantum technologies) or any level below (e.g., quantum sensors, specific quantum sensor technology, specific product, etc.).
3. **Clarify the objective of the roadmapping workshop.** For example, identifying the technology pathways of key quantum sensor platform technologies: engineered nitrogen vacancy (NV) centre ensemble in diamond, alkali vapour cells, etc. This could focus on a variety of things, for example, scaling up of technology X, manufacturing technology X, etc.
4. **Adapt roadmapping structure (e.g., layers) to answer key questions of interest** and ensure that important system elements are covered. The basic structure of a roadmap is presented in Figure 16. This includes resources, science and technology answering the question of HOW; system, service and product answering the question of WHAT; and business and market answering the question of WHY. These can be further broken

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[71] Pages 30-31 provide further details on the process: European Commission JRC (2023). Technology foresight for public funding of innovation: Methods and best practices.; More resources can be found in: Phaal et al. (2010). Roadmapping for strategy and innovation.

down into categories or adapted as needed. For example, technologies can be broken down as presented in Step 1. It is, for example, important to think about manufacturing technologies and engineering tools when it comes to commercializing emerging technologies, which in turn may require the addition of such categories. Likewise, OCA can be added as a separate category into the roadmap architecture if this is of interest.

5. **Ask experts to identify and select most interesting/ promising/ etc. application markets or sectors** when thinking about emerging technologies as this will enable thinking about the pathway from technology to application. This helps thinking about current and future needs along the way - materials, tools, manufacturing technologies, demonstration environments, skills, capabilities, supply chain, etc. Ranking sectoral applications based on factors of interest can be used to achieve consensus. Avoid selecting based on personal interest or hype.
6. **Ask experts to collectively fill the various roadmap layers connecting these from technology to final applications over time, identifying key enablers and barriers along the path.**
7. **Ensure good representation of experts** including scientists, engineers, product developers, but also systems engineers and integrators, manufacturing companies, materials and component suppliers. The latter are particularly important when it comes to emerging technologies that are of high complexity, requiring the development of new science and engineering tools, and manufacturing technologies.
8. **Engage with a technology expert who can help distil workshop output** for non-technical audience and help with policy recommendations given the highly technical nature of such exercises. Clearly defined analytical and policy questions could help communication.
9. **Assign facilitators.** Normally 1-3 expert facilitators are considered suitable. [72]

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[72] More resources can be found in: Phaal et al. (2010). Roadmapping for strategy and innovation.

USE CASE 4: International semiconductor technology roadmapping activity relying on international expertise (1998-today)

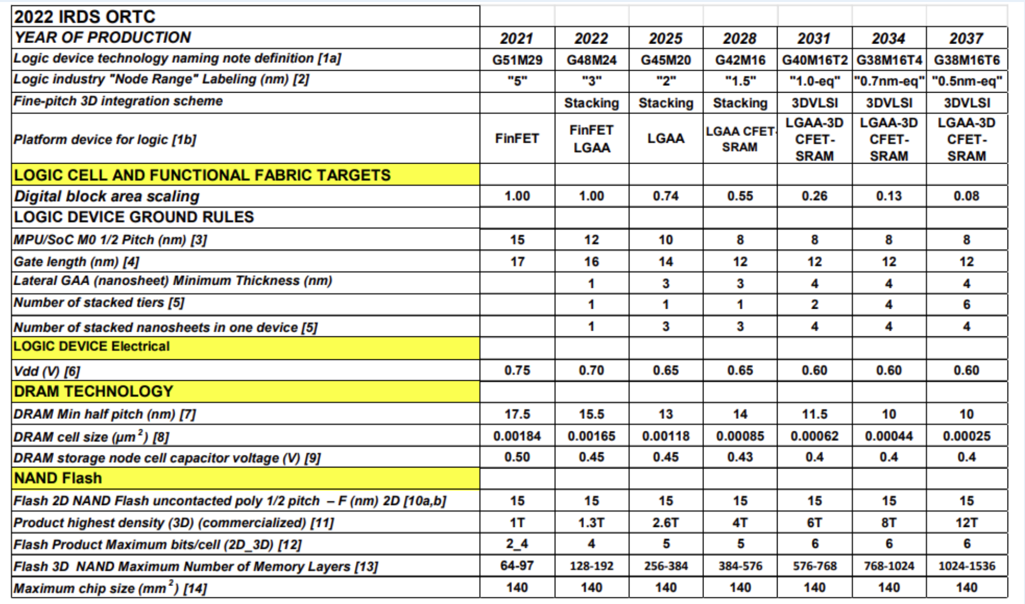
The International Technology Roadmap for Semiconductors (ITRS) is an exemplary effort that has led to roadmapping different semiconductor technology areas (e.g., process integration, system drivers and design, factory integration, emerging research materials). These were produced on annual basis between 1998 and 2015 by key industry experts from Europe, Taiwan, Korea, Japan, and US with an aim to provide a reference point into the future to stimulate innovation.

Given the evolving nature of the semiconductor industry, in 2012, the ITRS reorganized the semiconductor technology areas to reflect the renewed ecosystem and include new elements such as heterogenous integration and wireless connectivity.

Today, ITRS has been succeeded by the International Roadmap for Devices and Systems (IRDS) in 2016 with an aim to:

- To identify key trends related to devices, systems, and all related technologies by generating a roadmap with a 15-year horizon
- To determine generic devices' and systems' needs, challenges, potential solutions, and opportunities for innovation
- To encourage related activities worldwide through collaborative events, such as related IEEE (Institute of Electrical and Electronics Engineers, technical professional organization now hosting the IRDS) conferences and roadmap workshops’

Figure shows technical specifications of semiconductor technologies and their evolution over time as a result of the roadmapping process:



2022 IRDS ORTC							
YEAR OF PRODUCTION	***2021***	***2022***	***2025***	***2028***	***2031***	***2034***	***2037***
Logic device technology naming note definition [1a]	G51M29	G48M24	G45M20	G42M16	G40M16T2	G38M16T4	G38M16T6
Logic industry "Node Range" Labeling (nm) [2]	"5"	"3"	"2"	"1.5"	"1.0-eq"	"0.7nm-eq"	"0.5nm-eq"
Fine-pitch 3D integration scheme		Stacking	Stacking	Stacking	3DVLSI	3DVLSI	3DVLSI
Platform device for logic [1b]	FinFET	FinFET LGAA	LGAA	LGAA CFET-SRAM	LGAA-3D CFET-SRAM	LGAA-3D CFET-SRAM	LGAA-3D CFET-SRAM
LOGIC CELL AND FUNCTIONAL FABRIC TARGETS							
Digital block area scaling	1.00	1.00	0.74	0.55	0.26	0.13	0.08
LOGIC DEVICE GROUND RULES							
MPU/SoC M0 1/2 Pitch (nm) [3]	15	12	10	8	8	8	8
Gate length (nm) [4]	17	16	14	12	12	12	12
Lateral GAA (nanosheet) Minimum Thickness (nm)		1	3	3	4	4	4
Number of stacked tiers [5]		1	1	1	2	4	6
Number of stacked nanosheets in one device [5]		1	3	3	4	4	4
LOGIC DEVICE Electrical							
Vdd (V) [6]	0.75	0.70	0.65	0.65	0.60	0.60	0.60
DRAM TECHNOLOGY							
DRAM Min half pitch (nm) [7]	17.5	15.5	13	14	11.5	10	10
DRAM cell size (μm^2) [8]	0.00184	0.00165	0.00118	0.00085	0.00062	0.00044	0.00025
DRAM storage node cell capacitor voltage (V) [9]	0.50	0.45	0.45	0.43	0.4	0.4	0.4
NAND Flash							
Flash 2D NAND Flash uncontacted poly 1/2 pitch – F (nm) 2D [10a,b]	15	15	15	15	15	15	15
Product highest density (3D) (commercialized) [11]	1T	1.3T	2.6T	4T	6T	8T	12T
Flash Product Maximum bits/cell (2D_3D) [12]	2_4	4	5	5	6	6	6
Flash 3D NAND Maximum Number of Memory Layers [13]	64-97	128-192	256-384	384-576	576-768	768-1024	1024-1536
Maximum chip size (mm^2) [14]	140	140	140	140	140	140	140

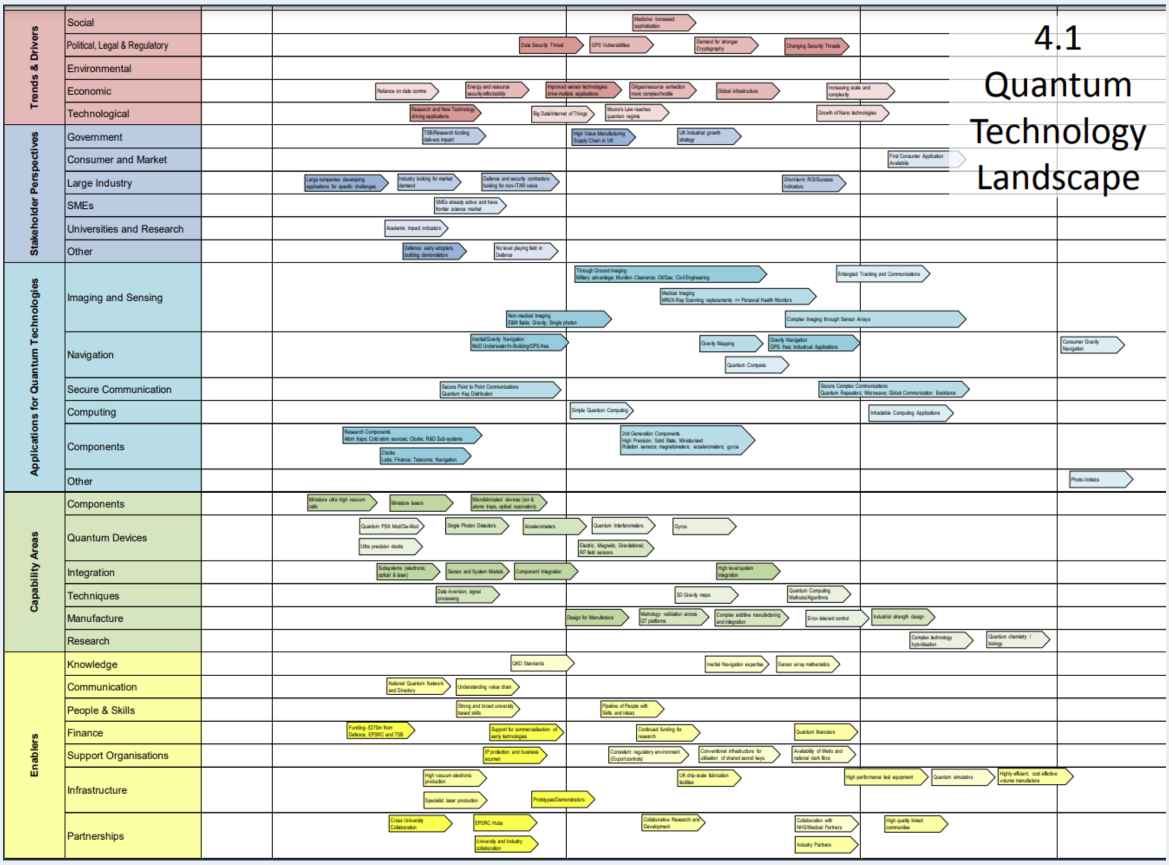
Source: IEEE (n.d.). IRDS website.; IEEE (2022). IRDS Executive Summary.

USE CASE 5: National quantum technology roadmap (2015) building on two quantum technology roadmapping workshops (2014)

A UK-based effort was the commissioning of a roadmapping exercise for better understanding commercialisation of quantum technologies in the UK. The Technology Strategy Board (TSB, today IUK) commissioned the Institute for Manufacturing (IfM) to undertake roadmapping for quantum technologies. This led to two workshops held around the same time in 2014 with near-identical processes.

The workshops led to the identification of priority stakeholder perspectives, short-, mid- and longer-term application opportunities, and critical technology and capability needs and enablers. Key outputs were fed back into the national roadmap *'A roadmap for quantum technologies in the UK'* to inform the sector's future activities.

Figure shows the structure of the roadmap and how its layers were broken down to enable exploring key questions of interest:



Source: TSB & IfM (2014). Quantum technology roadmap report.

Step 3. Capability and resource requirements

Key barriers and opportunities can be overcome and enabled by capabilities and resources that are required now and in the future. This step focuses on identifying and decomposing these capabilities and resources in detail.

a. <u>Identify capabilities and resources required to overcome and enable barriers and opportunities</u>

Resources can be understood as tangible and intangible assets (co-)owned by actors that are combined into capabilities. *Capabilities* are complex combinations of resources, including organisational competences, working under specific circumstances towards a desired outcome or strategy.[73]

A ***structured checklist of resources and capabilities*** developed in Figure 20 can be useful, but it is necessary to consider their complex combinations and complementarities, to achieve a sufficient and necessary mix of resources and capabilities, as illustrated in Figure 19.[74]

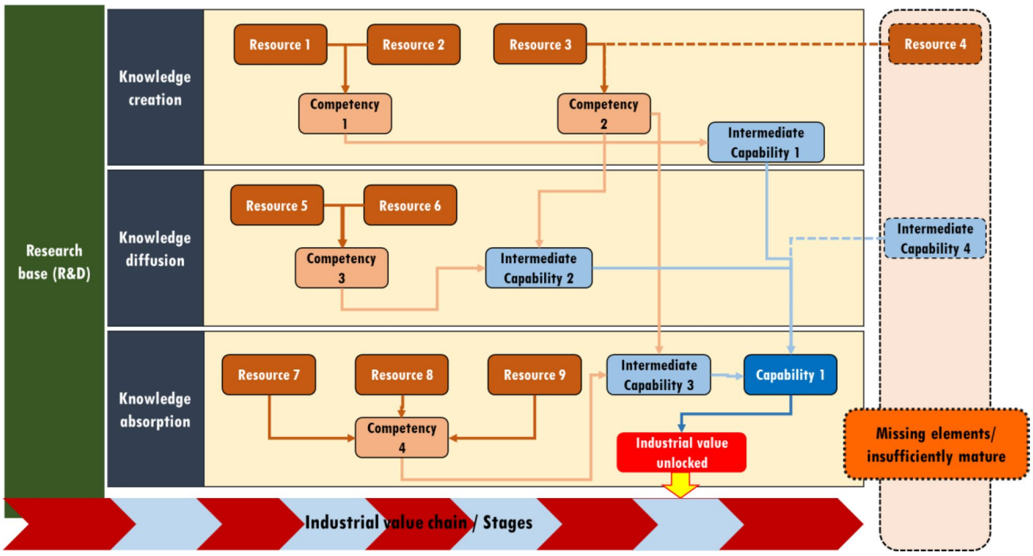


Figure 19 Visual representation of resources, competencies and capabilities, and their complex combinations and complementarities.[75] *Source: Ramirez Garcia, 2023.*

Resource and capability requirements can be explored at different technological and geographical levels, which is going to be determined by the initially set objective and technology scope. This is going to significantly influence whether the analysis of capabilities

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[73] Ramirez Garcia (2023). Opening the 'black box' of regional industrial-innovation systems.

[74] Grant (2022). Contemporary strategy analysis (11th Ed.).; Teece et al. (1997). Dynamic capabilities and strategic management.

[75] Note: Competencies can be defined here as the intermediate step between resources and capabilities (i.e., combining unique, sufficient, and compatible resources resulting from processes and routines used under specific conditions).

and resources will be predominantly focusing on national, regional, local, private, public or governmental resources and capabilities. Given the focus of Step 4 on actor level resources and capabilities, and Step 5 on the role of government, this section really aims to understand more holistically but in detail the capability and resource requirements regardless of their source. Nevertheless, this step can be easily merged with Steps 4 and 5.

Methodology in more detail:

In terms of analysis, Steps 1 and 2 should provide significant technical context and detail in terms of capability and resource requirements, especially if these steps are based on technology expert workshops. Capability and resource needs should also emerge as part of policy consultations or call for evidence – the utility of this to inform strategy is highly dependent on the level of detail. If neither are available, international sources of technical and/or policy evidence by other governments and organisations concerned with emerging technologies may be used.

The checklist above highlights some key aspects that may need to be considered, but more concretely, capability and resource requirements need to be assessed based on the strategic objective of the analysis. Each of the above checklist categories can be expanded and analysed at lower levels.

Furthermore, each capability and resource requirement can also be explored in-depth separately, for example, by undertaking a roadmapping workshop (see Step 2). This is especially important when the capability and resource is likely to significantly impact the future development of the emerging technology family in question (e.g., prototyping and foundry facilities for semiconductors and quantum technologies and the required workforce to operate these[76]).

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[76] RAEng (2024). Quantum infrastructure review.

Example checklist of resources and capabilities

Technological (see Step 1. for systematic disintegration and more detail)

☐ Science & technology research capability
☐ Product development & engineering capability
☐ Process development & manufacturing capability
☐ Test & demonstration capability
☐ Integration & system assembly capability
☐ Patents, copyrights, trade secrets
☐ …

Human

☐ Skilled workforce & training (researchers, technicians, engineers, systems engineers, entrepreneurial, organisational, managerial, etc.)
☐ Skills & know-how
☐ Higher education
☐ …

Organisational competences

☐ Organisational routines & processes for coordination & integration
☐ Organisational routines & processes for learning
☐ Capacity to integrate, build & reconfigure competences addressing rapidly changing environments
☐ Network resources including capacity for communication & collaboration & linking
☐ Network resources in terms of vertical & horizontal integration (e.g., supply chains)
☐ …

Infrastructural & physical

☐ Land
☐ Critical minerals & materials
☐ Energy availability & prices
☐ Transportation
☐ ICT, including data centres & storage, 5G etc.
☐ …

Governmental

☐ Patents, copyrights, trade secrets (IP regime)
☐ Regulation & standards
☐ Strategy, direction & stability
☐ Data & information sharing standards
☐ Strategies for developing new capabilities & workforce
☐ …

Financial

☐ Subsidies, taxes, etc.
☐ Scale-up financing
☐ Venture capital
☐ …

Behavioural & cultural

☐ Public acceptance/ culture
☐ Perceived public demand/ need
☐ Technology adoption & diffusion rates
☐ Societal benefit/ public good
☐ …

Figure 20 Example checklist for resource and capability requirements. Source: Adapted from Teece et al., 1997; Grant, 2022; Döme & O'Sullivan, 2025.

Step 4: Actors with capabilities and resources

a. Identify actors who have or could potentially have the capabilities and resources needed

Innovation system frameworks[77] and/or ***supply chain and value chain mapping***[78] can be used to identify key actors and their current and potential capabilities and resources in innovation and industrial systems. [79] These tools require mostly qualitative understanding and exploration of actors and their networks, institutional frameworks, industrial structures, cultural conditions, and their resources and capabilities.

Additional quantitative analyses can also be used to quantify and identify key actors, however, for these to be useful, they need to include significant amount of detail (e.g. detailed keyword searches, well defined or re-defined standard industry classification codes, etc.):

- Bibliometric and patent analysis identifying key authors, patent applicants, universities, companies, countries, funders, topics
- Citation network analysis exploring strengths of relationships between actors
- Firm level analysis as a proxy for key actors and their resources and capabilities
- Other descriptive statistics of innovation inputs, outputs and outcomes

b. Assess the role of actors with potential capabilities and resources against the own-collaborate-access (OCA) framework to understand where these (will) come from

Once actors with the necessary capabilities and resources — as well as those with the potential to develop them in the future — have been identified, the *own–collaborate–access (OCA) framework*[80] can be applied to guide strategic decisions about how and where to source these capabilities in the future.

The OCA framework helps assess whether emerging capabilities should be met by building capabilities domestically, collaborating with partners, or securing access through other means, each posing different benefits, costs, and risks.

The official definitions for own, collaborate, access are:

> “Own: where the UK has leadership and ownership of new developments, from discovery to large-scale manufacture and commercialisation. This will always involve elements of collaboration and access.

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[77] OECD (1999). Managing National Innovation Systems.

[78] UNIDO (2009). Value chain diagnostics for industrial development.; Gereffi & Fernandez-Stark (2016). Global value chain analysis: A primer.

[79] Tool 1, 2 and 3 could also be used for identifying actors and their networks: GO-Science (2023). An introductory systems thinking toolkit for civil servants.

[80] HMG (2021). Integrated review of security, defence, development and foreign policy.

> Collaborate: where the UK can provide unique contributions that allow us to collaborate with others to achieve our goals.
>
> Access: where the UK will seek to acquire critical S&T from elsewhere, through options, deals and relationships." [81]

The choice is dependent on the level of ownership and control required from a supply chain and national economic security, and defence point of view, but also on the foreseeable potential to develop these required capabilities based on current capabilities, and their economic and public value (including spillovers into the ecosystem in the form of complementary capabilities).

Key actors and their capabilities and resources can then usefully be assessed against the OCA framework as illustrated in Figure 21.

