UNIVERSITY OF CAMBRIDGE

Cambridge Industrial Innovation Policy

International Benchmarking: Advanced Manufacturing and Materials

Identifying mutually beneficial international research and innovation collaboration

SUMMARY REPORT

— Policy Links Unit, IfM Engage, University of Cambridge | July 2021

About this report

This summary report highlights the key findings from the "International Benchmarking: Advanced Manufacturing and Materials" study, commissioned by Innovate UK to provide insights into emerging advanced manufacturing and materials technology domains where international research and innovation collaboration could unlock strategic opportunities and help to position the UK as a global hub for innovation. For UK government employees, further detail on methods, disaggregated findings and results can be found in the **full report**.

The summary report findings are based on the authors' interpretation and analysis of the evidence reviewed, including insights and data shared by Innovate UK, the Steering Group of the project and the consulted stakeholders. However, these findings do not necessarily represent the views of Innovate UK; nor do they imply the expression of any opinion on their behalf.

Names of countries and territories follow widely accepted conventions and do not imply the expression of any opinion whatsoever on the part of the authors, their affiliated institutions or client concerning the legal status of any country, territory, city or area, or its authorities. Any mention of firm names or commercial products does not constitute an endorsement by the authors, their affiliated institutions or Innovate UK.

Innovate UK

Innovate UK helps businesses to access international innovation opportunities and collaboration, helping to build the global supply chains of the future, accessing markets and attracting inward investment.

Contributors and acknowledgements

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Executive summary

The advanced manufacturing and materials (M&M) sector makes a vital contribution to the UK economy. Manufacturing industries account for 8% of UK jobs but 42% of UK exports[1] and remain the largest contributors to R&D expenditure across the UK despite their relative decline as a share of the economy in recent decades. Manufacturing accounts for 42% of the UK's total gross expenditure on R&D (GERD), with pharmaceuticals, automotive and aerospace making up almost two-thirds of this figure.[2] Innovation in advanced materials underpins all manufacturing industries and therefore plays a strategic role in the country's long-term industrial performance. Indeed, the UK Innovation Strategy, published in July 2021, highlighted the importance of innovation for future British prosperity and the international nature of innovation.[3] This report provides analysis and intelligence to support the UK's mission to deliver on this innovation agenda.

The M&M sector is now entering a dynamic new phase. Resource scarcity, a circular economy and sustainable energy generation are all challenges that no individual country can tackle alone. The pace of change in technological developments and global competition are shifting the sources of value capture within industries and challenging traditional patterns of industrial leadership. Strategic international research and innovation (R&I) collaboration in the advanced manufacturing and materials sector is more vital than ever for the UK to strengthen its global position in the future "net-zero economy".

The key findings of this report include: the identification of key motivations and win–win principles for international research and innovation collaboration; the strengths of the UK advanced manufacturing and materials sector; the identification of UK technology priorities, and key opportunities for international collaboration; the identification of key partner countries; and the implications for the selection and funding of future international collaboration. An overview of these results is summarised in the remainder of the Executive Summary below.

International research and innovation (R&I) collaboration

International collaboration in research and innovation provides countries with access to broader sources of knowledge, talent, investment and new markets.[4] International R&I collaboration can also foster economic, diplomatic and political ties.[5] The UK has a strong track record of bilateral and multilateral research and innovation agreements, and the government has announced a commitment to deepening international partnerships around the world and incorporating science and technology as an integral element of national security and international policy.[6]

From the literature, this study has identified five key motivations for countries to pursue international R&I collaboration, and five "win–win" principles that should be followed when identifying partner countries and establishing collaboration, to ensure that it benefits all of the partners involved in an equitable and sustainable manner. The five key motivations for international R&I collaboration are: research and innovation excellence, economic competitiveness, grand challenges, diplomacy and additionality. The five "win–win" principles that should be followed when identifying partner countries and establishing collaboration are: reciprocity; transparency; accountability; equity; and the long-term perspective.

Key motivations for international R&I collaboration:

1. Research and innovation excellence
2. Economic competitiveness
3. Grand challenges
4. Diplomacy
5. Additionality

"Win–win" principles for international R&I collaboration:

1. Reciprocity
2. Transparency
3. Accountability
4. Equity
5. Long-term perspective

UK advanced manufacturing and materials R&I in perspective

The UK manufacturing sector is diverse, with activities ranging from automotive, heavy machinery, aerospace, pharmaceuticals, chemicals and biotech, to food and drink. When looking solely at which manufacturing sub-sectors have the highest R&D intensity, as measured by the expenditure on R&D as a percentage of sales, clear differences emerge: whereas pharmaceuticals and electronics and communication equipment have the highest R&D intensity, at around 35%, automotive and aerospace show a lower R&D intensity, at 6.6% and 6.4%, respectively. Between these, the computer sub-sector shows 22% R&D intensity, while all other manufacturing industries remain below 7.5% R&D intensity.

In terms of innovation output, although it is difficult to define the boundaries of exactly what scientific and technological fields fall under advanced manufacturing and materials, data on UK triadic patents by technology domain (as defined by the World Intellectual Property Organization – WIPO) shows a significant prevalence of patents in the medical technology and pharmaceutical fields. Notable advanced manufacturing and materials fields in this list include: electrical machinery, apparatus and energy; measurement; computer technology; basic materials chemistry; engines, pumps and turbines; and other consumer goods.

In terms of basic research output, data on UK scientific publications (2019–20) for the fields of engineering and materials science shows a wide variety of specialisation areas. Whereas electrical and electronic engineering and (miscellaneous) materials science show the highest number of publications and h-index,[7] industrial and manufacturing engineering falls towards the middle of the chart, which can be simply interpreted as an area with lower scientific activity compared to other fields in the UK.

UK technology priorities

In order to identify key opportunities for international research and innovation cooperation, this report suggests that it is first necessary to map technology areas of strategic value for various stakeholders across the UK national innovation system. A three-step approach has been followed to carry out this analysis:

1. **Broad map of UK technology priorities.** Identification of 205 technology domains through the review of: stated priorities from selected funding institutions and programmes; stated priorities from selected research and technology institutions; technology priorities, as perceived by the consulted experts; technology priorities extracted from a specialised literature review; and the technological scope of previous international collaboration.

2. **Quantitative analysis.** Prioritisation of the 48 technology domains most commonly found across the various sources of data from Step 1, including key technology domains put forward by the consulted experts.

3. **Qualitative analysis.** Prioritisation of 33 technology domains based on qualitative insights from the stakeholder consultation and literature review, considering three main criteria: the potential to enhance the competitiveness of existing UK industries; the potential to support the development of future industries; and the ability to support existing UK R&I strengths and/or address key weaknesses in the UK R&I landscape.

The list of technologies analysed in this study cannot be comprehensive given the diversity of fields covered and their changing nature. The fact that 33 technology domains were prioritised when exploring potential international collaboration does not imply that some technologies are more important than others. Rather, these represent an initial selection that was made considering the boundaries of this study for short-term consideration by Innovate UK.

Opportunities for international research and innovation collaboration

A variety of variables were considered when selecting potential countries for collaboration: not only "strengths" but also track record of collaboration with the UK, national priorities, availability of funding, and so on, as described in further detail in the body of the report. Efforts have also been made to come up with a balanced portfolio of partnerships that considers not only established but also emerging science and technology players and which aims for broad geographical coverage.

The investigation looked at "UK plc" as a whole, not just individual institutions. It was considered that UK manufacturing firms should be the main potential beneficiaries of any funding programmes derived from this study.

Efforts were made to assess the strengths and weaknesses of each potential opportunity, both in relation to one another and on an absolute basis, using a structured approach and a mix of quantitative and qualitative evidence. Naturally, a level of expert judgement is involved. Instead of basing the identification of collaboration opportunities on rigid statistical rankings alone, the assessment presented reflects the views of the stakeholders consulted, including their experience participating in international collaboration, as well the consulting team's interpretation of the evidence.

The main output of the study is a shortlist of the 16 top opportunities for international collaboration, including specific technology domains and suggested partner countries, as shown in Table 1, across the following themes: net zero, industrial digitalisation, supply chain resilience and other thematic priorities (including biomanufacturing and quantum computing). The shortlist covers nine countries/territories (the US, Germany, Singapore, Canada, Taiwan, Switzerland, Israel, India and the EU).

TABLE 1 SHORTLIST OF OPPORTUNITIES FOR INTERNATIONAL RESEARCH AND INNOVATION COLLABORATION IN ADVANCED MANUFACTURING AND MATERIALS

Theme	Selected technologies for international collaboration	Countries and territories shortlisted for international collaboration in this technology
Net Zero	Electric machines (including power electronics)	The EU, the US, Canada, Germany, the Netherlands, Singapore, India, Taiwan, Japan, South Korea, Scandinavian countries
	Hydrogen: aerospace	The EU (France, Germany), Switzerland, Japan, South Korea
	Hydrogen: fuel cells	Germany, the US, Japan
	Batteries	Germany, Canada, India, Israel, Switzerland, China, Australia, the US, Finland, Japan
	Carbon capture, utilisation and storage (CCUS)	Germany, Japan, Australia, Finland, the US, China
Industrial digitalisation and supply chain resilience	AI and machine learning	Singapore, Japan, Australia, Canada, Israel, Switzerland, China, Germany, South Korea, the US, Taiwan
	Augmented reality and virtual reality (AR/VR)	Switzerland, Japan, Singapore, Germany, South Korea
	Data science and sensors	Taiwan, Canada, Australia, Switzerland, Germany, Japan, South Korea
	Digital twins	India, the US, Singapore, Taiwan, France, Germany, Japan, South Korea, Estonia
	End-to-end supply chain integration	Singapore, Canada, Australia, India, the US, Taiwan, Germany, Japan, South Korea, Estonia
	Industrial cyber-security	Israel, the US, Australia, Canada, Switzerland, Germany, Japan, Singapore, Estonia, China
Other advanced manufacturing and materials thematic priorities	Additive manufacturing	The US, China, India, Switzerland, Australia, Germany, France, the Netherlands, Japan and Singapore
	Bio-derived materials manufacturing	The US, Japan, India, France
	Graphene & 2D materials	Germany, South Korea, Australia, Switzerland, China, the US, Denmark, Spain
	Quantum systems manufacturing	Canada, Israel, Germany, Singapore, the US
	Synthetic biology manufacturing	Singapore, India, Taiwan, the US, Israel, Japan, the EU

Implications for the selection and funding of future international R&I collaboration

The following observations for Innovate UK regarding the selection and funding of future international R&I collaboration emerged through the course of this work. These include:

- **Evidence for "win–win" collaboration.** A recurring theme during the stakeholder consultations was the risk that international collaboration could lead to UK know-how being exploited elsewhere. To mitigate this risk, future calls for proposals could challenge bidders to demonstrate how proposed international collaboration can lead to significant value capture in the UK. This might also include reflection on how the project could benefit broader industrial capabilities in both countries, considering differences in the levels of maturity and supply chain specialisation.