	Own	**Collaborate**	**Access**
Actor 1			
-capability X now	X	X	
-capability X in 5 years		X	
-capability Y now	none	none	none
-capability Y in 2 years			X
-capability Y in 4 years		X	X

Figure 21 Example use of the own-collaborate-access framework to assess capabilities. Source: NETS Handbook Project Team.

Methodology in more detail:

Systems mapping[82], a less frequently used mainly qualitative approach, is presented first for both innovation system mapping and value/ supply chain mapping (see Task A and B). This method generally enables the graphical visualisation and exploration of complex systems. Key system actors and activities can be usefully mapped for innovation and industrial systems with significant implications for understanding their networks, resources and capabilities. There are other useful methods that are also worth exploring for this type of analysis, as presented by tools 1, 2, and 3 in the GO-Science Toolkit.[83]

Nevertheless, the most used approaches to understanding innovation and industrial strengths are usually quantitative in nature focusing on backward-looking performance metrics, such as the number of academic publications and patents, number of start-ups and companies, and their investment volumes, volume of venture capital investment, share of R&D over GDP, size

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[81] HMG (2021). Integrated review of security, defence, development and foreign policy.

[82] European Commission (2023). Systems-based methods for research & innovation policy.; Tool 1, 2 and 3 could also be useful for identifying actors and their networks: GO-Science (2023). An introductory systems thinking toolkit for civil servants.

[83] Ibid.

of product exports, etc. Rather than providing a step-by-step guide to these commonly used tools, Tasks C and D go beyond the basic method and explore additional avenues for analysis of emerging technologies enabling more nuanced strategic analysis.

Needless to say, combining systems mapping approaches with quantitative analysis can yield the most useful results. For example, mapping key value chain activities/ stages qualitatively can provide significant input into the classification of companies across these different activities. Use Case 8 illustrates this point particularly strongly.

Task A. Mapping innovation systems

As introduced in Section 2.3, innovation systems focus on understanding key innovation actors, their relationships and the institutional framework shaping their interactions, which vary significantly across countries, regions, technologies, sectors, etc. Their mapping can thus help to uncover key capabilities and resources.

This section describes how innovation systems of emerging technologies can be mapped and tests this approach by mapping the UK's national innovation system broadly (see Use Case 6) and the UK's quantum technology system in more detail (see Use Case 7). Short interactive session-style workshops were used and tested to understand whether such format enables the preferred output. The sessions were held with relevant policy stakeholders at DSIT.

1. **Identify the scope of the system map by determining system boundaries** – whether the focus is on a national innovation system, technological innovation system, sectoral innovation system or others as presented in Section 2.3. For example, for national innovation systems, the focus is within national boundaries. For technological innovation systems, the scope might extend beyond national borders, involving international actors and networks. There is clearly also overlap between national, technological and sectoral systems, so it is important to define system boundaries.
2. **Clarify the objective of system mapping.** For example, the mapping exercise can focus on a specific issue area such as commercialization of an emerging technology or understanding education and vocational training, or it can be at a more general level mapping the key actors in the system. The latter being more useful for early stages of emerging technology when evidence is not well understood nor gathered. This step requires the clarification of the policy question and will depend on availability of evidence as well as the stage of technology and policy.
3. **Provide a structure to answer key questions of interest** and ensure that important system elements are covered. For example, as presented in Use Case 7, innovation functions, a system map with national and international boundaries (reproducing the own-collaborate-access (OCA) framework), and a list of key actors were used to provide structure to the interactive sessions held with relevant policy makers and analysts.

4. **Identify key actors and their linkages by undertaking desk research or organizing a workshop, roundtable, or interactive session.**
    - **Identify actors:** Actors could include firms of different sizes across different sectors, their R&D activities/labs, universities, university spinouts, public research organizations, research and technology organizations, government funding agencies, research councils, ministries, supporting organizations including regulatory bodies, standard setting agencies, those who provide and maintain research and innovation infrastructure, professional associations, trade unions, (corporate) venture capitalists, angel investors, banks, NGOs, user groups, etc.
    - **Assess the functions of these actors in the innovation system.** Do they contribute to knowledge generation? Do they contribute to commercializing research? Do they perform system intelligence activities or provide direction? See Section 2.3 for more information on the functions.
    - **Identify resources and capabilities**: Identify critical resources and capabilities that the different actors have, may potentially develop or have, or may need, such as funding, human capital, supporting technologies and tools (including testbeds, pilot plants, etc.), infrastructural technologies, incubators, accelerators, etc.
    - **Identify networks**: Understand formal and informal networks among the actors, such as industry clusters, research consortia, public-private partnerships, etc.
    - **Interaction types**: Categorize the types of interactions (e.g., collaboration in R&D projects, knowledge sharing, funding relationships, policy dialogue).
    - **Intensity and quality**: Assess the quality and intensity of these interactions. Are they strong and sustained or weak and sporadic? These could include arrows of different thickness and length.
5. **Analyse the institutional framework.** Map relevant policies, laws, and regulations that impact innovation. This includes intellectual property laws, research funding policies, standards, etc. Assess how these policies either facilitate or hinder innovation activities. Understand the cultural, social, and economic institutions that shape innovation. This might include norms, routines, and conventions that affect innovation dynamics.
6. **Benchmark against other systems – explore the key actors and their capabilities and resources in other countries**

USE CASE 6: Workshop on mapping UK's national innovation system

A one-hour interactive workshop session was held with members of the Technology Strategy and Security Team at DSIT with an aim to test the proposed methodology on innovation system mapping (Step 4, Task A).

The objective was to identify key actors in the UK's national innovation system. The objective was purposefully broad here to test how initial evidence (when no other evidence exists yet) can be gathered and how this would look in practice. The intention was to then zoom in on a specific emerging technology as presented in Use Case 7, building on these earlier insights regarding both the workshop process as well as the collected evidence.

Two frameworks were presented to participants, which then together provided the structure to the interactive session. CATWOE was used as one of the frameworks as it enables analysing complex problems by considering a situation/activity that may potentially be made real through six different perspectives (C=customers who will benefit from the activity if it was made real; A=actors who do the activities; T= the activity/transformation; W=worldview/motivation/agenda; O=owners of the situation or wider system decision; E=environmental constraints).

The second framework explains and categorizes the different innovation system functions that actors can play in the wider system, namely, knowledge generation, knowledge diffusion, and knowledge absorption (see Section 2.3 for a more in-depth discussion). An online whiteboard with the resulting template was used for participants to fill in.

The table below shows a snapshot of the results of the session for the three innovation functions.

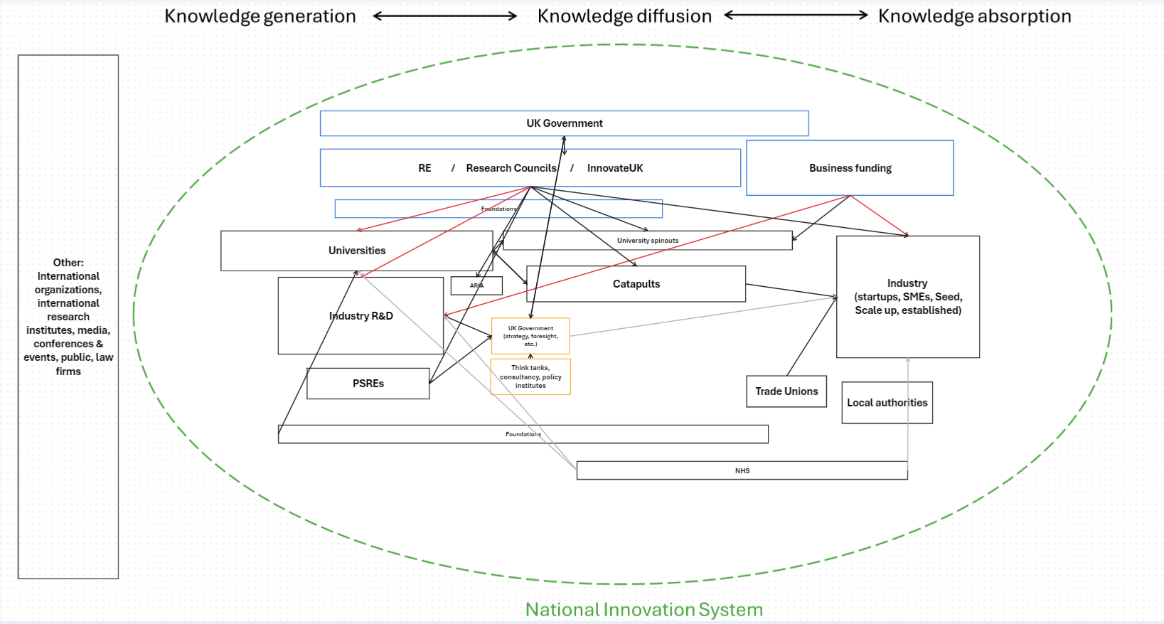
Actor/institution	**Knowledge generation**	**Knowledge diffusion**	**Knowledge absorption**
Investors	🟩	🟩	🟩
SMEs	🟩	🟩	🟩
Universities	🟩	🟩	🟩
UKRI	🟩	🟩	
Catapults		🟩	🟩
HMG	🟩		🟩
Businesses	🟩		🟩
Industry R&D	🟩		
Research institutes	🟩		
PSREs	🟩		
ARIA	🟩		
Philanthropy funds	🟩		
…	…	…	…

Note: The results reflect the experiences of those involved in a short-format workshop and may not necessarily be universally agreed upon. Validation of results with other experts could address this issue.

(continued on next page)

USE CASE 6 continued

Through an iterative process, the output was compiled into a system map by two analysts, who were also the facilitators. Interactions between actors, represented by arrows, were added by the analysts based on knowledge of the system and other available resources (e.g., UK Science and Innovation Network (2015). Innovation toolkit.; UKRI (2023). Explainer: UKRI's institutes.; Chart 2.10 in Cambridge Industrial Innovation Policy (2023). UK innovation report 2023.). The figure below represents an initial innovation system map:



Note: The results reflect the experiences of those involved in a short-format workshop and the analysts, which may not be universally agreed upon. Validation of results with other experts could address this issue.

Limitations and lessons learned:

Due to time limitations, interactions between actors and the wider institutional aspect could not be considered during the interactive session. Likewise, OCA considerations were not included. Follow-up sessions could address these issues as well as help validate findings.

While the objective here was purposefully broad, a more specific objective could provide more concrete answers. In other words, more targeted system maps (e.g., looking at a specific emerging technology) have the potential to provide more nuanced insights, see Use Case 7 as a case in point.

Choosing the right frameworks and creating simple and visually appealing templates influences the clarity of the exercise significantly.

A one-hour workshop can lead to useful input, but this significantly depends on the workshop structure/ template and experts invited.

Source: Interactive session held with policy makers and analysts at DSIT.

USE CASE 7: Mapping the quantum technology innovation system with a focus on the UK but with links to the wider international innovation system

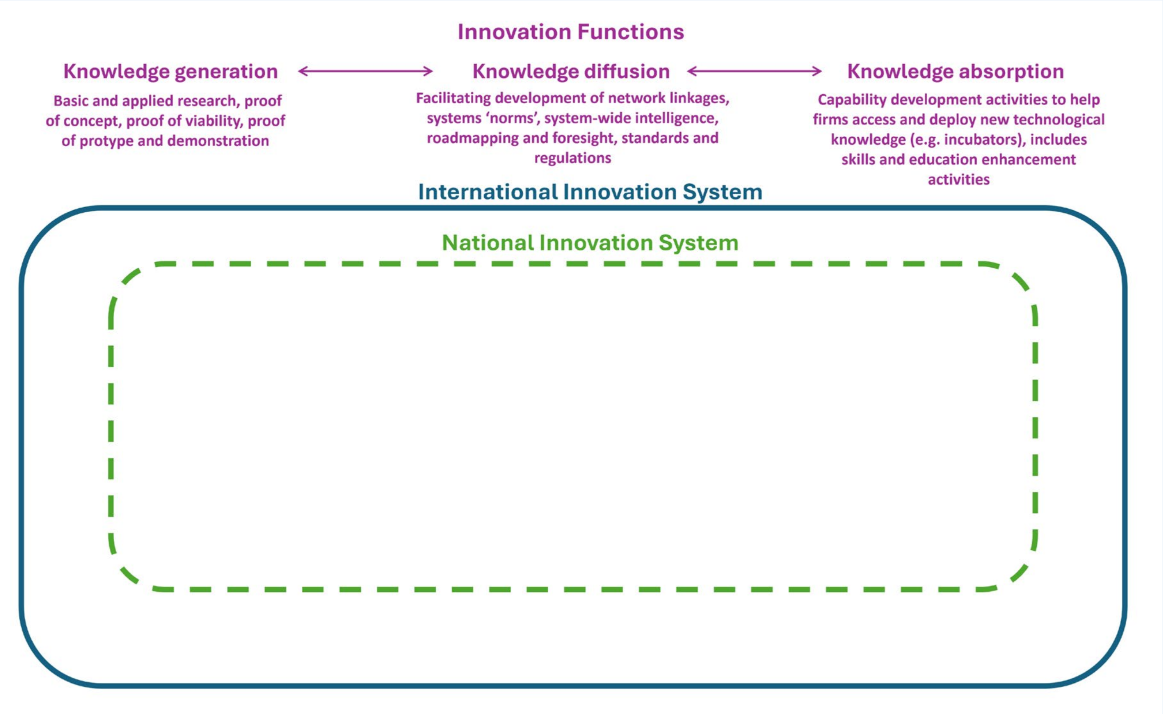
A one-hour interactive workshop session was held with members of the Office for Quantum at DSIT with an aim to identify key quantum technology actors and their linkages to the international innovation system (contributing to better understanding OCA).

A system map template (shown below) was presented to the participants via an online whiteboard. A distinction between the national system (in green) and international system (in blue) was made. The system map was further organized based on three key innovation functions (in purple): knowledge generation, knowledge diffusion and knowledge absorption; as introduced in more detail in Section 2.3.

A long list of actors identified based on earlier desk-based research and understanding of the quantum landscape was provided on the side for the participants to locate on the map. This was further supported by a long list of questions to guide the session and to underline the level of specificity that was desired. Example questions included: Which companies in what sectors? What firm networks and clusters? What public sector research enterprises (PSREs)? Which universities, Catapults? Etc.

The results were found to be useful by the workshop participants, suggesting how relatively short but structured sessions can help systematic analysis.

The template used to guide the workshop:



Source: Interactive session held with policy makers and analysts from the Office for Quantum at DSIT.

Task B. Mapping industrial value chains

The analysis of industrial systems and capabilities for emerging technologies is a difficult task given that emerging technologies by definition require the establishment of new or reconfiguration of old industrial systems.

As introduced in Section 2.4, mapping industrial value chains can help to identify current industrial capabilities across the value chain and anticipate potential high added value opportunities. This can be achieved through identifying 1) global value chain activities (from R&D, design, etc. all the way to post-production services), 2) domestic companies active across these value chain activities, which enables 3) understanding current domestic industrial capabilities, and 4) potential high value-added activities and future opportunities.[84]

The following section describes step-by-step how industrial value chains of emerging technologies can be mapped, providing example value chain illustrations along the steps. Following the guidance provided in the Global Value Chain Analysis Primer,[85] and best practice on value chain mapping, there are several steps that can be taken:

1. **Determine the scope of the industrial value chain** by clearly defining the sector, industry, technology or product/service of interest.
2. **Clarify the objective or purpose of the analysis**. Are you looking to understand the current industrial value chain, potential for growth and value addition, or to assess supply chain risks and resilience? Understanding the latter would for example lead to a slightly different unit of analysis (inputs and outputs moving through firms) compared to understanding value addition focusing on key value adding activities. This step requires posing a clear policy question.
3. **Map all/global industrial value chain activities.** Identify all (i.e., global) value chain segments/activities and their sequencing and create a visual representation, e.g., using stocks and flows. Break down key activities into further sub-activities. It is important to understand the technological complexity of different value chain activities and sub-activities here. This will help to understand how each activity contributes to overall value creation. See examples of global value chains with key activities and sub-activities identified (Figure 22 & Figure 23).

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[84] Gereffi & Fernandez-Stark (2016). Global value chain analysis: A primer.

[85] Ibid.

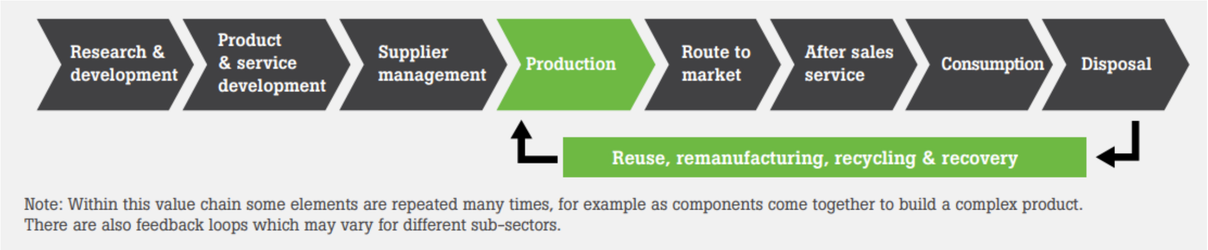

Figure 22 Simplified model of the manufacturing value chain as presented in 'The Future of Manufacturing'. Source: GO-Science, 2013.

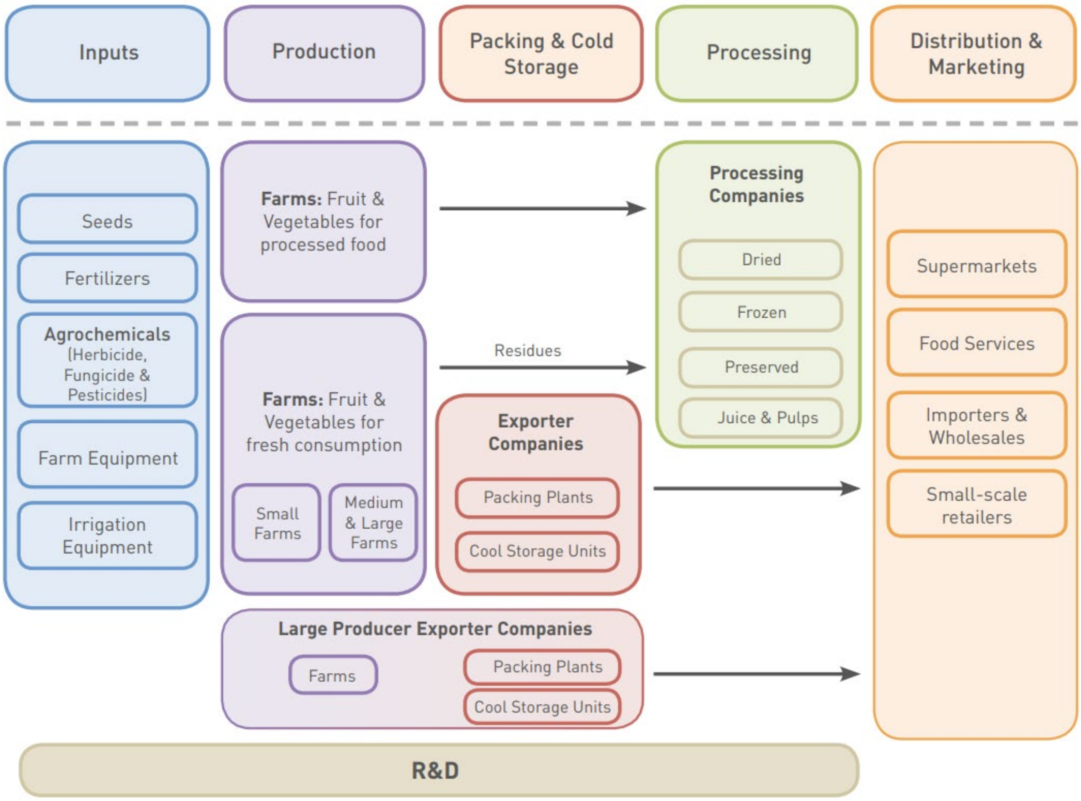

Figure 23 Map of the fruit and vegetable global value chain and underlying activities, structures and dynamics. Source: Gereffi & Fernandez-Stark, 2016.

4. **Identify and map key industry stakeholders and their roles across value chain segments**. This includes companies, industry associations, workers, educational and training institutions, government departments (trade, economy, education) and agencies (export promotion and investment attraction agencies), etc. (see Figure 24 for an example of emerging technology stakeholders segmented by some major value chain groups).

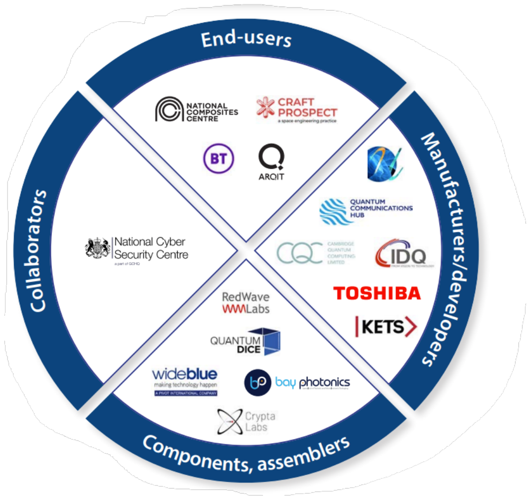

Figure 24 Key stakeholders in UK's quantum communications ecosystem segmented by value chain. Source: National Physical Laboratory, 2023.