- **Moving beyond value creation to ensure value capture.** To drive a focus on "win–win" collaboration, in future calls for proposals bidders could be asked to provide information on how working with the proposed international R&I partners offers the possibility of mutually beneficial outcomes. Even if funding for international R&I collaboration is not used to support programmes solely focused on technology adoption, calls for proposals could challenge applicants to think beyond value-creation metrics and describe specific pathways to value capture from a UK industry standpoint – such as IP creation, the development of new workforce skills or domestic manufacture of next-generation products.

- **Prioritise a variety of manufacturing-related R&D domains.** Portfolio managers may choose to prioritise different technology domains for investment. Previous studies have suggested that consideration should be given to framing future calls for proposals in terms of a mix of relevant R&D categories,[8] including: production

technology R&D; manufacturability R&D for key emerging application technologies; challenge-led manufacturing R&D; and manufacturing-enabling technology R&D. In particular, there is merit in considering R&D efforts of an enabling and cross-cutting nature that might not naturally fit into the thematic priorities considered by this project. Similarly, the importance of systems integration, engineering design and virtual product development and validation – which have the potential to underpin advances across manufacturing technology domains and sectors – was highlighted during the consultations.

- **National contexts, alignment and trust.** A clear message emerging from this project is the importance of trust among partners and a track record of collaboration when it comes to project prioritisation. This suggests the need to consider, as part of the management of international collaboration portfolios, directing efforts at better understanding the institutions, competitive dynamics, industrial context and cultural dynamics in partner countries. International missions were highlighted during consultations as a particularly effective mechanism to do this.

- **Towards a systemic approach to international R&I collaboration.** Opportunities exist to develop a more institutionalised approach to informing the funding of international R&I partnerships with other nations. In the UK, opportunities exist to more systematically leverage technological expertise in public research and technology organisations (particularly the High Value Manufacturing Catapult network); industrial perspectives from business organisations (including SME and technology-based firm organisations); insights into international science and technology trends (such as those captured by the Science and Innovation Network (SIN)); and foresight studies (such as those produced by the Government Office for Science (GO-Science)).

This summary report highlights the key findings from the "International Benchmarking: Advanced Manufacturing and Materials" study conducted for Innovate UK. It provides insights into key emerging advanced manufacturing and materials technology domains, where international research and innovation collaboration has the potential to unlock significant and strategic value-capture opportunities for the UK. For UK government employees, further detail on methods, disaggregated findings and results can be found in the full report.[9]

Introduction

Technology, social and environmental trends are transforming value creation in manufacturing. Increasingly, governments and industry are recognising the significant role of R&I in boosting the growth and competitiveness of the manufacturing sector. In the United Kingdom (the UK) manufacturing represents two-thirds of the total R&D expenditure performed by businesses.[10] In order to sustain and increase the rate of innovation and research in this sector, different policy measures will be needed, including strategic international collaboration. International R&I collaboration offers countries the possibility to strengthen capabilities and shorten innovation cycles through pooling resources and sharing risks. International collaboration can also contribute to scaling up R&I skills.

The UK has a strong track record of bilateral and multilateral research and innovation cooperation. Recently, the government announced its commitment to deepening international partnerships in the *International Research and Innovation Strategy* and the *UK Research and Development Roadmap*, citing reasons ranging from the ability to tackle global challenges, to accessing research expertise and facilities, and trade and diplomacy.

Progress has been made in strengthening international collaboration, for example, through collaborative R&I calls launched by Innovate UK with countries including the United States, South Korea and Canada. However, it is believed that additional opportunities exist to support international collaboration between the UK and partner countries.

Against this background, this study provides insights into key emerging technology domains, where international research and innovation collaboration has the potential

"We want to tackle the greatest challenges of the world including our four Grand Challenges by building well-funded collaborative partnerships with other nations."

HMG (2019). International Research and Innovation Strategy, p. 8.

"Research and innovation are inherently global, and international collaboration and mobility of talent are associated with more impactful research. The UK's leading researchers and innovators want to collaborate with the best talent in the world, in the best facilities in the world, regardless of borders. These international collaborations lead to new advances and discoveries, pushing the frontiers of knowledge faster and further. They underpin the UK's position as a world-leading knowledge economy and support trade, investment, diplomacy, defence and security."

HMG (2020). UK Research and Development Roadmap, p. 18.

to unlock significant and strategic value-capture opportunities for the UK advanced manufacturing and materials sector.

The approach followed in this study involved four key tasks (Figure 1):

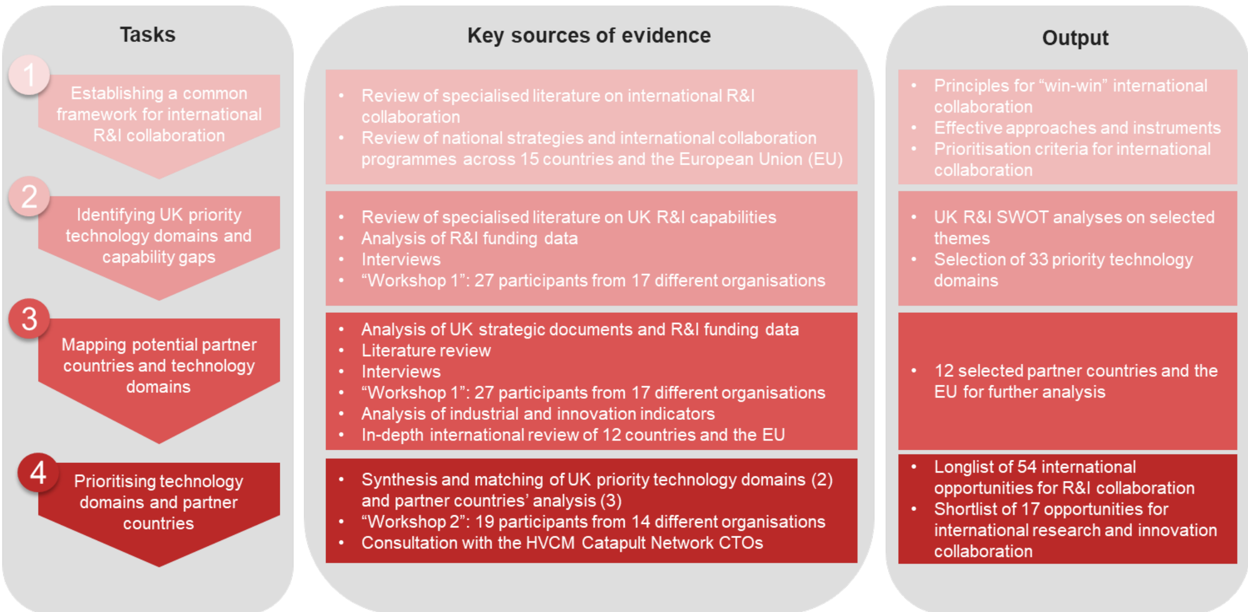
1. **Establishing a common framework for R&I international collaboration.** Defining principles for "win–win" international collaboration; identifying effective approaches and instruments; and developing prioritisation criteria for international collaboration.

2. **Identifying UK priority technology domains and capability gaps.** Identifying the key strengths and needs within the UK innovation system in relation to M&M; mapping the key technology domains of strategic value across the national innovation system; and selecting priority technology domains that could benefit from international collaboration.

3. **Mapping potential partner countries and technology domains.** Identifying key innovative countries/ territories in UK priority technology domains.

4. **Prioritising technology domains and partner countries.** Selecting strategic international R&I collaboration opportunities.

FIGURE 1 STUDY APPROACH



2. International R&I Collaboration

International R&I collaboration offers countries the possibility to strengthen capabilities and shorten innovation cycles through pooling resources and sharing risks. However, international collaboration can also involve more challenging governance structures and create new risks compared to projects involving domestic partners only. Drawing upon the review of national strategies and programmes, this section first discusses the motivations behind countries' participation in international R&I collaboration and the policy instruments employed in international practice to make it happen. It then discusses "win–win" principles to realise the intended benefits of international collaboration, reflects on what can go wrong and identifies criteria for prioritisation among potential collaboration opportunities.

2.1 Motivations for international R&I collaboration

Based on the review of previous studies and the international R&I collaboration strategies and programmes of 16 countries and territories (Australia, Canada, China, France, Germany, India, Israel, South Korea, Japan, Singapore, Sweden, Switzerland, Taiwan, the US, the UK and the EU), all characterised by strong industrial and innovation systems and a track record in international collaboration, five key motivations for international R&I collaboration were identified: (i) research and innovation excellence, (ii) economic competitiveness, (iii) grand challenges, (iv) diplomacy, and (v) additionality. These are summarised in Table 2.1.

TABLE 2.1 MOTIVATIONS FOR INTERNATIONAL R&I COLLABORATION (GOVERNMENT PERSPECTIVE)

Research and innovation excellence	Economic competitiveness	Grand challenges	Diplomacy	Additionality
Strengthening capabilities and improving scientific and innovation outcomes	*Enhancing industrial innovation capabilities and productivity*	*Contributing to the solution of global societal challenges*	*Supporting foreign policy goals and influencing R&I governance*	*Contributing to greater R&I activity*
Access to: • Knowledge and technology • Research facilities and equipment • Research talent • Additional research funds • Research and innovation networks • Education and training programmes	• Attraction of foreign direct investment Access to: • Global markets • Start-up ecosystem/ venture capital/ incubation support • Technology centres/ applied research centres • Industrial talent • Workforce development programmes • Critical production input	• Increased ability to address research and industrial challenges that require international collaboration • Exchange of expertise and lessons learned, with countries addressing similar societal challenges	• Trade policy priorities • Defence and security priorities • Influence in research and innovation governance (regulation, standards, ethics) • Contribution to international development • Contribution to regional linkages	• Public support, leading to greater private-sector R&I activity addressing market and system failures • Access to additional sources of funding • Alignment with UK strategic priorities