5. **Quantify number of companies, their size, revenue, exports and imports, segmented across the value chain activities** to understand where current domestic capabilities are. This is particularly important for understanding and developing growth strategies. This step can heavily draw on quantitative analysis/ data for companies but may require some additional classifications. See Figure 25 and Figure 26 for the medical devices sector in Costa Rica and materials innovation companies in the UK.

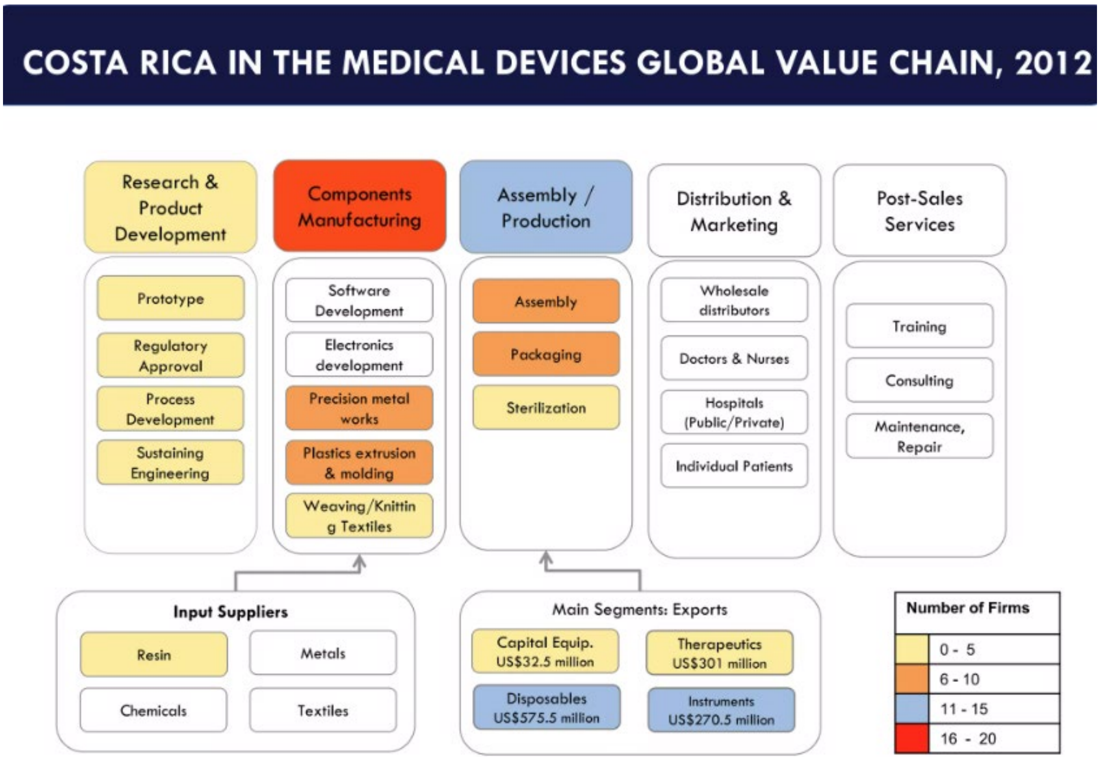

Figure 25 Global value chain activities in the medical devices industry and related industrial capabilities of Costa Rica. Source: Gereffi & Fernandez-Stark, 2016; Gereffi et al., 2019.

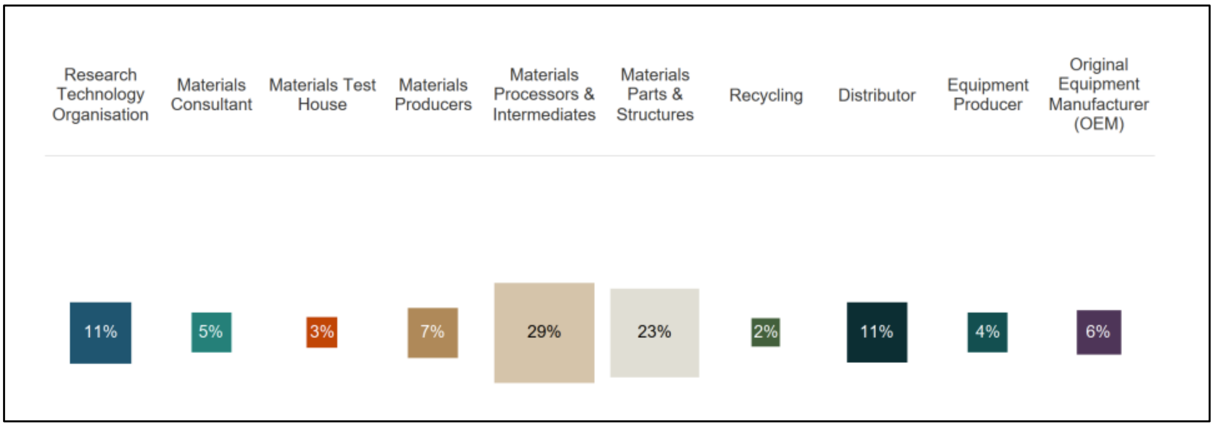

Figure 26 Value chain analysis of UK companies active in materials innovation as a share of all materials innovation companies in the UK. Source: Henry Royce Institute, 2024.

6. **Explore opportunities for economic upgrading.** Economic upgrading refers to "firms, countries or regions moving to higher value activities in GVCs [global value chains] in order to increase the benefits (e.g. security, profits, value-added, capabilities) from participating in global production." [86]

   This involves understanding and analysing dynamics over time – in the case of established industries, backward looking can help, but in the case of emerging technologies, understanding future technology trends may also be important. The former can be achieved by analysing the evolution of product exports, evolution of value chain activities, and backward linkages.[87] The latter can be achieved by looking into market analyses and estimates predicting the impact of emerging technologies on industries.

   See Figure 27 capturing the economic upgrading trajectory of Torreon, Mexico, into new higher added value segments of the textile value chain over time.

   The different economic upgrading strategies include:[88]
   - process upgrading, which transforms inputs into outputs more efficiently by reorganizing the production system or introducing superior technology
   - product upgrading, or moving into more sophisticated product lines
   - functional upgrading, which entails acquiring new functions (or abandoning existing functions) to increase the overall skill content of the activities
   - chain or inter-sectoral upgrading, where firms move into new but often related industries

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[86] Gereffi & Fernandez-Stark (2016). Global value chain analysis: A primer.
[87] Gereffi et al. (2019). Diverse paths of upgrading in high-tech manufacturing.
[88] Gereffi & Fernandez-Stark (2016). Global value chain analysis: A primer.

  - entry in the value chain, where firms participate for the first time in national, regional or global value chains. This is the first and one of the most challenging upgrading trajectories
  - backward linkages upgrading, where local firms (domestic or foreign) in one industry begin to supply tradable inputs and/or services to companies – usually multinational corporations – that are located in the country and are already inserted in a separate global value chain
  - end-market upgrading, which can include moving into more sophisticated markets that require compliance with new, more rigorous standards or into larger markets that call for production on a larger scale and price accessibility

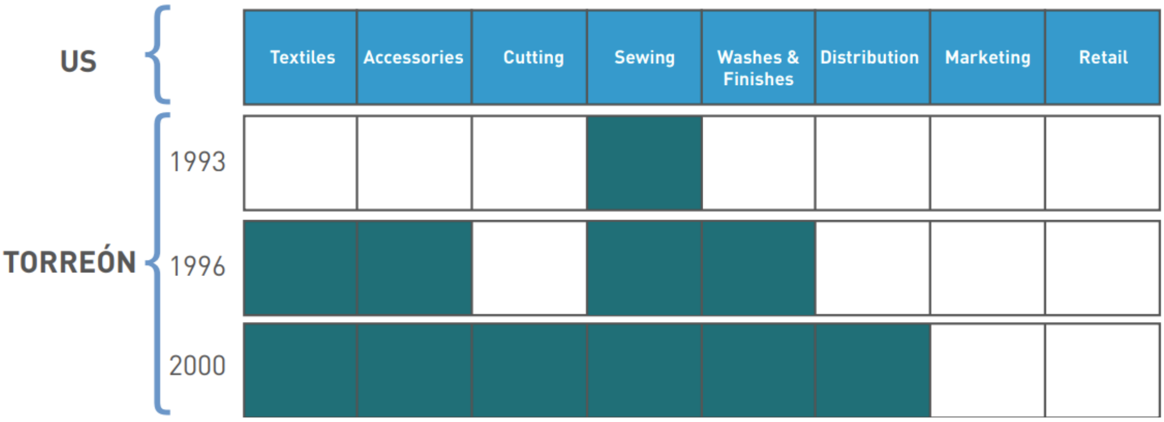


Figure 27 Economic upgrading of Torreon's (Mexico) apparel value chain and its evolution over time highlighted by green coloured blocks. Source: Gereffi & Fernandez-Stark, 2016.

Task C. Descriptive statistics of innovation inputs, outputs and outcomes

Data on traditional innovation metrics is often used to first explore the innovation landscape of a country. This includes traditional metrics on innovation inputs, outputs, and outcomes as presented in Box 3. These are usually available from a variety of sources, including:

- national statistical agencies (e.g., UK's Office for National Statistics [ONS])
- international organizations (e.g., OECD, Eurostat, World Bank)
  - OECD's Main Science and Technology Indicators database
  - OECD's Research and Development Statistics database
- specialized reports and databases (e.g., the Global Innovation Index, Data City, private sector reports)
- Figure 28 summarises key sources for the UK

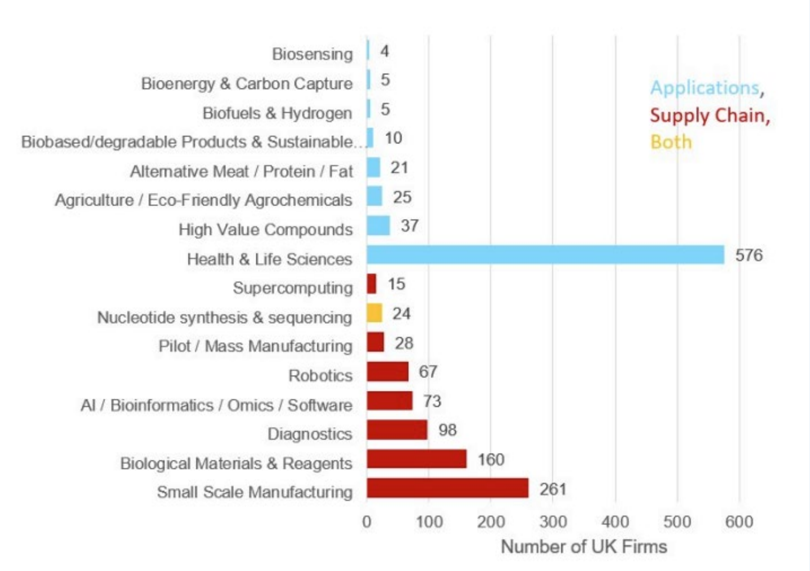
USE CASE 8: Assessing industrial capabilities in engineering biology

To provide evidence for *the National Vision for Engineering Biology*, analysts from the GO-Science and DSIT assessed the UK's industrial strengths in engineering biology by analysing and merging company data from several sources, including real-time industrial classifications (RTICs).

The aim of the exercise was to gain a deeper understanding of the innovation and industrial system and expanding this to include aspects of the 'own-collaborate-access' framework.

1. Initial steps involved keyword searches in major databases like that of Innovate UK, Biotechnology and Biological Sciences Research Council (BBSRC), GO-Science, etc.
2. As each of the databases uses their own taxonomies or their keyword search was of differing quality, the RTIC of The Data City platform was explored instead. This platform uses web scraping of UK company websites for data gathering and uses machine learning for classifying these firms based on patters of language, keyword frequencies and weights. See resulting engineering biology sector – application and supply chain – RTICs developed through collaboration with and scrutinised by DSIT internal subject matter experts and analysts, the cross-Whitehall Engineering Biology network and The Data City over the summer of 2023.
3. The resulting company list uses IDs assigned by Companies House (government agency), which helped merging the curated list with HM Revenue & Customs data. Export and import data on products and services were extracted to understand what the key products and services of these companies are. Frequencies of keywords were calculated as counts across engineering biology companies over counts across all companies. The lists of keywords were again scrutinized to ensure relevance.

Categorizing and counting engineering biology companies in the UK resulted in better understanding of industrial capabilities in the UK – see figure below. The analysis also provided understanding of supply chains in relation to product codes because it answered some key questions around where products are sourced from and what key inputs and outputs are – which may need to be considered.



Source: Discussion with GO-Science and DSIT analysts; DSIT (2023). National Vision for Engineering Biology.

The effectiveness of this approach depends heavily on data availability and data classifications used. Traditional classifications (for example, of companies based on Standard Industry Classifications, SIC codes) do not capture the emerging, dynamic and complex nature of innovation systems or specific policy questions of interest. They serve as proxies of innovation metrics. This point is even more significant in the case of emerging technologies with little data and developing classifications, especially in the early stages of technology lifecycles.

Machine learning and natural language processing have recently been used for emerging technology and industry classifications offering more up-to-date insights by incorporating broader data sources and advanced analytics to reflect the dynamic and complex nature of emerging technologies. However, commercial software is still in early stages of development and resulting **data requires manual checking** as large language models may wrongly classify data and skew results.

Combining more traditional innovation metrics (and traditional classifications) with more nuanced data is needed for better strategic analysis of emerging technologies.

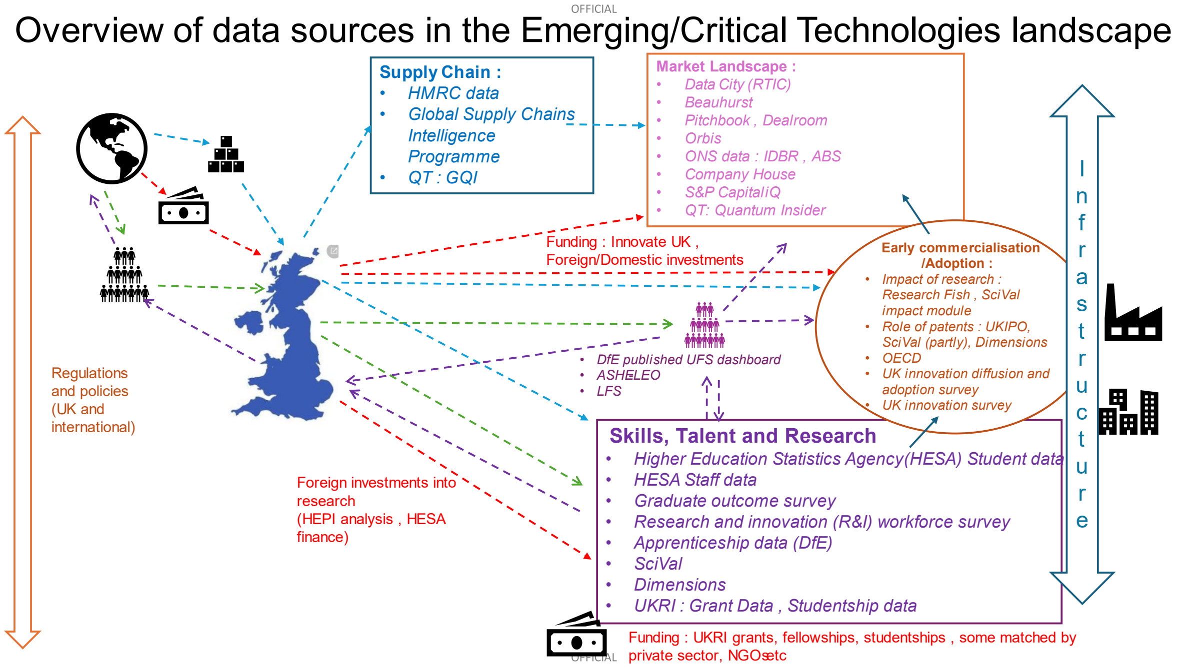


Figure 28 Examples of data sources in the emerging/critical technologies landscape. Source: Ameerudden, 2025.[89]

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[89] Based on analysis of Nafeessah Ameerudden, Lead Analyst for Cross-Cutting Projects for Technologies Policy, DSIT (2025).

BOX 3: Example metrics used for innovation input, output and outcome

Innovation input:

- R&D expenditure by sector, funder, performer, R&D stage, industry, technology
- R&D intensity (e.g., gross domestic expenditure on R&D as share of GDP)
- VC capital investment by company size, technology
- Number of companies by type (spin-offs, etc.), size, technology, industry
- Number of researchers by subject, industry
- Number of graduates by level, subject
- Spending on education by level, subject

Innovation output (for more details see Task D):

- Published academic articles by field/ technology, organisation, country
- Granted patents by technology, awardee type, organisation, country
- Number of companies by innovation measures (e.g., introduced new product/ process/ organisational innovations/ patents)

Innovation outcome:

- Export shares by industry (especially medium and high-technology products and knowledge-intensive services), country, region
- Gross value-added shares by industry (especially medium and high-technology products and knowledge-intensive services), country, region
- Employment shares by industry (especially medium and high-technology products

Task D. Bibliometric and patent analysis

Bibliometric and patent analysis are commonly used as performance metrics for ‘science’ and ‘technology’, respectively. Journal articles can be thought of as representing early-TRLs (1-3) and patents representing applied research, development and demonstration around mid-TRLs (4-6).[90]

The advantage of these approaches is that they rely on large datasets (in some cases freely available), which enable analysing science and technology trends. The available **datasets use own or standardized sets of classifications**, which include categories such as scientific discipline, technology (e.g., Nanoscience & Nanotechnology Category of Web of Science, one of the commercial databases of journal articles), journal names, or patent classifications (e.g., Cooperative Patent Classification, International Patent Classification). They also collect data

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[90] Schmoch (2007). Double-boom cycles and the comeback of science-push and market-pull.

on applicants, grantees, type of actor, publication date, patent granting date, sponsoring institution, etc. and enable searching titles, abstracts and main content of journal articles and patents. These are useful to better understand which actors are active in research and patenting.

In addition to available classifications, own search terms can be specified for querying these datasets. This can serve as a good starting point for emerging technologies for which classifications in these databases often do not exist yet. Furthermore, this feature enables **querying other key terms that may be of interest**. For example, where in the lifecycle of technology X are we currently at (e.g., queried through TRL, MRL, SRL-related keywords or simply comparing basic science and research with engineering science and research)? What are some manufacturing challenges that we are facing for technology X (e.g., queried through related keywords such as scaling-up, scale-up, reproducibility, low volume production, mid volume production, etc.)? Do we know anything about the supply chain (e.g., queried through technology keyword, but analysed based on patent grantees such as companies and universities)? While this may require technical expertise, key terms and definitions identified in Step 1 and Step 2 would be encouraged to use here.

Keywords selection is important as it determines the data quality and coverage. For example, a study shows that the 'Nanoscience & Nanotechnology Category of Web of Science' vs. keyword search of 'nano*' vs. detailed keyword for nanoscience and nanotechnologies identified very different numbers of journal articles: 0.5 million, 1.5 million and 2.3 million journal articles, respectively.[91]

Along with techniques such as text mining, machine learning, natural language processing and network analysis, bibliometric and patent analysis can answer a variety of questions. This includes concept extraction (identifying topics, summarizing topics and their evolution), future trends analysis (technology forecasting, horizon scanning, technology monitoring), relationship analysis (collaboration patterns, co-citation network, co-word networks, etc.).

Briefly a bibliometric or patent analysis can consist of the following steps, with the first step probably being the most important:

1. **Select keywords and technological domains**. Choose relevant keywords, science/technology classifications, and time periods. These should be similar for both bibliometric and patent analyses – with results of one exercise feeding into the other. While this may require technical expertise, key terms and definitions identified in Step 1 and Step 2 could be extremely useful here.
2. **Choose databases**. Select appropriate bibliometric databases (e.g., Web of Science, Scopus, Open Alex) and patent databases (e.g., USPTO, EPO, WIPO, UK IPO) for data collection**.**

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[91] Wang et al. (2019). Updating a search strategy to track emerging nanotechnologies.

3. **Extract relevant data**. For bibliometric analysis this could include article name, abstract, authors, authors' affiliations, geographical location, funding source, etc. For patent analysis this could include patent granting year, name, abstract, content, if possible, applicant name, applicant type, sponsoring institution, geographic location.
4. **Ensure the data is clean and standardized**, removing duplicates and normalizing names of authors, institutions, and patent assignees, etc.
5. **Analyse trends over time and key actors, use artificial intelligence methods to extract further information, and/or network analysis to understand relationships.**

Task E. Descriptive statistics of firms as a proxy for industrial capabilities

The most common way to assess national capabilities is by analysing firm, product and service or project data. As these are often based on standard industry classifications that cannot fully capture the emergence of technologies or industries, new methods are being explored. New commercial datasets relying on web scraping, machine learning, and natural language processing software are being used to classify companies using real-time classifications, as also described below (and in Use Case 8), but these models are still in development and require careful oversight.