Source: Policy Links, based on national and EU strategies and collaboration programmes and the following studies: Boekholt et al. (2009). Drivers of International collaboration in research; European Commission (2014). Basic principles for effective International Science, Technology and Innovation Agreements; Technopolis (2005). Drivers, Barriers, Benefits and Government Support of UK International Engagement in Science and Innovation; Ulrichsen, T. C. and Featherston C. (2017). The nature, location, and functioning of international research collaborations; Zacharewicz, T., Sanz Menendez, L. and Jonkers, K. (2017). The Internationalisation of Research and Technology Organisations.

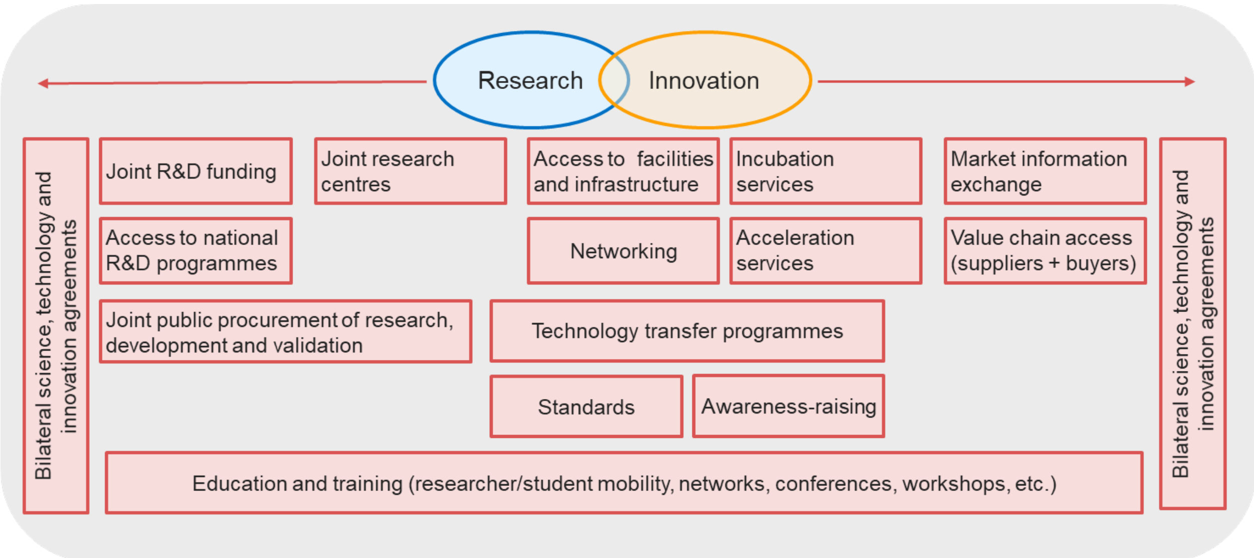
2.2 Instruments for international R&I collaboration

A variety of policy instruments can be deployed to enable international R&I collaboration, as Figure 2.2 illustrates. International R&I collaboration usually operates under the framework of bilateral science and technology and innovation (STI) agreements, often formalised through memorandums of understanding (MoU). For example, the UK has signed bilateral STI agreements with Canada, China, India, Israel, Japan, Singapore, South Korea and the US.

UK Research and Innovation (UKRI) and Innovate UK operate different instruments to support international R&I collaboration. Examples of these include:

- Bilateral and multilateral R&I funding programmes to support businesses in their collaborative innovation projects.
- Official development assistance (ODA). Through the Newton Fund and the Global Challenges Research Fund (GCRF), UKRI supports R&I collaboration between the UK and emerging knowledge economies.
- Global Business Innovation Programmes. Support for businesses to prepare for, and attend, overseas missions that can help them to explore and exploit innovation opportunities.
- Global Incubator Programme. Four-stage programme supporting companies' participation in a business incubator in a global market.
- Access to EU programmes. Support to facilitate business access to R&I EU programmes.[11]

FIGURE 2 INSTRUMENTS FOR INTERNATIONAL R&I COLLABORATION



Source: Policy Links, based on a review of international R&I programmes across 16 countries/territories (Australia, Canada, China, France, Germany, India, Israel, South Korea, Japan, Singapore, Sweden, Switzerland, Taiwan, the US, the UK and the EU).