Some of the key UK data sources available are presented in Figure 28 – a couple of examples include:

- Inter-Departmental Business Register (IDBR) dataset of business sites
- HM Revenue & Customs data of firms
- UKRI grants dataset of funded projects, including specific funding calls such as the UK Quantum Technologies Challenge Fund that regularly publishes a directory of quantum companies funded[92]
- Commercial datasets (e.g., PitchBook, Orbis)
- International datasets on inward and outward investment flows (e.g., FDI Markets)
- But also press releases, news, internal reports, blogs

The effectiveness of this approach depends heavily on data availability and the classifications used. Traditional classifications, such as Standard Industry Classifications (SIC codes), do not adequately capture the emerging, dynamic, and complex nature of industrial capabilities or address specific policy concerns. Therefore, these classifications are often used as rough proxies for assessing industrial performance. This issue is especially relevant for emerging industries, where limited data and evolving classifications can make accurate analysis difficult, particularly in the early stages of industry development.

More recent methods include the use of commercial datasets that rely on web scraping, machine learning and natural language processing which enable companies to be grouped

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[92] UKRI (2024). Quantum technology projects brochure.

according to real-time classifications. However, the commercial tools available for this are still in early stages, and the resulting data often **requires manual verification** since large language models can misclassify information, leading to under- or overestimating industrial capabilities.

The most common metrics used to evaluate industrial capabilities are the number and type of companies, number of employees, revenue, investment size, company size, etc. – by different industry or product/service classification. Export and import data are also often used to understand which products and services are key.

Use Case 8 exemplifies evidence gathering and analysis of industrial capabilities in engineering biology, underpinning the government's *National Vision for Engineering Biology*.[93] It makes use of several databases also exploring real-time company classifications as a potentially useful tool to analyse emerging technologies.

There are however several limitations that need to be considered and minimized when possible:

- Technology and industry taxonomy/groups/classification can vary significantly across departments, funding agencies with different priorities, but also across countries (non-English terms), stages of analysis (bibliometric, patent, firm analysis), and stages of emerging technology development. Steps 1 and 2 aim to deal with this limitation as well as with the carrying over of terms across different stages of analysis, adjusting them where possible (e.g., going from scientific fields through technology keywords to products and services).
- Data, for example, on exports and imports (and product codes) is often self-reported by companies. This could include misreporting, leading to over and under-reporting – whether that is intentionally or unintentionally.
- Real-time classifications of companies relying on web-scraping and machine learning may include or exclude companies that are important. This could happen when company websites are not suitable for web scraping, they do not provide enough information or have no online presence. But also, when keywords based on which companies are classified are not relevant.

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[93] DSIT (2023). National Vision for Engineering Biology.

Step 5. The role of government

a. Explore the role of government in addressing capability and resource needs

The role of government in emerging technology development and commercialisation is inevitable. Steps 2, 3 and 4 (or other analytical exercises with similar goals) should provide a more detailed context of key capability requirements and hints at which of these need to be addressed by the government.

Literature on innovation policy suggests that the role of government can extend beyond correcting 'traditional' market failures such as information asymmetries and knowledge spillovers.[94] There are structural system and transformational system failures, which if addressed, help to shape the capacity of innovation actors to adapt, learn, and collaborate over time with a clearer sense of direction, demand, and opportunities for experimentation. While these 'other classes' of failures are essentially market failures also, they come from different literatures to more traditional market failures, from more recent understanding of innovation systems and transformative change literature.

The ***checklist of failures (or needs)*** in Figure 29 provides an initial framework for identifying when and where policy interventions may be needed. The failures highlighted in orange were also identified as crucial for emerging technologies during interviews.

Methodology in more detail:

As presented in Steps 1, 2, 3 and 4, understanding the technology of interest, key technology pathways to sectoral applications, barriers and opportunities, and actors in more detail will significantly contribute and help uncover the role of government. **Identified needs and failures can be converted into more structured and hierarchical lists, where trade-offs, impact and the public/private nature of these needs have to be assessed to uncover the role of the government.**

1. **Use the provided checklist of failures for an initial round of structuring** and thinking about needs and failures emerging from previous analyses. Create hierarchical sub-lists if failures include several sub-categories.
2. **Prioritise failure types**: Not all failures are equally important, and prior analysis should help highlight those that are more relevant (often repeated frequently). Use criteria like public/private good nature, urgency, risks and benefits, system impact including cross-sectoral/technology impact, short-medium-long-term implications, policy alignment, etc. to prioritise where government effort is most needed.

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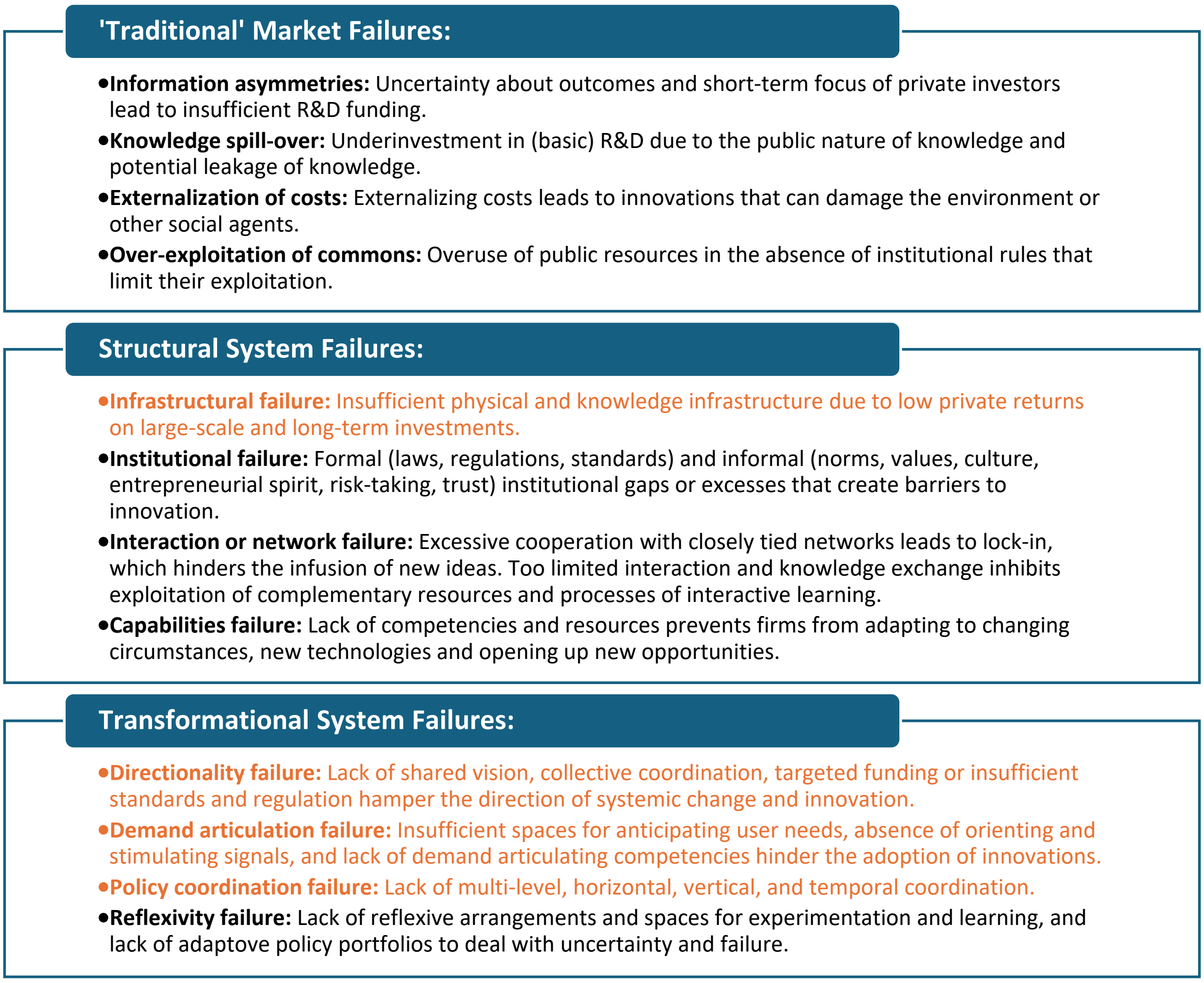
[94] For example: Weber & Rohracher (2012). Legitimizing research, technology and innovation policies for transformative change.; BIS (2014). The case for public support of innovation.; Smith (2000). Innovation as a systemic phenomenon: Rethinking the role of policy.; Mazzucato (2011). The entrepreneurial state.

3. **Analyse interdependencies**: Many failures are interconnected, where addressing the more superficial failure may overshadow more serious issues. It is therefore important to consider their interdependencies.
4. **Further expert consultations or stakeholder workshops** can help to prioritise failures based on such criteria and identify interdependencies.
5. **Assess feasibility of policy levers**: Not all gaps can be addressed by direct funding or tax credits. Some require soft coordination, regulatory reforms, or capability-building initiatives among others.
6. **Incorporate timing and sequencing**: Some interventions are needed early (e.g., demand articulation), while others (e.g., reflexivity) support long-term adaptation.



'Traditional' Market Failures:

- **Information asymmetries:** Uncertainty about outcomes and short-term focus of private investors lead to insufficient R&D funding.
- **Knowledge spill-over:** Underinvestment in (basic) R&D due to the public nature of knowledge and potential leakage of knowledge.
- **Externalization of costs:** Externalizing costs leads to innovations that can damage the environment or other social agents.
- **Over-exploitation of commons:** Overuse of public resources in the absence of institutional rules that limit their exploitation.

Structural System Failures:

- **Infrastructural failure:** Insufficient physical and knowledge infrastructure due to low private returns on large-scale and long-term investments.
- **Institutional failure:** Formal (laws, regulations, standards) and informal (norms, values, culture, entrepreneurial spirit, risk-taking, trust) institutional gaps or excesses that create barriers to innovation.
- **Interaction or network failure:** Excessive cooperation with closely tied networks leads to lock-in, which hinders the infusion of new ideas. Too limited interaction and knowledge exchange inhibits exploitation of complementary resources and processes of interactive learning.
- **Capabilities failure:** Lack of competencies and resources prevents firms from adapting to changing circumstances, new technologies and opening up new opportunities.

Transformational System Failures:

- **Directionality failure:** Lack of shared vision, collective coordination, targeted funding or insufficient standards and regulation hamper the direction of systemic change and innovation.
- **Demand articulation failure:** Insufficient spaces for anticipating user needs, absence of orienting and stimulating signals, and lack of demand articulating competencies hinder the adoption of innovations.
- **Policy coordination failure:** Lack of multi-level, horizontal, vertical, and temporal coordination.
- **Reflexivity failure:** Lack of reflexive arrangements and spaces for experimentation and learning, and lack of adaptove policy portfolios to deal with uncertainty and failure.

Figure 29 Innovation system frameworks underline that the role of government goes beyond market failures. The 'failures' highlighted in orange were identified as crucial for emerging technologies during interviews. Source: Weber & Rohracher, 2012; BIS, 2014.

Step 6. International benchmarking

Each step of the emerging technology strategy process requires understanding whether data and evidence is universal globally (e.g., Steps 1-3 are most likely not to be country-specific) or whether it is country-specific (e.g., Steps 4-5 are most likely to be country-specific). Nevertheless, each step of the process requires consideration for both the domestic and the international context to ensure relevance, comparability and strategic positioning.

a. Benchmark internationally in each step, if not possible, undertake as a separate step here

Wherever possible, international benchmarking should be integrated throughout the process. If this is not feasible due to timing, resources, or availability of data, it can be consolidated into a dedicated benchmarking step at the end of the process.

The goal is to assess relative strengths, weaknesses, and positioning in a given emerging technology family, in comparison to international peers and frontrunners. To be useful, international benchmarking should go beyond high-level metrics and examine the emerging technology family at a sufficient level of detail. Specifically, it should explore:

- **Technology definitions and classifications:** How do other countries define the emerging technology family and classify its sub-categories?
- **Strategic focus areas:** Which use cases, applications, or sub-categories are other countries prioritising?
- **Key barriers and opportunities:** What barriers and opportunities for development and commercialisation have other countries identified and addressed?
- **Capabilities and resources:** What capabilities and resources do other countries see as critical and how do they plan to supply these?
- **Actor landscapes:** Who are the current and potential key actors with these capabilities and resources?
- **Policy and programme responses:** What strategies, policies or programmes are being used — and what lessons can be drawn?

b. Take advantage of international analysis already available

As suggested in the introduction of Section 3, for each step, scanning the international landscape can help to understand whether there is already existing evidence and analysis that can be used (e.g., technology definitions, technology classifications, technology roadmaps, etc.), specially produced by countries that are at a more advanced stage of strategic analysis. In many cases, significant efforts into evidence gathering have already been undertaken, lowering time and financial costs. Especially Steps 1-3 may benefit from non-country specific evidence, while Step 4-5 may benefit from the knowledge of policymakers undertaking significant consultation with key stakeholders.

Methodology in more detail:

1. **Create a shortlist of comparator countries or regions based on technological relevance, strategic positioning, or policy maturity.**
2. **Use publicly available databases** (e.g., OECD STIP Compass, EU Joint Research Centre's database, Overton) to initially collect consistent policy data.
3. **Conduct document analysis** of strategy documents, programme evaluations, roadmaps, etc. using predefined analytical lenses (e.g., technology classifications, opportunities and barriers, capabilities, actors). Explore key policies and programmes, funding amounts, key institutions and their activities, news, press releases, but also different datasets and evidence already gathered. Benchmark not only static policies but also governance models, institutional roles, and learning processes.
4. **Interview international experts (e.g., policymakers, analysts, academics) for up-to-date, nuanced insights or hold online workshops.**
5. **Compare findings using visual tools to support interpretation and communication.**

4 Case studies on evidence and strategic analysis for policy: Quantum technology and engineering biology in the UK

This section explores the role of evidence and strategic analysis in shaping UK's policies and strategies for emerging technologies. It specifically focuses on quantum technology and engineering biology as a case study, as both have received significant government attention and support over the past decade due to their potential to strengthen the UK's competitive advantage.

By reviewing historically used evidence and analysis across selected policy decisions for the two emerging technologies, as well as gathering insights from relevant policy makers and external experts through interviews, this section aims to shed light on the lessons learned and effective practices for emerging technology evidence and analysis and how this links to decision-making processes (and potentially programme design, implementation, etc.). It also examines the gaps in evidence, overlooked perspectives, and areas for improvement in the analytical approaches used to shape these policies.

The case studies track the UK's efforts alongside global developments; to assess how evidence-based analysis can inform better policy decisions. The type of evidence and analytical tools that underpin the emerging technology policy choices are tested against the key frameworks introduced in Section 2 as they are expected to enable more systematic analysis of the complex emerging technology landscapes. A repository of strategy documents and supporting evidence documents/ reports is provided in Appendix A. This serves as an initial resource for a living document that captures previous efforts.

4.1 UK's quantum technology policy: Evidence gathering and strategic analysis

The next section introduces the timeline of events related to quantum technology policy with a specific focus on the UK and then moves onto analysing the evidence and analysis that was historically used to underpin two of its key quantum technology strategies.

The UK's leadership in quantum technologies stems from early academic advocacy—most notably that of Sir Peter Knight—and early support from government departments such as EPSRC, TSB (now Innovate UK), Dstl, GCHQ, and NPL, especially in relation to security-related opportunities and risks.[95] A meeting in 2013 at Chicheley Hall, organized by Dstl and the Royal Society, catalysed development of the *UK Quantum Technology Landscape* report,[96] which outlined key technologies, capabilities, and infrastructure needs, as the initial evidence base for the UK.

Quantum technologies gained political traction with their inclusion in the *2013 Autumn Statement*,[97] and in the *Eight Great Technologies* strategy,[98] followed by a £270 million commitment. Around this time, the Quantum Technology Strategic Advisory Board (QT SAB) was established to coordinate UK efforts in quantum technologies. It brought together representatives from academia, industry, and government under the leadership of former EPSRC Chief Executive David Delpy.[99] In 2014, QT SAB launched the *UK National Quantum Technology Programme (NQTP)*[100] with the initial £270 million investment over five years.

As part of *NQTP*, four university-led Quantum Technology Hubs were funded based on a competitive peer review process,[101] operating in communications, sensing, imaging, and computing. The second phase of *NQTP,* running from 2019 to 2024, added £94 million to expand the hubs' remit and established additional centres of excellence such as the Quantum Metrology Institute (QMI), the National Quantum Computing Centre (NQCC), and the Fraunhofer Centre for Applied Photonics (CAP).

NQTP also laid the groundwork for commercial innovation through the *Commercialisation of Quantum Technologies Challenge under the Industrial Strategy Challenge Fund (ISCF).* This included competitive grants (feasibility studies, R&D, germinator, and investment accelerator)

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[95] Engineering and Physical Sciences Research Council (EPSRC), Technology Strategy Board (TSB) now Innovate UK (IUK) under UK Research & Innovation (UKRI), National Physical Laboratory (NPL), Defence Science and Technology Laboratory (Dstl) under the Ministry of Defence (MoD), Government Communications Headquarters (GCHQ)

[96] Dstl (2014). UK Quantum Technology Landscape 2014.

[97] HMT (2013). Autumn Statement 2013.

[98] BIS (2013). Eight Great Technologies: Speech.

[99] Today, the NQTP Board is the one which coordinates across NQTP organisations, while the NQTP SAB serves as an external expert group, chaired by Sir Peter Knight, with industry and academic representatives. NQTP (n.d.). Governance.

[100] NQTP (n.d.). UK National Quantum Technology Programme.

[101] UKRI (2020). Strategic Intent.

and industry-led pilots, ultimately attracting nearly £700 million in private investment[102] and funding 139 projects.

Strategic planning efforts included the 2015 *National Strategy for Quantum Technologies*[103] and *Roadmap*[104], which emphasized strong capability foundations, workforce development, market readiness, creating the right regulatory context, and international engagement.

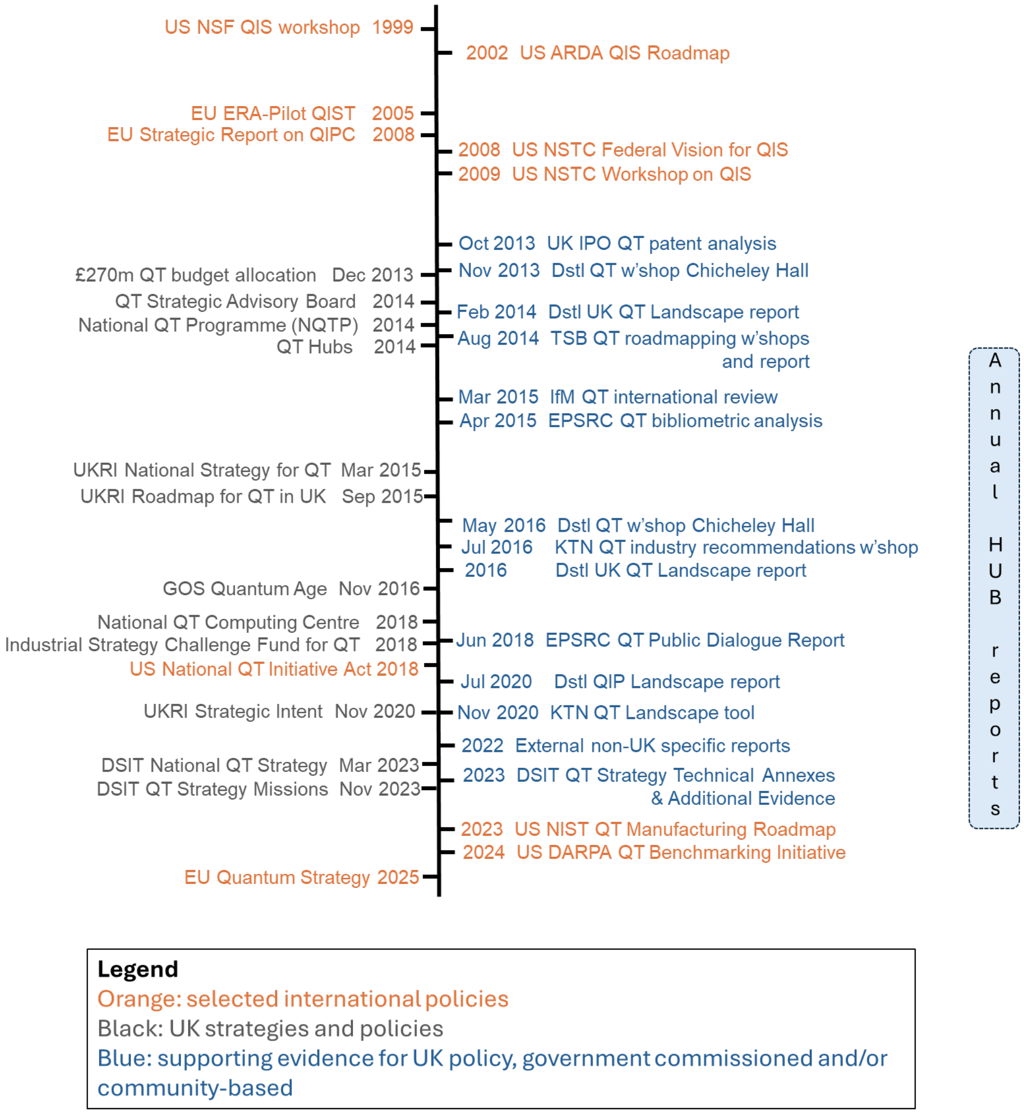

Figure 30 Timeline of selected key quantum technology policies and evidence base.[105] *Source: NETS Handbook Project Team.*

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[102] UKRI (2024). UK Quantum Technologies Challenge Directory.