Joint R&D funding programmes are the most common instrument used for collaborating internationally in research activities. The Canada–UK Artificial Intelligence Initiative is an example of this type of programme. Launched in 2019 and funded by the FIC, the aim is to promote interdisciplinary AI research. The initiative was coordinated by four research councils, part of UK Research and Innovation (UKRI) and three Canadian federal research funding agencies.[12]

Joint R&D funding programmes can focus exclusively on supporting collaboration between research organisations or support collaborative R&I between firms and between firms and research organisations, usually at higher TRLs. The German Central Innovation Programme for SMEs (ZIM), for example, supports collaboration between SMEs and between SMEs and research organisations. Projects supported should focus on the development of new products, technical services and better production processes, with high market potential.[13]

The EU's Horizon 2020 (H2020) is the world's largest multinational programme for research, development and innovation, with a budget of €100 billion.[14] Innovation activities funded by H2020 include: prototyping, testing, demonstrating, piloting, large-scale product validation and market replication.[15] An evaluation of the UK involvement in the round ran for the period 2007–13 and found that the opportunities most valued by UK business from their participation in the programme included: (i) prototype development, demonstrations and pilots; (ii) newly acquired knowledge about industrial processes or business parameters; (iv) improving skills; and (iv) accessing research infrastructure or equipment.[16]

Joint research centres, either virtual or physical, are commonly used as an umbrella for collaboration. India, for example, has established several bi-national science and technology centres, including: the Indo-French Centre for Promotion of Advanced Research (IFCPAR/CEFIPRA);[17] the Indo-US Science & Technology Forum (IUSSTF);[18] and the Indo-German Science & Technology Centre (IGSTC).[19]

There are international R&I programmes that focus on specific needs, such as access to facilities and infrastructure, and the development of standards, which contribute to research, as well as to innovation activities. In Australia the Linkage Infrastructure, Equipment and Facilities (LIEF) programme facilitates collaborative arrangements for the acquisition and use of research equipment and infrastructure for both higher education organisations and industry.[20]

In Germany the *Plattform Industrie 4.0* and related bilateral and multilateral cooperation agreements tackle, among other issues, the development of reference architecture, standards and norms for Industry 4.0 technologies. Germany is collaborating in this area with Australia, Austria, China, the Czech Republic, Italy, France, Japan, Mexico, the Netherlands, the US and Switzerland.[21]

H2020 Coordination and Support Actions (CSA) grants fund "accompanying measures" that facilitate the diffusion of knowledge, including: standardisation, awareness-raising, networking and policy dialogues.[22] Eureka is another EU programme supporting international R&I collaboration, particularly involving market-driven industrial R&D. According to a recent evaluation, the higher flexibility of Eureka is beneficial for industrial stakeholders. Eureka is a framework that groups together several instruments, including Eureka Clusters, which supports the creation and consolidation of consortiums of SMEs, large companies, research institutes, universities and end-users.[23]

A number of countries have developed international collaboration programmes to support the incubation and acceleration of companies, similar to Innovate UK's Global Incubator Programme. Israel, for example, operates a programme that facilitates collaboration between Israeli start-ups and multinational corporations (MNCs). France and China are also collaborating in this area. In 2011 the French Institut Pasteur Shanghai (IPS) and the Chinese Academy of Sciences (CAS) established the start-up accelerator Advance BioChina (ABC). This decision responded to the fast growth experienced by the biomedical sector in China.[24] ABC is based in Shanghai and provides assistance to biotech start-ups. Support offered includes: technical expertise, access to laboratories and hospitals and advice on the protection of intellectual property.[25]

Israel also supports start-ups reaching partners in emerging markets and adapting their products to these markets. The Israeli Incentive Program for Adapting Products for Emerging Markets funds up to 50% of the expenditure required to make technological and engineering adaptations to their products in accordance with the standards and needs of the target market.[26]

International collaboration can also contribute to scaling up R&I skills. For example, the EU's Marie Sklodowska-Curie European Industrial Doctorate (EID) programme helps PhD candidates to develop skills in industry. Individuals are enrolled in a doctoral programme and jointly supervised by academic and non-academic partners in at least two different EU or associated countries.[27]

Public procurement and inducement prizes are policy instruments that are increasingly used in international R&I collaboration. In comparison with the instruments discussed before, which focus on supporting the supply side of research and innovation, public procurement aims to leverage the demand side. Public procurement and inducement prizes are particularly well suited to addressing "grand" challenges. Pre-commercial public procurement (PCP), public procurement for innovation (PPI) and inducement prizes are among the EU's H2020 instruments used to fund research and innovation activities. Challenges funded through these instruments in the last five years include: an ageing population, CO2 reuse, clean car engines, cyber-security, and materials for clean air.[28]

2.3 Principles for "win–win" international R&I collaboration

In order to ensure that international R&I collaboration benefits all of the partners involved in an equitable and sustainable manner, some principles should be followed when identifying partner countries and establishing collaboration. Based on the review of previous studies[29] and international R&I collaboration strategies and programmes across 16 countries/territories,[30] five key principles for "win–win" international R&I collaboration were identified:

- **Reciprocity**. Establishing collaboration that strengthens R&I capabilities and involves mutual benefits and the true intellectual participation of all partners. Effective and reciprocal collaboration usually builds on complementary competencies and evident synergies and thus a good understanding of partners' capabilities and the risks involved in the collaboration.

- **Transparency**. Establishing open communication channels and defining clear specifications on the rights and duties of all the partners involved, including: sources of funding; data management; publication procedures; intellectual property rights frameworks; contingency provisions; mediation; and conflict resolution.

- **Accountability**. Monitoring and evaluation of collaboration programmes are needed to measure and understand pathways to impact and improve the economic and social benefits derived from public investment.

- **Equity**. Recognising the different capabilities of the partners involved and defining goals and key performance indicators accordingly. An equitable partnership also involves defining goals collaboratively and embracing cultural differences.