[103] UKRI (2015). National strategy for quantum technologies: A new era for the UK.

[104] UKRI (2015). A roadmap for quantum technologies in the UK.

[105] National Science Foundation (NSF), Advanced Research and Development Activity Agency (ARDA), European Research Area (ERA), quantum information science/technology (QIS/T), quantum information processing and communication (QIPC), National Science and Technology Council (NSTC), Intellectual Property Office (IPO),

In 2023, the UK launched a new *UK National Quantum Strategy.* [106] This strategy, now managed by the newly formed Office for Quantum at DSIT, outlines 13 priority actions and five missions to be achieved by 2035. It focuses on commercialization, procurement mechanisms, infrastructure development, and real-world applications, positioning the UK as a global quantum leader.

In 2025, under the UK's Modern Industrial Strategy and its accompanying *Digital and Technologies Sector Plan,*[107] an investment of £670 million was announced to accelerate the impact of quantum computers from energy to healthcare. For more details on key events and perceived success factors and opportunities in UK quantum technology policy see Appendix B.

The timeline of key strategies, decisions and underpinning evidence is also presented in Figure 30 with a repository of documents and reports in Appendix A. The next section focuses on understanding the evidence and analysis that was used to underpin the two key strategies: the 2015 Strategy and the most recent 2023 Strategy.

4.1.1 *National Strategy for Quantum Technologies* (2015)

Quantum technologies appeared prominently in UK policy making for the first time in the *Autumn Statement of 2013* as a 'cutting-edge technology'.[108] In December 2013, a budget of £270 million was allocated over 5 years for developing Quantum Technology Hubs and supporting the translation of the UK's world leading quantum research into application. This came at a time when the UK has just launched its *Eight Great Technologies strategy*, [109] an effort led by the then UK Science Minister David Willets in 2012.

Following the setting up of the QT Strategic Advisory Board (QT SAB), it developed the first *UK National Strategy for Quantum Technologies* in 2015. [110] This was shortly followed by a *Roadmap for Quantum Technologies in the UK document*[111] with an aim to understand near-, mid- and longer-term potential for commercial application of quantum technologies.

While several important QT evidence-gathering initiatives were launched around the time the 2015 Strategy was published, the way they were sequenced and how they informed one another was not clearly defined.

Engineering and Physical Sciences Research Council (EPSRC), quantum technology (QT), Defence Science and Technology Laboratory (Dstl), Knowledge Transfer Network (KTN), Department for Science, Innovation and Technology (DSIT), UK Research and Innovation (UKRI), National Institute of Standards and Technology (NIST)

[106] DSIT (2023). National Quantum Strategy.

[107] DBT & DSIT (2025). Digital and Technologies Sector Plan.

[108] HMT (2013). Autumn Statement 2013.

[109] BIS (2013). Eight Great Technologies: Speech.

[110] UKRI (2015). National strategy for quantum technologies: A new era for the UK.

[111] UKRI (2015). A roadmap for quantum technologies in the UK.

Key evidence includes:

- In-depth roadmap[112] for quantum technologies in the UK based on two expert roadmapping workshops[113] held by TSB with representatives from industry, academia and the government as an addendum to main document. Collected data on QT trends/drivers, stakeholder perspectives, opportunities/applications areas, capabilities and enablers.
- Brief estimates on future market potential, e.g., semiconductor industry, oil and gas industry
- Possibly insights from Dstl and the Royal Society-organized meeting of key academics, industry representatives and government departments at Chicheley Hall exploring the UK's initial strategy and potential to exploit emerging quantum technologies. This led to the development of an initial evidence base in the form of a comprehensive *UK Quantum Technology Landscape document* published in February 2014.[114]
- Possibly patent analysis by UK IPO
- Possibly international review by the Institute for Manufacturing
- Possibly bibliometric analysis by EPSRC

Strengths in evidence and strategic analysis:

- **Several significant QT evidence-gathering exercises were commissioned** around the time of the publishing of the *2015 Strategy,* including bibliometric analysis, patent analysis, international review, roadmapping workshops. Bibliometric analysis helped map research activity and scientific output in the field, identifying areas of strength and international standing. Patent analysis shed light on commercial activity, innovation hotspots, and trends in intellectual property related to QT. An international review offered comparisons with other leading countries, informing where the UK could lead or where gaps existed. Roadmapping workshops provided qualitative insights from experts about potential technology trajectories. This variety of evidence if well sequenced and defined could inform strategy early in the lifecycle of an emerging technology.

- **Significant roadmapping activity:** The development of a roadmap was a central feature of the strategy-making process. Initially, in the *2015 Strategy*, a brief roadmap (or timeline) outlined future commercial uses for quantum technologies on a time scale from today to 30 years' time, providing a high-level framework. This was followed by a more detailed roadmap informed by two expert-led workshops, which dove deeper into trends and drivers, stakeholder perspectives, opportunities and

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[112] UKRI (2015). A roadmap for quantum technologies in the UK.

[113] TSB & IfM (2014). Quantum Technology Roadmap Report: Consolidated from Workshops in London and Glasgow.

[114] Dstl (2014). UK Quantum Technology Landscape 2014.

applications areas, capabilities and enablers. This layered approach allowed for iterative and structured refinement of strategic goals and alignment with stakeholder input, facilitating better planning and coordination across the quantum technology ecosystem.

- **Establishing a forum for a community with an interest in quantum science and technologies** leading to a comprehensive assessment of UK's landscape and future opportunities as evidence for a business case (e.g., meeting in Chicheley Hall) and aligned vision for the future (e.g., QT SAB).
- **Acknowledging the variety of technologies** (i.e., technology strata in Section 2.2) that need to be considered for quantum technologies: fabrication, test facilities, demonstrators, system integration (reliability engineering, interoperability, modularity, standardisation). It also highlights that systems integration and components for R&D will be probably key early applications of QT.
- **Focusing on the dimension of time and technology development lifecycles:** Besides roadmapping workshops setting out a short-, mid- and long-term vision beyond 2045, early adopters and early applications were mentioned several times. For example, the strategy (and roadmap more precisely) considers nearest-term commercial opportunities and identifies potential early adopters—such as sectors where QT could deliver value before full-scale commercialisation. This focus helps align current R&D efforts with realistic market opportunities, supporting smoother technology translation and helping attract early investment and engagement from industry.

  "Both workshops identified many potential applications for Quantum Technologies that could be commercialised between 2014 and 2040. In the short term, the priority applications were seen as Components for the R&D community and early adopters; Quantum Clocks for financial and telecoms applications, with secure point-to-point communications based on Quantum Key Distribution. Medium term applications commencing in 2020 and developing through to 2030 included multiple EM and Gravity imaging applications including through-ground imaging for multiple industries; inertial navigation; and second generation components. Longer terms applications focussed on gravity navigation and secure complex communications with interesting possibilities in other areas e.g. quantum computing and direct extraction of electrical power from heat.

  The critical technologies and capabilities identified by participants included those short-term components essential for development of the sector: miniaturised ultra high-vacuum cells and lasers; sub-systems and micro-fabricated devices; sensors and

> *system modules; component integration; design for manufacture and high level systems integration."* [115]

Opportunities in evidence and strategic analysis:

- **Sequencing and feedback:** The evidence gathered could be better sequenced in time in a way that the results of one exercise could inform the other. For example, if definitions are set out up front in an initial taxonomy exercise, this could then feed into keyword searches in bibliometrics, which could then feed into patent analysis, in an iterative fashion.
- **Integrating evidence:** There were several quantum technology analyses and reports developed over time published by a variety of actors. This had consequences for the effectiveness of integrating evidence and analysis into key strategy documents. There is a need to reduce information asymmetries by utilizing and better integrating the evidence base available (e.g., drawing on the comprehensive landscape documents, technical roadmaps and annual reports of the Quantum Technology Hubs[116]). For example, key evidence on UK's key strengths was available in the Dstl UK Quantum Landscape report but its integration into the final document is not visible. This could have enabled a better anchored strategy as opposed to providing a high-level vision only. Repositories (e.g., Appendix A) and overarching documents could help deal with information overflow.
- **Defining scope of strategic analysis:** There is an opportunity to better target strategic analysis by clarifying the scope of the strategic analysis, which can be the highest level of technology classification (e.g., quantum technologies) or any level below (e.g., quantum sensors). This is the boundary object, which serves to define the scope of the analysis as well as to prevent miscommunication.
- **Defining technology subgroups and platform technologies (see Section 3, Step 1):** There is an opportunity to better target strategic analysis by clarifying technology subgroups (beyond quantum technology) and identifying the different core platform technologies with different underpinning science that make up these technology subgroups. This would reveal similarities and differences in terms of required innovation and industrial infrastructure, as well as skills.
- **Systematizing thinking around the varieties of technology** that will be needed for quantum technology R&D and scale-up, as presented in Section 2.2.

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[115] TSB & IfM (2014). Quantum Technology Roadmap Report: Consolidated from Workshops in London and Glasgow.
[116] NQCC (n.d.). National Quantum Computing Centre Technology roadmap.

- **Learning from international competitors early on** could prevent duplication of resources for example if they have already provided suitable definitions or ran technology roadmaps assessing future challenges and opportunities.
- **Strategising for and thinking about supply chains**, especially in a forward-looking manner in the context of building domestic QT supply chains.
- **Market potential and sectoral applications:** Exploring more in-depth the potential impact on other technologies and sectors (e.g. semiconductors) could make a stronger case for an emerging technology.

4.1.2 *National Quantum Strategy* (2023)

In 2023, the *National Quantum Strategy*[117] was published in support of the government's ambitions to make the UK a scientific and technologic superpower.[118] The *Quantum Strategy* details the UK's vision for the next ten years with 13 priority actions, which include R&D, missions and challenges, skills, procurement, infrastructure among others. To support this ambition, DSIT has also established a new Office for Quantum, which has developed the strategy and is now working on its implementation.

The *2023 Quantum Strategy* focuses extensively on commercialization and pulling through quantum technologies through use cases, applications, and missions. It delves into the importance of providing facilities including test beds for quantum computer testing and system integration for use cases but also on developing new application-oriented Quantum Technology Research Hubs and the Quantum Missions.

The Office for Quantum has also published a set of five key missions to be achieved by 2035 under the *National Quantum Strategy Missions* later in 2023.[119] The *Quantum Strategy* furthermore also highlights procurement through Small Business Research Initiative (SBRI), National Security Strategic Investment Fund (NSSIF) and the new catalyst Fund. All the above highlight the importance of pulling science and technology through to market through a variety of mechanisms, which suggests commercialization of quantum science and technology as a key priority for the government.

Key evidence is presented across a number of both internal and external analyses including National Quantum Strategy: Technical Annexes;[120] National Quantum Strategy: Additional Evidence;[121] National Quantum Strategy Missions;[122] UK National Quantum Technologies

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[117] DSIT (2023). National Quantum Strategy.

[118] DSIT (2023). Press release.

[119] DSIT (2023). National Quantum Strategy Missions.

[120] DSIT (2023). National Quantum Strategy: Technical Annexes.

[121] DSIT (2023). National Quantum Strategy: Additional Evidence.

[122] DSIT (2023). National Quantum Strategy Missions.

Programme; and external reports from Oxford Economics, Boston Consulting Group, Ernst and Young, McKinsey, etc.

Key evidence includes:

- Insights from the call for evidence[123]
- Insights from consultations, workshops and discussions
- Insights from the independent Strategic Advisory Board (NQTP SAB) chaired by Sir Peter Knight,[124] and to the Institute of Physics, the Institution of Engineering and Technology, techUK, the Royal Academy of Engineering and UKQuantum
- Insights from the *Quantum Readiness Survey*[125]
- References to domestic programs and policies[126]
- References to domestic ecosystem, including research centres, companies, facilities, clusters (e.g., Scotland Photonics Cluster, Wales Semiconductor Cluster)
- Estimates of future benefits, market potential or revenue[127] [128] [129]
- Estimates of scholarly outputs and field-weighted citation impact using SciVal database using a pre-defined research category for Quantum Technologies within the platform
- Estimates of international patent families and relative specialisation index by UK IPO analysis of PatentSight
- Estimates of private equity investment by tech area (hardware components, software, quantum sensing & imaging, etc.), funding type (series A, B, etc.) with international comparison using Quantum Insider
- Estimates of the number of companies by tech area, employee size, UK regional data with international comparison from using Quantum Insider
- Estimates of UK's market share in quantum technologies - DSIT analysis combining Quantum Insider and ISCF data sets
- Estimates of the number of companies active in the UK QT sector and funded by ISCF Commercialising Quantum Challenges
- Estimates of the number of researchers and top institutes with international comparison from Zeki Research
- Estimates of the number of postgraduate research students using UKRI student data EPSRC fellowships filtering for quantum studentships

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[123] DSIT (2022). UK Quantum Strategy: Call for evidence.
[124] NQTP (n.d.). Governance.
[125] Ernst & Young (2022). Quantum Readiness Survey.
[126] UKRI (n.d.). UK National Quantum Technologies Programme.
[127] Oxford Economics (2025). Ensuring that the UK can capture the benefits of quantum computing.
[128] Boston Consulting Group (2021). What happens when 'if' turns to 'when' in quantum computing?
[129] McKinsey (2021). Shaping the long race in quantum communication and quantum sensing.

- Estimates of the number of countries UK universities are partnering with using EPSRC call on International Networks in Quantum Technology
- Estimates of the number of international links generated from Quantum Technologies for Fundamental Physics (QTFP) funded projects through Science and Technology Facilities Council (STFC)
- Survey of 85 (54 responses) UK companies on importing elements of their supply chain as part of ISCF Challenge’s yearly impact review

Strengths in evidence and strategic analysis:

- **Leadership councils and multi-stakeholder involvement**: The involvement of both the NQTP Board, NQTP SAB and wider community through a call for evidence enabled bringing together stakeholders from government, funding agencies, academia and industry, leading to reaching consensus, assessing progress, updating recommendations, and shaping priorities for future implementation of the *2023 Strategy*.

- **Call for evidence:** The call for evidence demonstrates a commitment to informed policymaking, featuring well-articulated and thoughtfully structured questions that encouraged meaningful input from a diverse range of stakeholders. By seeking evidence in a systematic and transparent manner, the process not only enhanced the depth of analysis but also ensured that multiple perspectives—spanning industry, academia, and policy experts—were considered. This approach reflects best practices in strategic decision-making, reinforcing the importance of robust evidence-gathering from subject matter experts in shaping effective and forward-looking policies for emerging technologies.

- **Involvement of engineering perspectives:** While the call for evidence results and survey respondents are not publicly available, the NQTP SAB and the wider community consulted includes several system integrators, engineering perspectives, etc. Increased involvement of perspectives from manufacturing organisations, engineers, operations managers, technical workforce, EPSRC, etc. ensures that innovations are manufacturable, scalable, and commercially viable. This is particularly important at times when technology and industry lifecycles are more advanced.

- **Significant quantitative evidence base** including investment landscape, research output and impact, patent output, and increasingly the current and potential future economic impact of the technologies. Supervised machine learning combined with expert reviews was used to produce a list of quantum technology companies in the UK, which underpinned several pieces of analysis. This also led to categorisation of quantum technologies into 4 classes.

- **Quantitative evidence for technology subgroups (see Section 3, Step 1):** The estimates for private equity investment was divided by technology area, which to some extent resembles value chain parts and to some extent technology subgroups, as presented in Figure 31. Such detail and even more granular analysis can enable better targeted strategic analysis by clarifying technology scope, technology subgroups, different core platform technologies, similarities and differences in terms of required innovation and industrial infrastructure, skills, and value chain parts.

  > *"Companies in scope for tracking: sell hardware that are used in quantum computers and quantum devices; provide software that helps make quantum computers usable or useful; develop quantum computers (QPUs, chips, full stack offerings); provide hardware and software aimed at addressing quantum security and post quantum cryptography; provide quantum sensing and imagine technology; or, are involved in other parts of the quantum technology supply chain (e.g. Consultancy). Quantum Insider get their investment data for these companies by searching through publicly available sources and collating this for each company."* [130]

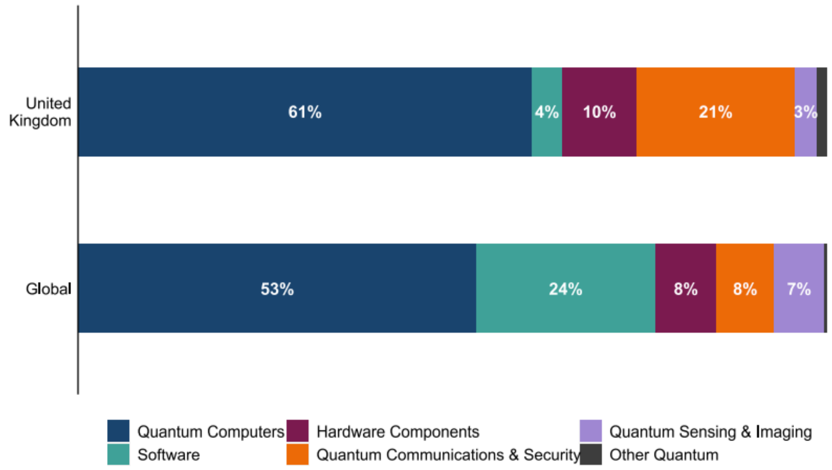

Figure 31 Proportion of total private equity investment by technology area globally and in the UK for the period 2012-2022. Source: DSIT, 2023.

- **Supply chain questions posed to companies** are a useful way to assess domestic supply chain challenges, risks and opportunities. While significant amount of work has been undertaken internally within DSIT, access to high quality firm-level trade data is crucial for assessing potential supply chain vulnerabilities.

- **Account of domestic ecosystem**, including research centres, facilities, companies and their sizes, clusters, etc. can help business investment decisions. Such internal data as

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[130] DSIT (2023). National Quantum Strategy: Additional Evidence.

also presented through the Quantum Landscape tool[131] could be systematized and presented in a coherent narrative, an updated comprehensive landscape document.

- **Narratives provided in terms of potential future applications and reasons for investment and support.**
- **Initiatives that focus on metrology tools and standards and system integrators** - e.g., the establishing of Advanced Quantum Metrology Laboratory (AQML) at NPL, which already has the existing Quantum Metrology Institute (QMI), or the continued support of the National Quantum Computing Centre (NQCC).
- **Acknowledging convergence of various technologies** (semiconductors, AI, high performance computing, cloud computing) – however understanding the links between adjacent technologies and sectors could be more systematized.

Opportunities in evidence and strategic analysis:

- **Defining scope of strategic analysis, technology subgroups and platform technologies (see Section 3, Step 1):** Since the publishing of the *Strategy*, internal analysis within DSIT and GO-Science focused on defining quantum technologies, its technology subgroups, underpinning platform technologies, cross-cutting infrastructure needs, etc. Having such understanding and definitions early on could significantly improve strategic analysis during strategy development, not just at implementation stage. Providing definitions and making use of systematic frameworks could mitigate the risk of conflating important groups and missing interdependencies. This could also avoid inconsistency and miscommunication when evidence is gathered from several sources and several stakeholders with diverse priorities are involved.
- **Integration and sequencing of analysis as presented in point above.**
- **Focusing on the dimension of time and technology development lifecycles:** More systematic and structured methods could be used to enable forward-looking strategy that anticipates challenges and opportunities, such as roadmapping (see Section 3, Step 2). This is especially important at more advanced stages of technology development. This would also enable connecting research strengths and funding calls with missions and applications to identify technology pathways to commercialization – enabling the identification of barriers along the way. This could also include thinking about lifecycles (see Section 2.5) and where different quantum technologies are with regards to technology development.

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[131] KTN (2020). Quantum Landscape tool.

- **Integrating earlier evidence:** In the case of quantum technologies, significant earlier work was undertaken on roadmapping. There is an opportunity to continue with this type of exercise, significantly drawing on earlier evidence and tacit knowledge.
- **International policy strategies**: Understanding international developments especially current policies, funding, and activities, could enable a better assessment of where other countries are at and where investments are flowing. This may also prevent duplication of efforts but also allow for a more thorough assessment of planned efforts (including collaborations etc.).
- **International benchmarking:** Understanding domestic innovation and industrial strengths in comparison to international peers could enable better understanding of comparative advantage and thus more targeted interventions.
- **Acknowledging and systematically analysing convergence and links between adjacent technologies could potentially lead to identifying overlaps** – i.e., these could highlight where most support is needed and where most opportunities lie.

4.2 UK's engineering biology policy: Evidence gathering and strategic analysis

The next section briefly introduces the timeline of events related to engineering biology[132] policy in the UK and then moves onto analysing the evidence and analysis used to underpin two key UK policy decisions.

In 2009, the Royal Academy of Engineering published a report identifying synthetic biology as an emerging and enabling technology with the potential to deliver cross-sector solutions in areas such as healthcare, chemicals, agritech, and advanced materials. [133] In 2013, the UK government committed a £126 million investment through the *Synthetic Biology for Growth Programme*[134] and named synthetic biology as one of the *Eight Great Technologies*.[135]

Over the last decade, the UK has made substantial progress in developing its synthetic biology landscape. More than £300 million in public funding was invested to strengthen research capacity, leading to the creation of six Synthetic Biology Research Centres, five DNA synthesis facilities (i.e. today six biofoundries), several doctoral training centres, a dedicated Innovation and Knowledge Centre at SynbiCITE[136] and seed funding for innovative companies.

This momentum was further supported by the publication of strategic documents, including the 2012 *Synthetic Biology Roadmap*[137] and the 2016 *Biodesign for the Bioeconomy*,[138] both of which attempted to focus turning the UK's scientific strengths in synthetic biology into commercial and societal outcomes. The decade also saw the formation of over 150 start-ups and spinouts, underscoring the field's growing entrepreneurial impact. A dynamic community began to take shape through initiatives like Innovate UK Business Connect's Synthetic Biology Special Interest Group.[139]

In 2011, the UK Government established the Synthetic Biology Leadership Council (SBLC) – later renamed to the Engineering Biology Leadership Council (EBLC) – consisting of researchers and business experts to provide an independent steering structure to assess progress and update recommendations and shape priorities for future implementation of the synthetic biology roadmap for the UK. SBLC/EBLC also provided strategic coordination across funding agencies, academia, government departments, and other stakeholders, including societal and ethical representatives.[140]

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[132] Synthetic biology and engineering biology are used interchangeably.
[133] RAEng (2009). Synthetic Biology: Scope, applications and implications.
[134] UKRI (2025). Synthetic Biology for Growth.
[135] BIS (2013). Eight Great Technologies: Speech.
[136] http://www.synbicite.com/
[137] TSB (2012). A Strategic Roadmap for Synthetic Biology in the UK. (Roadmap available in original document).
[138] SBLC (2016). Biodesign for the Bioeconomy.
[139] Innovate UK Business Connect (n.d.). Engineering Biology Leadership Council.
[140] Ibid.

SBLC/EBLC was recently replaced with the governmental Engineering Biology Steering Group (EBSG), which was renamed the Engineering Biology Advisory Panel (EBAP)[141] set up to advise the government on the development and delivery of the *National Vision for Engineering Biology*.[142] The strategy document was published in 2023, accompanied by £100m of public investment in 2024.

The timeline of key strategies and underpinning evidence is presented in Figure 32 with a repository of references in Appendix A. The next section focuses on understanding the evidence and analysis used to underpin two policy decisions: the 2013 investment into synthetic biology and the most recent *National Vision for Engineering Biology*.

Figure 32 Timeline of engineering biology documents and underpinning evidence. Source: Adapted from SBLC, 2020.

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[141] GOV.UK (n.d.). Engineering Biology Steering Group.
[142] DSIT (2023). National Vision for Engineering Biology.

4.2.1 Synthetic biology as one of the *Eight Great Technologies* (2013)

The UK government's strategic commitment to synthetic biology was solidified in 2013 when it announced a £126 million investment in the *Synthetic Biology for Growth Programme*. [143] Synthetic biology was also officially recognized as one of the *Eight Great Technologies*[144] in which the UK aimed to become a world leader.

The *Programme* consisted of four streams of investment:

- Multidisciplinary Synthetic Biology Research Centres
- DNA synthesis
- Better training for students
- Synthetic Biology Seed Fund

A significant portion of the funding announcements came directly from the then-Science Minister David Willetts, who underscored the importance of the 2012 *Synthetic Biology Roadmap*[145] in shaping public policy. His speech in July 2013 further reinforced this position, as he stated, "the roadmap has been an invaluable guide to public policy since it was produced." This acknowledgment highlighted the government's emphasis on evidence-based decision-making and strategic foresight in shaping the UK's synthetic biology sector.[146] The Synthetic Biology Leadership Council (SBLC) established in 2011 played a crucial role in developing the *Roadmap* and providing evidence.

Key evidence includes:

- The Royal Academy of Engineering Report 2009[147]
- A Synthetic Biology Roadmap for the UK 2012[148]
- Two workshops attended by more than 70 representatives from industry, public bodies, academia and other organisations
- Insights from the independent SBLC, which consisted of researchers, industry experts, funders, government organisations, and ethical and societal representatives
- References to international literature, conferences, symposiums, including references to papers which consider UK's publication output relative to other countries
- References to estimates of current and future market value of synthetic biology (globally, in the US, in the EU). Including Boston Consulting Group's estimate of market growth from US$1.6 billion in 2011 to US$10.8 billion by 2016

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[143] UKRI (2025). Synthetic Biology for Growth.
[144] BIS (2013). Eight Great Technologies: Speech.
[145] TSB (2012). A Strategic Roadmap for Synthetic Biology in the UK. (Roadmap available in original document).
[146] Marris, C. & Calvert, J. (2020). Science and Technology Studies in policy: The UK Synthetic Biology Roadmap.
[147] RAEng (2009). Synthetic Biology: Scope, applications and implications.
[148] TSB (2012). A Strategic Roadmap for Synthetic Biology in the UK. (Roadmap available in original document).

- Timeline of key synthetic biology funding activities and policy activities in the UK, as well as international collaborations
- References to relevant sectoral estimates and their importance for the UK (e.g., foreign direct investment volumes, number of jobs, contribution to GDP of the chemical, pharmaceutical, energy industries)
- References to international regulations and standards, as well as international cooperation, links to international policy and funding bodies
- Insights from the Synthetic Biology Dialogue[149]

Strengths in evidence and strategic analysis:

- **Scope of strategic analysis defined building on earlier work:** Synthetic biology was explicitly defined in the *2012 Roadmap*, adapted from the *2009 RAEng study*, [150] providing clarity for the strategic analysis, recommendations, roadmapping exercise and policy decisions.

> "Synthetic biology is the design and engineering of biologically based parts, novel devices and systems as well as the redesign of existing, natural biological systems. It has the potential to deliver important new applications and improve existing industrial processes – resulting in economic growth and job creation."

- **Roadmapping activity in early stages of both technology and policy development**: The development of the *2012 Roadmap* brought together key stakeholders, fostering long-term strategic thinking towards application sectors and thus alignment across sectors early on in policy developments. This has contributed to creating a community of interest, a shared vision, identification of key challenges across stages of technology development, in an integrated manner.

> *"This roadmap takes a holistic view of the innovation process, to anticipate issues and facilitate progression of applications and services towards the ultimate goal of realising a clear vision for a UK synthetic biology sector."*

> *"The process of generating the roadmap is itself an integral part of opening up stakeholder discussion, seeking consensus and starting the process of building an informed, energised and effectively supported UK-wide community."*

> *"The workshops considered the roadmap landscape as a whole, across a range of timeframes, stretching out towards a post 2030 vision. This was populated in detail from both a 'top-down' perspective, considering trends and drivers, and a 'bottom-up'*

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[149] BBSRC & EPSRC (2010). Synthetic Biology Dialogue.

[150] RAEng (2009). Synthetic Biology: Scope, applications and implications.

> *perspective, considering enablers, capabilities and technology, leading to consideration of value-creation opportunities and value-chain perspectives."*

> *"Important considerations identified in the workshops included the need to be clear what should be the main areas of focus, recognising the need for genuine market pull for products and for selecting key categories in which the UK can excel, and how to accelerate progress – reducing development time to market – acknowledging the essential role of public funding."*

- **Recognising the importance of an integrated approach: Value chain from science to market, and the importance of providing access to critical resources and supportive operating environment through each stage of development.** The *Roadmap* highlights the importance of an integrated approach from a variety of perspectives, not only referring to multi-stakeholder involvement, but also the importance of each stage of technology development, including supporting facilities, demonstrators, networks, collaboration, multidisciplinary funding, regulatory frameworks, skills, etc., as presented in Figure 33.

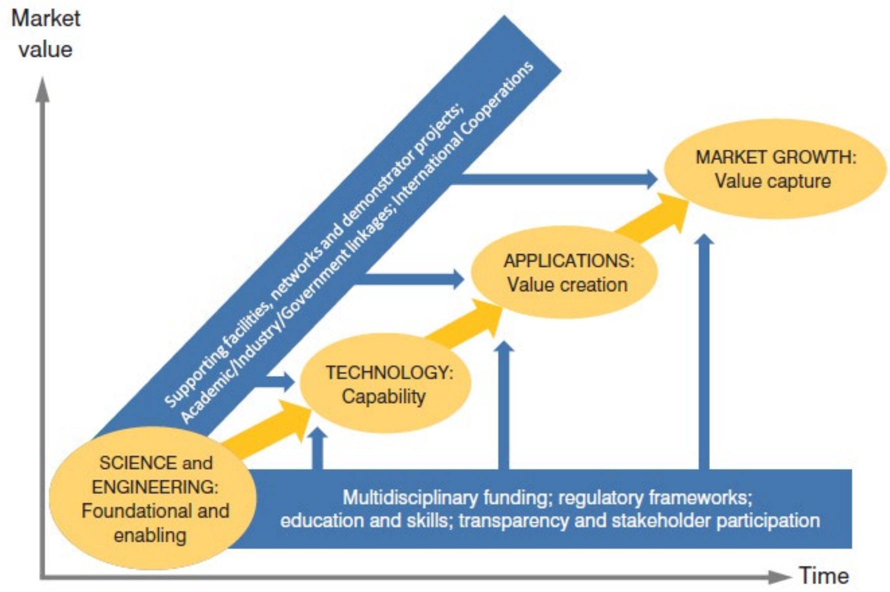

Figure 33 Progression of an idea through to market in synthetic biology as presented in the 2012 UK Synthetic Biology Roadmap. Source: TSB, 2012.

- **Leadership councils and multi-stakeholder involvement**: The establishment of the SBLC in 2011 provided a governing body to bring together stakeholders, reach consensus, assess progress, update recommendations, and shape priorities for future implementation of the *Roadmap*, along which TSB also played a particularly important role.

> *"An essential first stage is the building of a cohesive stakeholder community including academics, industrialists, public and private organisations. Workshops held to date have already begun this process, helping to shape the vision. Energising this growing*

community around the vision, supported as needed through effective resourcing and training, will stimulate the development of applications of significant value.”

“The vision and recommendations for the UK grew out of series of workshops attended by more than 70 people representing a broad range of stakeholders from industry, public bodies, academia and other organisations. It also draws upon the large and rapidly growing body of world literature and the numerous conferences, symposia and discussion forums that have recently focused on synthetic biology. Although specifically a roadmap for the UK, working with international stakeholders remains an essential part of implementing the roadmap (as reflected in our recommendations). We reviewed a number of thematic areas in reaching a set of recommendations, which, if advanced effectively, will establish and grow a successful synthetic biology sector.”

- **Institutional feedback**: The SBLC’s engagement provided valuable insights to policymakers, ensuring that strategic decisions were informed by both academic and industry expertise.
- **Account and timeline of key synthetic biology funding and policy activities as presented in Figure 34.**

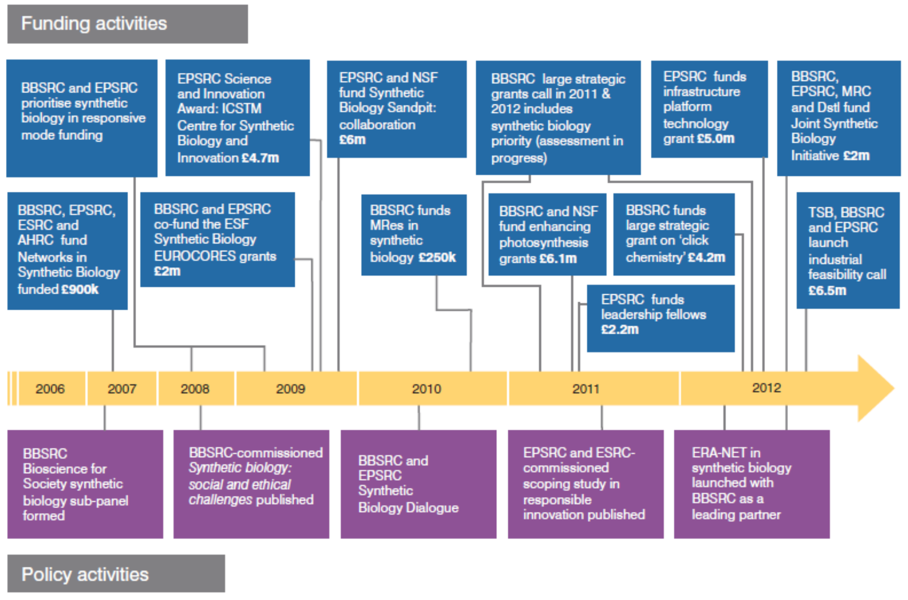

Figure 2: Funding for synthetic biology has been consistently applied by UK research councils since 2007, totalling more than £62m ($95m) to date.

Acronyms: NSF (United States, National Science Foundation) ICSTM (Imperial College of Science, Technology and Medicine), Dstl (Defence Science and Technology Laboratory), ESF (European Science Foundation), MRes (Masters in Research) and ERA-NET (European Research Area Networks)

Figure 34 Key funding and policy activities in synthetic biology reported in the 2012 UK Synthetic Biology Roadmap. Source: TSB, 2012.

Opportunities in evidence and strategic analysis:

- **Opportunity for engagement with engineering**: Broader representation from engineering-focused institutions early on could help to ensure a more holistic approach, especially given the complexity of scaling-up emerging technologies, and the fact that engineering biology tends to be considered a field of engineering as opposed to biology. This is particularly important in terms of accelerating technology development with implications for strategic advantage. TSB (newly Innovate UK) played an important role in ensuring this broader engagement with various research Councils and companies through several funding programmes.
- **Roadmapping challenges**: While the *2012 Roadmap* provided high-level strategic direction as set out in its aim, addressing technology strata and scale-up challenges in a more detailed and structured manner could be critical for transitioning from research to commercialisation, using frameworks such as presented in Section 2.2. This is also related to the importance of representation/ participant sampling at workshops and council-like organisations.
- **Defining technology subgroups and platform technologies (see Section 3, Step 1):** There is an opportunity to better target strategic analysis by clarifying technology subgroups (beyond synthetic biology) and identifying the different core platform technologies with different underpinning science that make up these technology subgroups. This would reveal similarities and differences in terms of required innovation and industrial infrastructure, as well as skills.
- **International policy strategies**: More integration with and learning from international best practice and global synthetic biology strategies could accelerate UK's competitive positioning.
- **Quantitative evidence**: Publication, patent and firm analyses could all contribute to understanding early R&D strengths in a fairly detailed manner, especially given modern methods using data analytics.

4.2.2 *National Vision for Engineering Biology* (2023)

The UK government published its *National Vision for Engineering Biology,*[151] accompanied by £100 million of public investment in 2024, aiming to position the country as a global leader in this transformative field. The *Vision* outlines the importance of engineering biology in addressing major societal and economic challenges, from healthcare advancements through

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[151] DSIT (2023). National Vision for Engineering Biology.

agriculture and food to sustainable manufacturing and low carbon fuels. The *Vision* focuses on four aspects including R&D, infrastructure, skills, regulations and standards.

The evidence base that underpins the *Vision* is based on a variety of quantitative and qualitative sources with advancements in methodology but also thinking about commercialisation (and related infrastructure), sectoral applications, and supply chains, in comparison to earlier documents. Roadmapping that would enable longer term strategy and structured thinking around scale-up infrastructure and value chains could be utilised to further support the *Vision*.

Key evidence includes:

- *Engineering biology call for evidence*[152] resulting in 81 responses across the academic and business community
- Insights from the Engineering Biology Leadership Council (EBLC) and the Engineering Biology Steering Group (EBSG)/Engineering Biology Advisory Panel (EBAP)
- Reports by the Prime Minister's Council for Science and Technology[153]and the Government Chief Scientific Advisor on regulation[154]
- Estimates from the report *The Bio Revolution*[155]
- Scholarly output for the period between 2018 and 2022 with specific keywords developed by the GO-Science using SciVal publications database (number and field weighted citations)
- Engineering biology firms identified and categorised as an application, part of the supply chain, or both. This methodology was developed by DSIT based on Real Time Industrial Classification using The Data City as presented in Use Case 8 in Section 3.
- Estimates of total funds raised and number of start-ups in the UK using Pitchbook investment database and GO-Science keywords
- International government strategies and investments (US, Japan, EU, Korea, Canada)
- Insights from the *Synthetic Biology Dialogue*[156]

Strengths in evidence and strategic analysis:

- **Scope of strategic analysis defined**: The *Vision* benefits from an upfront definition of engineering biology, providing a foundation for strategic analysis. In general, having a

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[152] DSIT (2023). Engineering Biology: Call for evidence.

[153] Council for Science and Technology (2023). Letter to the Prime Minister on engineering biology.

[154] Government Chief Scientific Advisor (2023). Pro-innovation Regulation of Technologies Review: Life Sciences and the government response.

[155] McKinsey (2020). The Bio Revolution.

[156] BBSRC & EPSRC (2010). Synthetic Biology Dialogue.

clear definition from the outset helps define boundaries, avoid miscommunication, and unify stakeholders.

> *"Government defines engineering biology as the design, scaling and commercialisation of biology-derived products and services that can transform sectors or produce existing products more sustainably. It draws on the tools of synthetic biology to create the next wave of innovation in the bioeconomy."*

- **Advanced company identification and categorisation**: The methodology developed to identify companies across the applications and supply chain of engineering biology overcomes the usual issues of Standard Industry Classifications that tend not to pick up companies active in emerging technologies, as presented in Figure 35. This level of sophistication goes beyond previous approaches, ensuring a more comprehensive understanding of the industry's landscape and needs. Reporting more on the methodology and making this accessible across Government could prove useful for analysis of other emerging technologies.

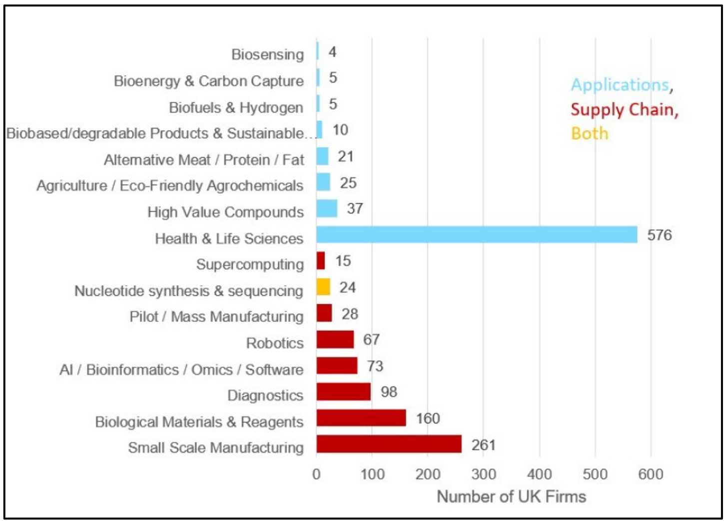

Figure 35 DSIT's methodology to identify engineering biology companies and categorise these across the supply chain as presented in the National Vision for Engineering Biology. Source: DSIT, 2023.

- **Mapping key R&D and industry clusters** is an important tool that can help companies make decisions in terms of future investments.
- **Call for evidence:** The call for evidence demonstrates a commitment to informed policymaking, featuring well-articulated and thoughtfully structured questions that encouraged meaningful input from a diverse range of stakeholders. By seeking evidence in a systematic and transparent manner, the process not only enhanced the depth of analysis but also ensured that multiple perspectives—spanning industry, academia, and policy experts—were considered. This approach reflects best practices

in strategic decision-making, reinforcing the importance of robust evidence-gathering from subject matter experts in shaping effective and forward-looking policies for emerging technologies.