- **Long-term perspective**. Adopting a long-term vision in the establishment of international collaboration that allows partners to scale up projects and catalyse national initiatives. This involves aligning international collaboration programmes with national priorities and establishing a shared vision with the partners involved. Predictability and commitment of long-term funding among the different actors involved is also essential for the establishment of sustainable partnerships.

2.4 Prioritisation criteria for international collaboration

Five criteria were defined to prioritise options for international R&I collaboration in this study: **(i) research and innovation excellence, (ii) economic competitiveness, (iii) grand challenges, (iv) additionality and (v) feasibility** (see Table 2.2). The first four criteria refer to opportunities that international R&I collaboration can unlock. While diplomacy was identified as a motivation for embarking upon R&I collaboration, it falls outside the scope of functions of R&I national agencies and was therefore omitted from the final criteria.

The feasibility criterion is defined as the viability of implementing collaboration in practice. It comprises ensuring the availability of long-term funding and appropriate institutions, as well as the existence of previous successful collaboration. This involves developing an adequate understanding of potential partners' capabilities and the risks involved in the collaboration, as well as the monitoring and evaluation of current collaboration to inform future decision-making.

TABLE 2.2 PRIORITISATION CRITERIA FOR INTERNATIONAL COLLABORATION

Opportunity	**Research and innovation excellence**	*The extent to which collaboration could help to strengthen UK research and innovation capabilities and improve scientific and innovation outcomes*	• Does collaboration offer UK actors access to knowledge and technology? Does it offer access to basic research facilities and equipment? • Does it offer access to research talent? • Does it offer access to research and innovation networks? • Does it offer access to education and training programmes?
	Economic competitiveness	*The extent to which collaboration could help gain access to markets and enhance the UK's industrial competitiveness*	• Does collaboration offer UK actors access to global markets? • Does it have the potential to attract foreign direct investment to the UK? • Does it offer access to start-up ecosystem/venture capital/incubation support? • Does it offer access to technology centres/applied research centres? • Does it offer access to new workforce skills? • Does it offer access to workforce development programmes?
	Grand challenges	*The extent to which collaboration could contribute to the solution of global societal challenges*	• Does collaboration help the UK to address societal challenges (net zero, ageing population, etc.)? • Does it enable an exchange of lessons learned/expertise, with countries addressing similar societal challenges?
	Additionality	*The extent to which collaboration could lead to greater research and innovation activity in the UK*	• Does collaboration leverage public funding, leading to greater private-sector R&I activity? • Does it offer access to additional sources of funding? • Is it aligned with/does it contribute to UK strategic priorities?
Feasibility		*The viability of implementing collaboration in practice*	• Does collaboration build on a previous track record of success? • Are resources and appropriate institutions available in the partner country? • Is there a long-term commitment to funding?

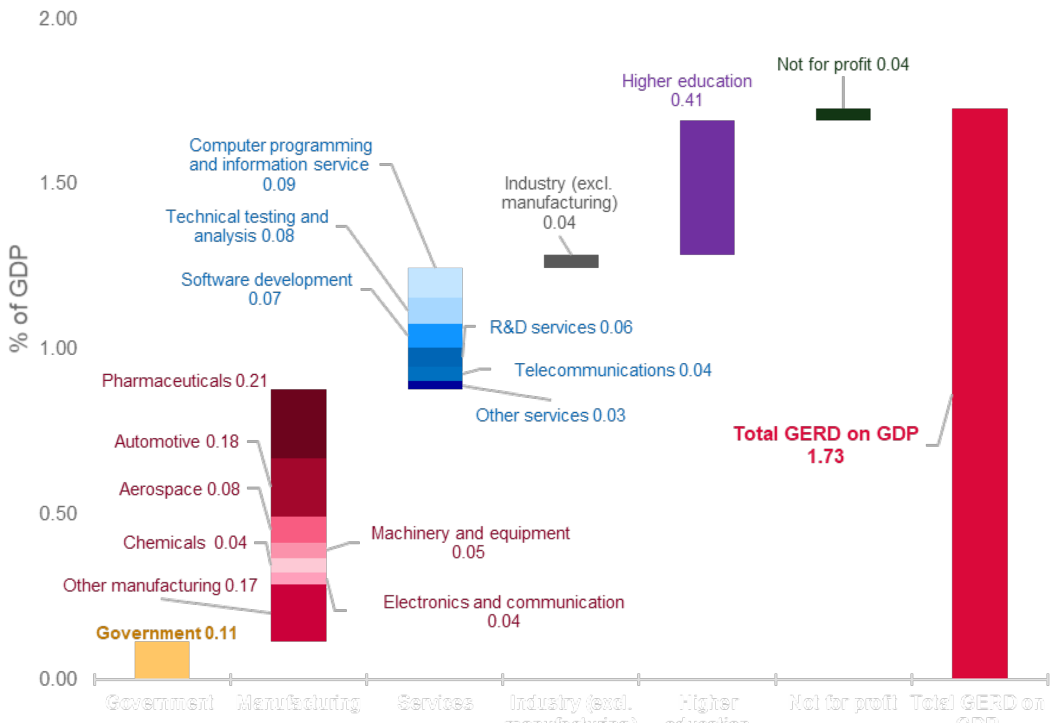
Source: Policy Links.