- **Multi-stakeholder involvement**: The involvement of EBLC and EBSG/EBAP enabled bringing together stakeholders, reaching consensus, assessing progress, updating recommendations, and shaping priorities for future implementation of the *Vision*.
- **Commercialisation (and related infrastructure) and well-articulated questions and differences:** Key issues related to scaling up the UK's strong scientific base in engineering biology, including scale-up infrastructure needs, regulatory barriers, financing challenges, and supply chain complexities, are explicitly discussed and properly distinguished. The call for evidence also asks clear questions regarding related issues. Recognizing these barriers is particularly important for emerging technologies as they matter at key inflection points in terms of transitioning from research to commercial success.

  "We will develop a plan for UK facilities that supports lab-scale and pilot-scale innovation. We will explore the range of public and private funding models that could increase accessibility. We will consider how to create resilient supply chains to reduce costs, time and complexity in the ecosystem. We will consider the benefits and drawbacks of both distributed and centralised models for open-access facilities. A distributed network could align future infrastructure capabilities with specialisms within the UK's academic and industrial clusters… We will learn from examples found overseas, including BioBase Europe (Belgium) and BioMADE (US). Government will also understand how to make existing facilities more relevant, accessible and discoverable…"

  The letter by the Council for Science and Technology[157] provides interesting insights into UK's needs on commercialisation as exemplified by the below excerpts.

  "Recommendation two: *The government should seek to become a world leader in measuring complex biological systems. The Department for Science, Innovation and Technology (DSIT) should convene the relevant national standards bodies to establish a bio-sector measurement standards and metrology board."*

  "Recommendation four: *The government should work with industry and UKRI to establish multidisciplinary Biomanufacturing Innovation Centres, for testing, scale up, and commercialisation of non-health engineering biology applications, including materials and fuels. This integrated scale up hubs should be in locations with a relevant industry base, and link to universities with strong engineering biology capability and technical skills infrastructure."*

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[157] Council for Science and Technology (2023). Letter to the Prime Minister on engineering biology.

- **International policy comparisons**: The *Vision* references recent international government strategies, such as those from the United States and South Korea, allowing for benchmarking and alignment with leading economies. These references ensure that the UK remains competitive by learning from international efforts and avoiding policy blind spots that other countries may have already addressed.

  "The UK is not the only advanced economy to prioritise support for this technology. The US has committed $2 billion for biotechnology and biomanufacturing. Japan aims to realise 'the world's most advanced bioeconomy' by 2030. France is spending €800 million to develop and produce biomedicines. China's most recent 5-Year Plan pledges to 'accelerate the development' and 'increase the size and strength' of its bioeconomy. And the EU states 'biotechnologies and biomanufacturing are key to the competitiveness and modernisation of EU industry.'"

Opportunities in evidence and strategic analysis:

- **Involvement of engineering perspectives:** The call for evidence responses but also the Council for Science and Technology members suggest strong dominance of academics, government agencies, national research organisations, SMEs, etc. Increased involvement of perspectives from manufacturing organisations, engineers, operations managers, technical workforce, EPSRC, etc. would ensure that engineering biology innovations are manufacturable, scalable, and commercially viable. This is particularly important at times when technology and industry lifecycles are more advanced.

- **Institutional dominance**: While the BBSRC and Innovate UK play a key role in funding engineering biology, broader representation from engineering-focused institutions, including EPSRC and further cooperation with wider central government departments, could ensure a more holistic approach, once again focusing on more applied and advanced technology, product and industry lifecycles. Engagement with ESRC could also provide an opportunity for ethics and social science contributions ensuring that barriers to commercialisation and technology adoption are addressed.

- **Defining technology subgroups and platform technologies (see Section 3, Step 1):** There is an opportunity to better target strategic analysis by clarifying technology subgroups (beyond engineering biology) and identifying the different core platform technologies with different underpinning science that make up these technology subgroups. This would reveal similarities and differences in terms of required innovation and industrial infrastructure, as well as skills.

- **Structured frameworks enabling technology and manufacturing scale-up:** As commercialisation becomes more important in the lifecycle of an emerging technology, understanding needs in terms of tools, standards, development and demonstration environments, production technologies become increasingly important. While this is well articulated in the *Vision*, using frameworks such as presented in Section 2.2 could enable deepening relevant recommendations in a structured manner and define key platform technologies, especially if also analysed across a temporal dimension (such as roadmapping presented in Section 3, Step 2). This can enable anticipating challenges and potentially accelerating development and scale-up, leading to competitive advantage. Understanding and mapping concrete value chains could therefore also benefit this work, as presented in Section 2.4.

- **Structured frameworks enabling longer term strategy and thinking across temporal dimension:** Roadmapping exercises, which could align stakeholder goals, highlight future challenges, and anticipate sectoral demand and impact, could enable structured and longer-term thinking. They would also enable analysing the temporal dimension of technology, product, and industry lifecycles with important implications for strategic advantage.
- **Building on previous analyses**: While the *Vision* makes several references to legacy programmes such as the stakeholder dialogue, prior evidence such as the *2012 Roadmap*, could provide valuable insights and historical context that would enrich the evidence base and help ensure continuity in strategy. Once again, this highlights the importance of capturing the list of previous analyses for easy access.
- **Supply chain analysis**: As highlighted in the *Vision* for future steps, further depth in analysing supply chain dynamics and vulnerabilities would enhance strategic decision-making. Understanding how engineering biology integrates into existing supply chains and where potential bottlenecks or risks lie is critical for successful implementation.

5 Reconciling technology-push, demand-pull, security and economic considerations

Technology-push, demand-pull (including sectoral- and mission-pull), and security and economic value considerations are often treated as separate domains, due to a variety of reasons including institutional structure, political ideology, economic theory, path dependency, etc. Yet, real-world technological development and deployment suggests that these forces are interconnected and inseparable.

To foster resilient, competitive, and forward-looking innovation and industrial systems, policymakers must move beyond isolated approaches and create strategies that integrate these perspectives. This section briefly explores why these dimensions work better together, grounded in economic theory, innovation systems thinking, industrial economics, and national security literature.

5.1 Technology-push and demand-pull: Two sides of the innovation equation

Technology-push refers to innovation driven primarily by advances in scientific research and technological development. The concept assumes that breakthroughs in fundamental research create new opportunities, markets, and products, even if there is no perceived immediate demand.

This is rooted in linear models of innovation (e.g., Vannevar Bush's *Science: The Endless Frontier*[158]), evolutionary economics as well as analyses of forces that shape innovation.[159] Technology-push posits that investment in R&D will 'naturally' flow downstream into applications and economic value.

Technology-push generally encourages long-term, high-risk research that may open entirely new markets (e.g., semiconductors, biotechnology, quantum computing). However, without market signals or clear missions, technology-push alone may lead to 'technology for technology's sake' or innovations that struggle to achieve commercialization.

Bush's approach became known as the 'pipeline' model for science investment. The federal government would load basic science into one end of an innovation pipeline hoping that industry would pick up the early- and late-stage technology development and prototyping roles inside the pipeline, with new technology products emerging from industry at the end.

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[158] Bush (1944). The Endless Frontier.

[159] Di Stefano et al. (2012). Technology push and demand pull perspectives in innovation studies.

In contrast, **demand-pull** innovation is driven by specific market, sectoral, or societal need. Within this framework, companies and industries innovate in response to clear demand signals or mission-oriented challenges.

Derived from evolutionary economics and sectoral innovation systems theory,[160] sectoral pull emphasizes the role of industry structures, value chains, and competitive dynamics in shaping innovation.

Mission-driven innovation focuses on driving and aligning R&D and industrial policy through setting out missions. Initially, these missions were technology/project specific missions at DARPA and NASA-like agencies, but more recently, the term missions has been used for grand societal and environmental challenges (e.g., climate change, aging population, health).[161]

In general, this perspective ensures innovation pathways are tied to real-world applications and accelerates time-to-market. However, it may discourage long-term, high-risk, blue skies research if short-term market viability dominates investment decisions.

The ***UKRI Technology Missions Fund*** exemplifies how these two perspectives may potentially work together. It sets out funding across UK's five critical technology priorities, but for each technology, it sets out clear missions.

Another oft-cited example is ***US's DARPA***, which operates explicitly at the intersection of tech-push and mission-pull, funding speculative technologies while maintaining a clear line of sight to national defence applications.

5.2 Security and economic value considerations: Balancing risk and opportunity

National security considerations in innovation policy stem from the need to protect current and future critical technologies, infrastructure, and supply chains from geopolitical risks, espionage, and economic coercion. Security literature emphasizes the importance of technological sovereignty, resilience, and dual-use technologies.[162]

This perspective ensures that critical technologies remain under national or allied control, mitigating strategic vulnerabilities. However, it tends to overemphasize security, which can lead to innovation protectionism, limiting collaboration and slowing technological progress.

In parallel, **economic value considerations** focus on maximizing competitiveness, productivity, and long-term industrial growth through innovation. Drawn from Porter's competitive strategy[163] and other economic growth models, these perspectives generally emphasize

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[160] Malerba (2002). Sectoral systems of innovation and production.

[161] Mazzucato (2013). The Entrepreneurial State.

[162] Greene (n.d.). Owen Greene: Professor of International Development.

[163] Porter (1980). Competitive strategy.

competitive strategies, global market leadership, and supply chain efficiency. However, short-term economic incentives may conflict with long-term security or resilience goals.

Security and economic value are often seen as competing imperatives, but a balanced approach strengthens both dimensions. For example, the ***UK's Integrated Review***[164] explicitly addresses this intersection, recognizing that leadership in emerging technologies like engineering biology is both an economic opportunity and a national security necessity.

5.3 Holistic view for innovation and industrial strategy

Innovation and industrial policy must move beyond binary choices and isolated frameworks. By recognizing the dynamic interplay between technology-push, demand-pull, security and economic value considerations, as shown in Figure 36, policymakers can build more effective, resilient, and forward-looking innovation ecosystems.

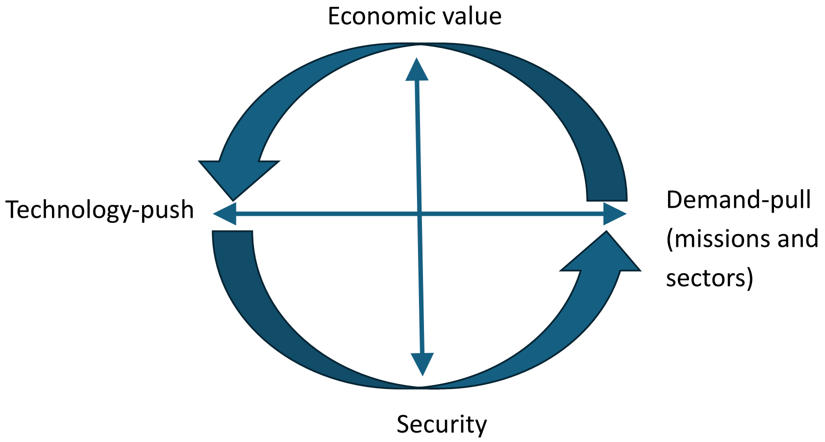

Figure 36 Integrating technology-push, demand-pull, security and economic value considerations. Source: NETS Handbook Project Team.

Feedback loops: Technologies and markets co-evolve most effectively when supply and demand forces are designed to reinforce each other.

Strategic alignment: Aligning innovation policies with national missions while safeguarding economic competitiveness and security ensures long-term resilience.

Adaptive ecosystems: In a rapidly shifting global environment, adaptive, integrated policy frameworks enable governments to lead in both technological advancement and strategic autonomy.

Therefore, the question is not really whether one is more important than the other, but how these two should be connected and feed back into and enable one and another. There is a need to explore successful mechanisms and create a repository.

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[164] HMG (2021). Global Britain in a Competitive Age.

Appendix A: Repository of quantum technology and engineering biology-related documents

Technology	***Key documents***	***References to other supporting documents***
Quantum Technology	**UK National Quantum Strategy (DSIT, 2023)**	National Quantum Strategy: Technical Annexes (DSIT, 2023)
		National Quantum Strategy: Additional Evidence (DSIT, 2023)
		UK National Quantum Technologies Programme (UKRI, n.d.)
		National Quantum Strategy Missions (DSIT, 2023)
		Commercialising quantum technologies challenge (UKRI, n.d.)
		UK Quantum Technologies Challenge Directory (UKRI, 2022)
		Quantum devices, components and systems (EPSRC)
		What Happens When 'If' Turns to 'When' in Quantum Computing? (Boston Consulting Group, 2021)
		Shaping the long race in quantum communication and quantum sensing (McKinsey & Company, 2021)
		Quantum Technology Monitor (McKinsey & Company, 2022)
		Quantum Readiness Survey (Ernst & Young, 2022)
	National strategy for quantum technologies: A new era for the UK (QT SAB, 2015)	A roadmap for quantum technologies in the UK (NQTP, 2015)
		Quantum Technology Roadmap Report: Consolidated from Workshops in London and Glasgow (TSB & IfM, 2014)
	Other documents	UK Quantum Technology Landscape 2016 (Dstl, 2016)
		UK Quantum Technology Landscape 2014 (Dstl, 2014)
		Strategic Intent (NQTP, 2020)
Engineering/ Synthetic Biology	**National Vision for Engineering Biology (DSIT, 2023)**	Engineering biology call for evidence (DSIT, 2023)
		Letter to the Prime Minister on engineering biology (Council for Science & Technology, 2023)
		Pro-innovation Regulation of Technologies Review: Life Sciences and the government response (Government Chief Scientific Advisor, 2023)

		The Bio Revolution (McKinsey & Company, 2020)
		Synthetic Biology Dialogue (BBSRC & EPSRC, 2010)
		Engineering Biology Steering Group (GOV.UK, n.d.)
		Engineering Biology Leadership Council (Innovate UK Business Connect, n.d.)
	Eight Great Technologies: Speech (BIS, 2013).	Science and Technology Studies in policy: The UK Synthetic Biology Roadmap (Marris & Calvert, 2020)
	A Strategic Roadmap for Synthetic Biology in the UK (TSB, 2012)	Synthetic Biology: Scope, applications and implications (RAEng, 2009)
		Synthetic Biology Dialogue (BBSRC & EPSRC, 2010)
		Synthetic Biology for Growth (UKRI, 2025)
		Engineering Biology Leadership Council (Innovate UK Business Connect, n.d.)
	Other documents	Don't fail to scale: Seizing the opportunity of engineering biology (House of Lords, 2025)
		Building Back Better (2020)
		Synthetic Biology in the UK 2009-2019 – A Decade of Rapid Progress (2019)
		A Living Foundry for Synthetic Biological Materials – A Synthetic Biology Roadmap to New Advanced Materials (2018)
		SBLC response to the Court of Justice of the European Union (CJEU) ruling of 25th July 2018 on the regulation of products developed using genome editing techniques (2018)
		UK Synthetic Biology Strategic Plan 2016 – Biodesign for the Bioeconomy (2016)

Appendix B. History of UK's quantum technology policy

In addition to increasing international interest, heightened interest in quantum technologies in the UK emerged through the early and persistent advocacy of several technology experts from academia, especially in relation to security risks and opportunities – namely that of Sir Peter Knight, and heightened interest of government departments including EPSRC, TSB (now IUK), NPL, Dstl and GCHQ.[165] This interest was sparked in relation to the 2010 'flash crash' when US equity markets experienced the worst price decline due to an automated computer ordered execution programme, which sold US$4.1 billion worth equities based on high frequency trading.[166]

As quantum technology could enable time stamping to identify who is at blame, this opened the question of risks and opportunities of the technology in relation to nation security and pushed up quantum technologies on the political agenda. [167] Academic advocates and interested government departments were aligned in making the case for a national quantum programme and its importance for security, defence, and the wider UK economy. EPSRC has played an important role in the preceding years, when it focused primarily on demonstrating the UK's strengths in quantum science, which was already a priority area for UK research councils (especially EPSRC) at the time.[168] **The persistence of individuals inside and outside government has played an important role in the stability and continuity of government support.**

In November 2013, Dstl in partnership with the Royal Society, organized a meeting of key academics, industry representatives and government departments at Chicheley Hall, the Royal Society's conference centre. The meeting explored UK's initial strategy and potential to exploit emerging quantum technologies leading to the **development of a strong evidence base** in the form of a comprehensive *UK Quantum Technology Landscape document* published in February 2014.[169] This document describes in-depth the range of quantum technologies and their potential applications, and suggests the importance of other overlapping and underlying technologies broadly defined, such as specialist materials, specialist semiconductor microstructures, nanofabrication facilities, packaging technology, testbeds, etc. It also highlights UK's commercial capabilities, future applications, and some basic timescale

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[165] Engineering and Physical Sciences Research Council (EPSRC), Technology Strategy Board (TSB) now Innovate UK (IUK) under UK Research & Innovation (UKRI), National Physical Laboratory (NPL), Defence Science and Technology Laboratory (Dstl) under the Ministry of Defence (MoD), Government Communications Headquarters (GCHQ)

[166] Knight (2013). Presentation: Quants, Quantum Physics and the Flash Crash.

[167] Ibid.

[168] Knight & Walmsley (2019). UK national quantum technology programme.

[169] Dstl (2014). UK Quantum Technology Landscape 2014.

estimates for technologies reaching commercialization, suggesting the need for detailed roadmaps.

Following the development of a business case for quantum technologies and **engagement with UK political leadership**, quantum technologies appeared prominently in UK policy making for the first time in the *Autumn Statement of 2013* as a 'cutting-edge technology'.[170] In December 2013, a budget of £270 million was allocated over 5 years for developing Quantum Technology Hubs and supporting the translation of the UK's world leading quantum research into application. This came at a time when the UK has just launched its *Eight Great Technologies strategy*, an effort led by the then UK Science Minister David Willets in 2012. The strategy aimed to provide a narrative of key technologies in which the UK demonstrated or had the potential to demonstrate competitive advantage, which made quantum technology suitable as the ninth great technology (with the Internet of Things also added later as the tenth).

The Quantum Technology Strategic Advisory Board (QT SAB) was established at this time as a coordinating body for UK interests with a visible focus on quantum technologies. It was chaired by former EPSRC Chief Executive David Delpy for a period of 5 years and had representatives from industry, academia, and government.[171] QT SAB developed the still ongoing *UK National Quantum Technology Programme (NQTP)* in 2014,[172] with the initial budget allocation of £270 million for a period of 5 years. The *NQTP* was initially a coordinated effort between QT SAB and the Department for Business, Innovation and Skills (BIS), EPSRC, TSB, NPL, Dstl, GCHQ and MoD, which have **worked to align their investments** with quantum technology priorities.[173] The first phase of the programme has eventually seen about £360 million of public investment between 2014 and 2019 as shown in Figure 37.

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[170] HMT (2013). Autumn Statement 2013.

[171] Today, the NQTP Board is the one which coordinates across NQTP organisations, while the NQTP SAB serves as an external expert group, chaired by Sir Peter Knight, with industry and academic representatives. NQTP (n.d.). Governance.

[172] NQTP (n.d.). UK National Quantum Technology Programme.

[173] UKRI (2015). National strategy for quantum technologies: A new era for the UK.

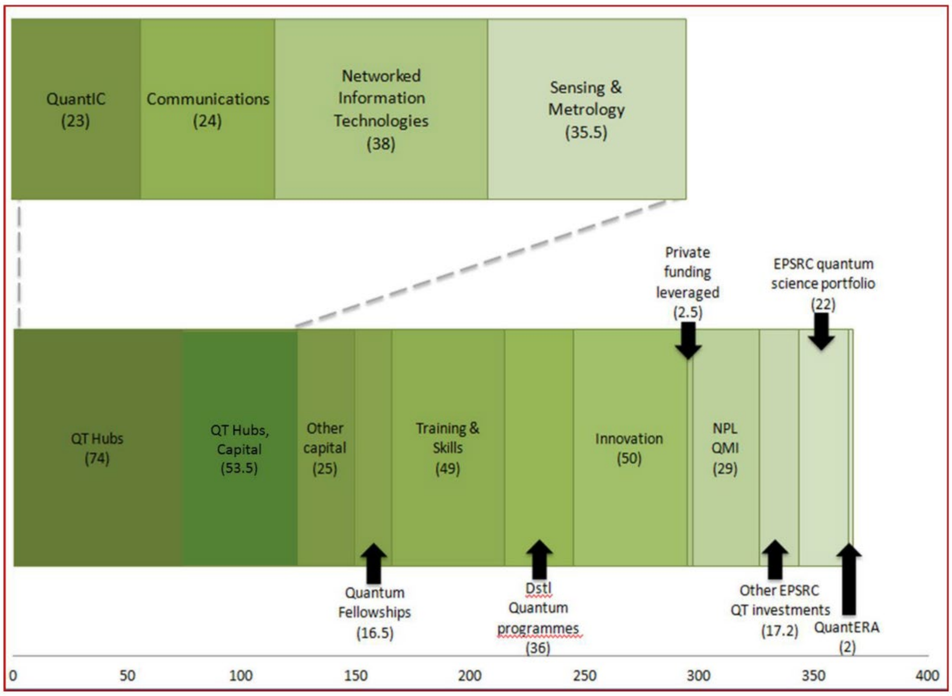

Figure 37 UK's budget allocation for quantum programmes in million £ in the first 5 years. Source: Dstl, 2016.

Calls for ideas on delivery mechanisms of *NQTP* opened in 2014. One of the key mechanisms and strongest features of *NQTP* has been the **development of a national quantum ecosystem through a 'hub and spoke' model used to ensure wide engagement**. As shown in Figure 37 and Figure 38, EPSRC funded 4 university-led Quantum Technology Hubs selected based on a competitive peer review process through a £120 million investment over 5 years.[174] The Quantum Technology Hubs initially involved 17 universities and more than 50 partner organisations collectively contributing a further £60 million support. They were established in December 2014 focusing on **4 key quantum technology areas identified at earlier workshops**:

- Quantum Communications Hub led by the University of York
- Quantum Technology Hub in Sensors and Metrology led by Birmingham University
- Quantum Imaging Hub (QuantIC) led by the University of Glasgow
- Networked Quantum Information Technologies (NQIT)

A second phase of funding was agreed for an additional five years between 2019-2024**. The Hubs were set up to achieve objectives that were well beyond the first phase of funding**. This has led to their additional funding of £94 million during the second phase upon **their refreshing of agendas based on most recent national and global trends in quantum technologies.**

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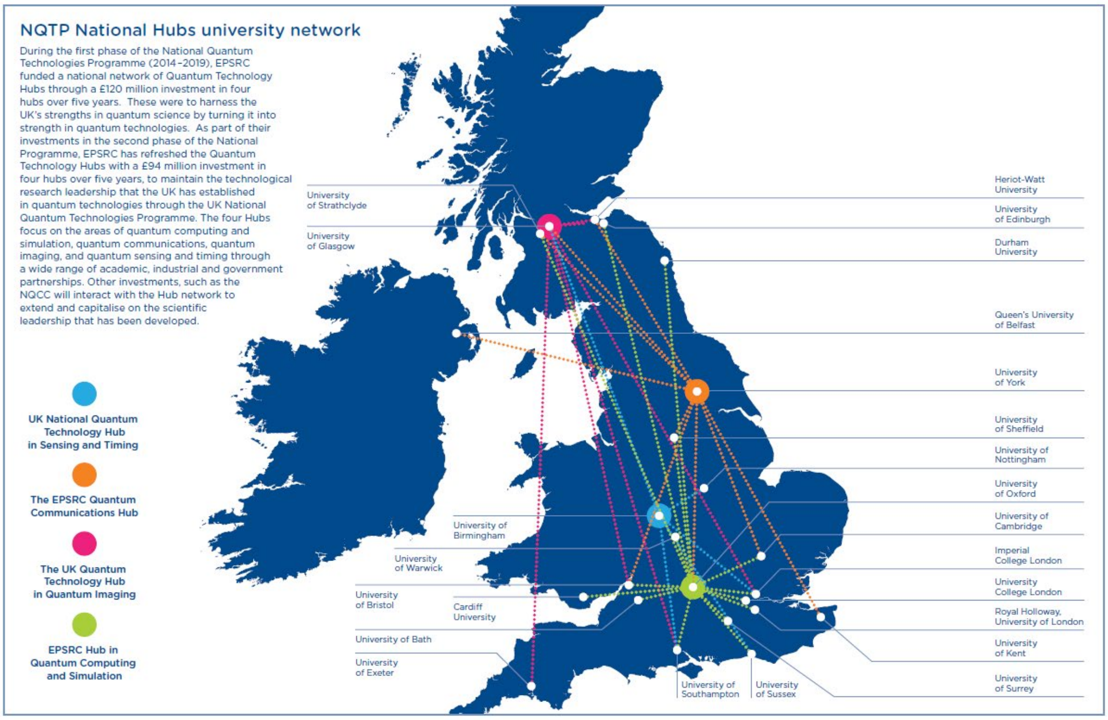
[174] UKRI (2020). Strategic Intent.

Other regional centres of excellence were also set up. These include the:[175]

- Quantum Metrology Institute (QMI) at the National Physical Laboratory (NPL) launched in 2015 focusing on quantum test and evaluation infrastructure to accelerate commercialisation, extended by the Advanced Quantum Metrology Laboratory (AQML) in 2021
- National Quantum Computing Centre (NQCC) in Harwell, launched in 2020 with a funding of £93 million
- Fraunhofer Centre for Applied Photonics (CAP) in Glasgow – receiving core funding from the Scottish Government, from competitive R&D calls including the *ISCF*, and from commercial contracts

The UK has set an example by creating such an ecosystem early in the development of an emerging technology as it has enabled a collaborative environment bringing together industry, academia, and the government to continue leading in technological innovations.

As mentioned earlier, *NQTP* builds on a strong base in quantum physics and engineering built by EPSRC programmes, which were strengthened through a budget allocation under the first phase of funding by the building of Centres for Doctoral Training at the University of Bristol, Imperial College and University College London and the Quantum Technologies Fellowships.



NQTP National Hubs university network

During the first phase of the National Quantum Technologies Programme (2014–2019), EPSRC funded a national network of Quantum Technology Hubs through a £120 million investment in four hubs over five years. These were to harness the UK's strengths in quantum science by turning it into strength in quantum technologies. As part of their investments in the second phase of the National Programme, EPSRC has refreshed the Quantum Technology Hubs with a £94 million investment in four hubs over five years, to maintain the technological research leadership that the UK has established in quantum technologies through the UK National Quantum Technologies Programme. The four Hubs focus on the areas of quantum computing and simulation, quantum communications, quantum imaging, and quantum sensing and timing through a wide range of academic, industrial and government partnerships. Other investments, such as the NQCC will interact with the Hub network to extend and capitalise on the scientific leadership that has been developed.

Figure 38 NQTP Quantum Technology Hubs network. Source: UKRI, 2020.

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[175] DSIT (2023). National Quantum Strategy.

MoD allocated further £30 million (later £36 million) for quantum technologies under its *Chief Scientific Adviser's Disruptive Technology Programme.* This program follows a similar model of the US Defence Advanced Projects Research Agency (DARPA) in a sense that it is devoted to the investigation of emerging disruptive technologies and their rapid development and deployment often in a fast-track model allowing for sufficient risk. It comprised of two demonstrators: quantum navigation system and quantum gravity imager. This program was designed to be complementary with NQTP largely benefiting from the capabilities of the Quantum Research Hubs.

In parallel with these developments, the QT SAB developed the first *UK National Strategy for Quantum Technologies in 2015.*[176] It suggested the need for **further and sustained support in the form of a 10-year programme** and identified 5 key areas of importance:

- enabling a strong foundation of capability in the UK
- stimulating applications and market opportunity in the UK
- growing a skilled UK workforce
- creating the right social and regulatory context
- maximising benefit to the UK through international engagement

The *2015 Strategy* was shortly followed by a *Roadmap for Quantum Technologies in the UK document* [177] **with an aim to understand near-, mid- and longer-term potential** for commercial application of quantum technologies. It was based on two expert workshops held by TSB with representatives from industry, academia and the government. It collected key data on quantum technology drivers and trends, stakeholder perspectives, application opportunities, capabilities, and enablers.[178]

These two documents pointed to the **need to better understand future technology and market potential and early adopters, suggesting the need for feasibility studies, market analysis, demonstrators, roadmapping and implementation of standards.** With the early budget of £50 million for an innovation program, IUK (£32m), EPSRC (£18m) and Dstl first ran a program for **Feasibility Studies, which was later extended to also support Collaborative R&D**. The latter was specifically developed to provide support for challenge-led projects with clear ideas for commercialization as the next step after feasibility studies to produce commercial prototypes and demonstrators.[179]

This has essentially been incorporated into the *Industrial Strategy Challenge Fund (ISCF) under the programme called Commercialisation of Quantum Technology Challenge,* which could be seen as one of the largest enhancements of the *NQTP* during the second phase of funding. In

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[176] UKRI (2015). National strategy for quantum technologies: A new era for the UK.
[177] UKRI (2015). A roadmap for quantum technologies in the UK.
[178] TSB & IfM (2014). Quantum Technology Roadmap Report: Consolidated from Workshops in London and Glasgow.
[179] Dstl (2016). UK Quantum Technology Landscape 2016.

2018, a pilot programme focused on industry-led challenges with £20 million of government funding matched by the private sector. **This program had 4 relatively clearly defined challenges – they focused on capabilities and impact, not on the underlying science or platform technologies**:[180]

- Situational Awareness: Situational awareness during transportation in highly hazardous conditions (e.g. darkness, fog or dust) that is as safe or safer than, that in normal.
- Infrastructure Productivity: Increased productivity in the deployment, improvement or maintenance of the built environment and critical national.
- Seeing the Invisible: Identification and understanding of features and states in key critical areas (medical, environmental, security) which are impossible to access by conventional means.
- Trusted Peer to Peer Communication: Complete and long-term trust in the secure peer to peer transfer of data and information (e.g. across smart cities and environments).

The pilot programme with good industry engagement led to an extension of the *ISCF* with further £153 million announced by the UK Prime Minister in June 2019. The *Commercialising Quantum Technologies Challenge* makes use of a **mix of general IUK and novel funding instruments, which were employed in a staged fashion** starting from earlier stage, smaller-scale projects including feasibility studies and germinator projects to larger-scale collaborative R&D activities. This enabled building in opportunities to adapt funding calls to arising needs and programme learning and enable beneficiaries to progress through the various funding stages. The calls also attracted a variety of collaborators across the supply chain including component developers, system integrators, end-users. The funding instruments include:[181]

- Collaborative R&D grants supporting industry-led projects aimed at creating game-changing quantum technology products and services with a requirement for demonstrable end-user involvement
- Feasibility Studies grants supporting shorter-term studies focused on innovative components and supply chain elements for quantum technologies
- Technology Project grants supporting industry-led R&D projects developing key underpinning quantum technologies with widespread potential applications
- Germinator grants providing a small number of grants for high risk/high reward practical projects, led by industry or academia, seeking to develop new paradigms and concepts to build a pipeline of new quantum technologies for the longer-term.
- An Investment Accelerator aimed to de-risk private sector investment in early-stage QT companies by matching venture capital investment with *ISCF* grant funding.

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[180] Knight & Walmsley (2019). UK national quantum technology programme.

[181] RAND Europe & Frontier Economics (2023). Evaluation of the Industrial Strategy Challenge Fund.

The overall public investment of £184 million has attracted almost £500 million in private sector funding with an expectation of reaching £715 million by 2025.[182] It continues to provide grant-based funding for commercialising products and technologies based on quantum science with an expected end in 2025. Thus far, it has funded about 139 projects and 141 quantum organizations.[183]

One of its key contributions has been the Quantum Landscape tool created in 2020, which is continuously updated.[184] The tool gathers information on quantum "capabilities in the form of an interactive, searchable and open access tool, mapping the existing businesses, publicly funded projects and research groups, the UK national centres and the available postgraduate training programmes. It has since been updated adding fabrication facilities and a list of quantum computers launched by companies that have operations in the UK." The aim of the tool is to become a point of reference for quantum capabilities in the UK and point of contact making connections across different actors.

In 2016, the 2014 landscape document was updated, once again drawing on expert input from several meetings held in Chicheley Hall in 2016 and the wider quantum community, as well as the *2015 National Quantum Strategy, and the 2015 Roadmap for Quantum Technologies in the UK. The 2016 Quantum Technology Landscape document*[185] moves beyond describing quantum technologies, applications and other enabling technologies. It describes in-depth the UK's quantum landscape, national strategy and progress made but also **looks at international comparators and their key policy initiatives and draws on the evidence in the 2015 roadmap.**

A document published on *NQTP*'s Strategic Intent[186] and progress was published in 2020. This document updates the strategic vision for the next 10 years to create a quantum enabled economy that plays an integral part in UK's digital backbone and manufacturing base. This would draw on the UK's interconnected ecosystem of world-leading quantum experts and companies. It provides a map of the 4 Quantum Technology Hubs and key universities involved as shown in Figure 38. The document particularly emphasizes the importance of industrial scale-up and the need to stimulate market pull and shift the balance between public and private funding (through continuing the challenge-led activities and focusing on application markets). It focuses on infrastructure and capabilities such as the newly established National Quantum Computing Centre for developing UK capabilities in hardware building and software development, but also mentions NPL's testing and evaluation capabilities, Dstl laboratories, Science and Technology Facilities Council (STFC) facilities and wider regional laboratory and fabrication facilities. It also summarizes key government policies and their budgets while

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[182] UKRI (2023). Commercialising quantum technologies challenge.

[183] DSIT (2023). National Quantum Strategy.

[184] KTN (2020). Quantum Landscape tool.

[185] Dstl (2016). UK Quantum Technology Landscape 2016.

[186] UKRI (2020). Strategic Intent.

providing some data on the number of projects, partnerships, companies, spinouts, and students supported.

In 2023, the *National Quantum Strategy* was published in support of the government's ambitions to make the UK a scientific and technologic superpower.[187] This ambition is enshrined in the Science and Technology Framework[188] backed by £370 million by the Department for Science, Innovation and Technology (DSIT), with quantum technologies being one of the 5 critical technologies.

At the same, DSIT has also published the *National Quantum Strategy*[189] detailing UK's vision for the next ten years with 13 priority actions, which include R&D, missions and challenges, skills, procurement, infrastructure. It has also established the new Office for Quantum, which has developed the strategy and is now working on its implementation. The quantum strategy focuses extensively on commercialization and pulling through quantum technologies through use cases, applications, and missions. It delves into the importance of providing facilities including test beds for quantum computer testing and system integration for use cases but also on developing new application-oriented Quantum Technology Research Hubs and the Quantum Missions. The Office for Quantum has also published a set of five key missions to be achieved by 2035 under the National Quantum Strategy Missions later in 2023.[190] The quantum strategy furthermore also highlights procurement through SBRI, NSSIF and the new catalyst Fund. All the above highlight the importance of pulling science and technology through to market through a variety of mechanisms, which suggests commercialization of quantum science and technology as a key priority for the government.

Appendix B.1. Perceived success factors in quantum technology policy

- **Early advocacy and continued persistence of stakeholders** inside and outside government for the quantum agenda (e.g., individual academics, EPSRC, Dstl).
- **Continuity and stability of government support** for quantum technologies through long-term and consecutive budget allocations (two 5-year budgets, followed by a new 10-year budget).
- **Provision of a forum for a community with an interest in quantum science and technologies** leading to a comprehensive assessment of UK's landscape and future opportunities as evidence for a business case (e.g., meeting in Chicheley Hall and later QT SAB). Also leading to an aligned vision across the community making a stronger case for government support.

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[187] DSIT (2023). Press release.
[188] DSIT (2023). Science and Technology Framework.
[189] DSIT (2023). National Quantum Strategy.
[190] DSIT (2023). National Quantum Strategy Missions.

- **Establishment of an ecosystem bringing together academia, governments, and industry early on** (e.g., meetings in Chicheley Hall, QT SAB and the Quantum Technology Hubs). This enabled bringing together a variety of capabilities and working towards a common vision, continuously making a case for further government support. The indirect benefit is the detailed knowledge of the ecosystem and key stakeholders in it. This could enable a good understanding of current capabilities, resources, and infrastructure, which however need to be captured (e.g., in writing) and continuously updated. This is in contrast with emerging technologies that enter the policy agenda later in their lifecycle (e.g., semiconductors) or those whose ecosystem has emerged relatively more organically.
- **Early recognition of commercialization needs** (e.g., demonstrators funded by MoD/Dstl), identification of early adopters (e.g., in the 2015 Roadmap), key sectors and applications (the ISCF Challenge) and more recently missions (National Quantum Strategy Missions). These highlight several examples of mechanisms that have likely contributed to enabling the pull through of technologies to the market. There is a need to consider both technology-push and market-pull forces early on to be able to reap benefits from investments into research.
- **Systems thinking and value chain considerations** including the setting up of the NQTP early on (as made in the point above) and the setting up of the NQCC to fill the gap of a systems integrator.
- **Focusing not only on technology development but the pull-through of these technologies to the market**, especially in early years of government support. One relatively early mechanism was the Industrial Strategy Challenge Fund (ISCF) Commercializing Quantum Technologies that had 4 relatively clearly defined challenges – they focused on capabilities and impact, not on the underlying science or platform technologies.[191]
- **Increasing focus on procurement programmes** including NSSIF and SBRI.[192] [193]
- **Early and continued consideration for supporting infrastructure and initiatives beyond key platform technologies** including testbeds, standards, demonstrators, R&D components and tools, etc.
- **Provision of an early roadmap with an opportunity to update** based on workshops represented by a variety of actors from academia, industry, and government.
- **Account of ongoing government initiatives and their impact.** Both the Quantum Technology Research Hub and the ISCF Challenge programs seem to have played an

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[191] Knight & Walmsley (2019). UK national quantum technology programme.

[192] DSIT (2024). Press Release.

[193] GOV.UK (n.d.). Funding Competition.

important role. Given the number of new programmes, it is important to clearly differentiate between these and to define clear objectives for each. This could help navigate the funding landscape and ensure that the effectiveness and impact remain manageable.

- **Working closely and continuously with the internal NQTP Programme Board and the external Quantum Strategic Advisory Board** (QT SAB) and implementing agencies holding onto key knowledge about current science and technology progress and capabilities could enable a better understanding of the current landscape, which is essential for emerging technology strategy development.

Appendix B.2. Perceived opportunities in quantum technology policy

- **Integration and sequencing of evidence.** There has been a large number and type of quantum technology documents developed over time published by a variety of actors. This has had consequences for the effectiveness of integrating evidence and analysis into key strategy documents. There is a need to reduce information asymmetries by utilizing and better integrating the evidence base available (e.g., drawing on the comprehensive landscape documents, technical roadmaps and annual reports of the Quantum Technology Hubs[194]). But also, by identifying where this evidence is lacking.
- **A repository of evidence and documents** (see Appendix A for initial list), including supplementary information, could enable more effective integration and provide a comprehensive data service to those who want to make a strong case for the technology (e.g., government departments, investors, researchers). Referencing in key strategies to this evidence and documents could also enable transparency.
- **Defining quantum technology, but also each quantum technology subgroup** (quantum sensor technologies, quantum computing technologies, etc.) and technology stratum (production technologies, R&D tools, engineering tools, etc.) are needed to enable data integration and ensure communication within and beyond government. The assessment of the latter across quantum technology groups could easily highlight overlaps in capabilities and gaps.
- **Defining technology strata and the quantum value chain** (beyond hardware, software and components) would better enable seeing where current gaps are. For example, the need for fabrication facilities is mentioned several times but there is no clear focus on low to high-volume production facilities and challenges, and whether this will be achieved through own capacities, collaboration, or access (OCA). Considering these systematically and early on, not only in the context of quantum technologies but across the board, can confer a competitive advantage and accelerate the process of technology development and scaling-up. This approach allows for the potential

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[194] NQCC (n.d.) National Quantum Computing Centre Technology roadmap.

simultaneous development or at least planning of various aspects, rather than in a staged manner, thereby enhancing comprehensiveness and efficiency.

- **Tracking and updating progress in quantum technologies, capabilities and opportunities** in a similar depth as undertaken in the comprehensive Dstl 2016 Quantum Technology Landscape document[195] or the 2020 Dstl Quantum Information Processing Landscape document. The former is, for example, based on expert inputs collected from meetings organized for the purpose of reviewing the state of quantum developments; input from the quantum community; the 2015 National Quantum Strategy and the 2015 Roadmap for Quantum Technologies document. The analysis covers several important aspects, including current capabilities, current state of technology development and future opportunities and needs, technology roadmaps, technology 'strata', but also the key stakeholders and policy initiatives. As quantum developments have progressed significantly since the publication of these documents, and global competition has increased, there is potential for an in-depth review of different system elements present or absent in the UK, including international benchmarking as discussed in Section 2. The Quantum Landscape tool[196] compiled through the Knowledge Transfer Network provides comprehensive data on this. However, there is potential in analysing and integrating this data into a coherent narrative, updating UK's current landscape.

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[195] Dstl (2016). UK Quantum Technology Landscape 2016.

[196] KTN (2020). Quantum Landscape tool.

Institute for Manufacturing (IfM)

The IfM is part of the University of Cambridge's Department of Engineering. It brings together expertise in management, technology and policy to address the full spectrum of issues which can help industry and governments create sustainable economic growth.

Centre for Science, Technology & Innovation Policy (CSTI)

The Centre for Science, Technology & Innovation Policy carries out applied research into programmes, processes and practices for translating publicly funded R&D (in particular science and engineering research) into new technologies, industries and economic wealth. CSTI is an applied policy research unit exploring what makes national innovation systems effective at translating new science and engineering ideas into novel technologies and emerging industries. Research projects are designed to support the evidence needs of Science, Technology & Innovation (STI) policymakers, in particular those officials in public research agencies who are responsible for programme design, portfolio management and strategy development. The CSTI research agenda is shaped in collaboration with policy and research agency partners.

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