3. UK Manufacturing and Materials Research and Innovation in Perspective

The UK is an attractive partner for international collaboration in manufacturing, with a strong research and innovation profile. The UK manufacturing sector is diverse, with activities ranging from automotive, heavy machinery, aerospace, pharmaceuticals, chemicals and biotech, to food and drink. In terms of innovation and research output, the UK has numerous strengths in advanced manufacturing. It is these strengths that the UK could bring to international R&I collaboration in advanced manufacturing and materials.

The UK government has pledged to increase investment in R&D to 2.4% of GDP by 2027, and to increase public funding for R&D to £22 billion per year by 2024/25.[31] In this context, manufacturing industries remain the largest contributors to R&D expenditure (i.e. use of funding) across the UK, accounting for 42% of total GERD, with pharmaceuticals, automotive and aerospace performing 26.8% of total GERD, as shown in Figure 3.1. In terms of funding sources for R&D activities, the UK business sector as a whole contributes nearly 55% of the total.[32]

FIGURE 3.1 UK R&D EXPENDITURE BY SECTOR OF PERFORMANCE (GROSS DOMESTIC EXPENDITURE ON R&D AS PERCENTAGE OF GDP, 2018)

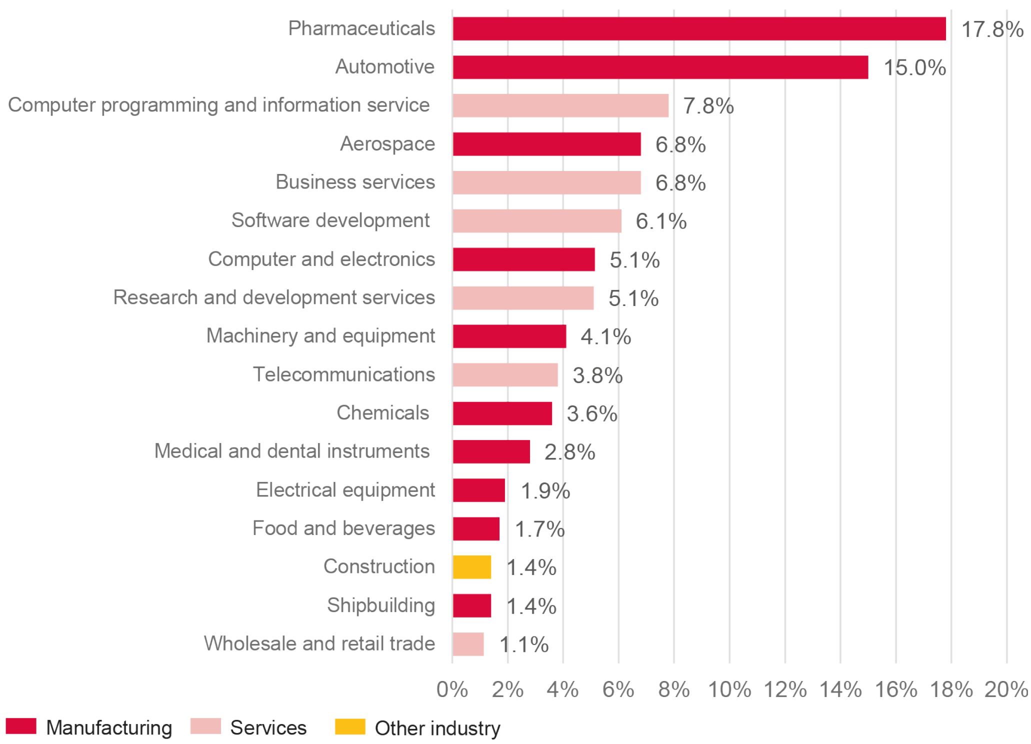


Note: Industry includes: agriculture and fishing; extractive industries; electricity, gas and water; construction.
Source: Policy Links (2020). UK Innovation Report. University of Cambridge. Elaborated with data from ONS (2020). Research and Development in UK Businesses, 2018 Datasets; OECD (2020). Main Science and Technology Indicators.

A closer examination of the business R&D expenditure in the UK, shown in Figure 3.2, indicates that in 2018 pharmaceuticals, automotive and the aerospace industries accounted for around 40% of total business R&D expenditure in the UK. These are followed by other manufacturing sectors such as computers and electronics (5.1%), machinery and equipment (4.1%), chemicals (3.6%), medical and dental instruments (2.8%), electrical equipment (1.9%), food and beverages (1.7%) and ship-building (1.4%).

When looking solely at which manufacturing sub-sectors have the highest R&D intensity, as measured by the sector expenditure on R&D as a percentage of sales, clear differences between sectors emerge: whereas pharmaceuticals and electronics and communication equipment have the highest R&D intensity, at around 35%, automotive and aerospace show a lower R&D intensity, at 6.6% and 6.4%, respectively. Between this, the computer sector shows 22% R&D intensity, while all other manufacturing sectors remain below 7.5% R&D intensity.

FIGURE 3.2 BUSINESS R&D EXPENDITURE IN THE UK (PERCENTAGE OF TOTAL BUSINESS ENTERPRISE R&D EXPENDITURE [BERD] BY PRODUCT, 2018)



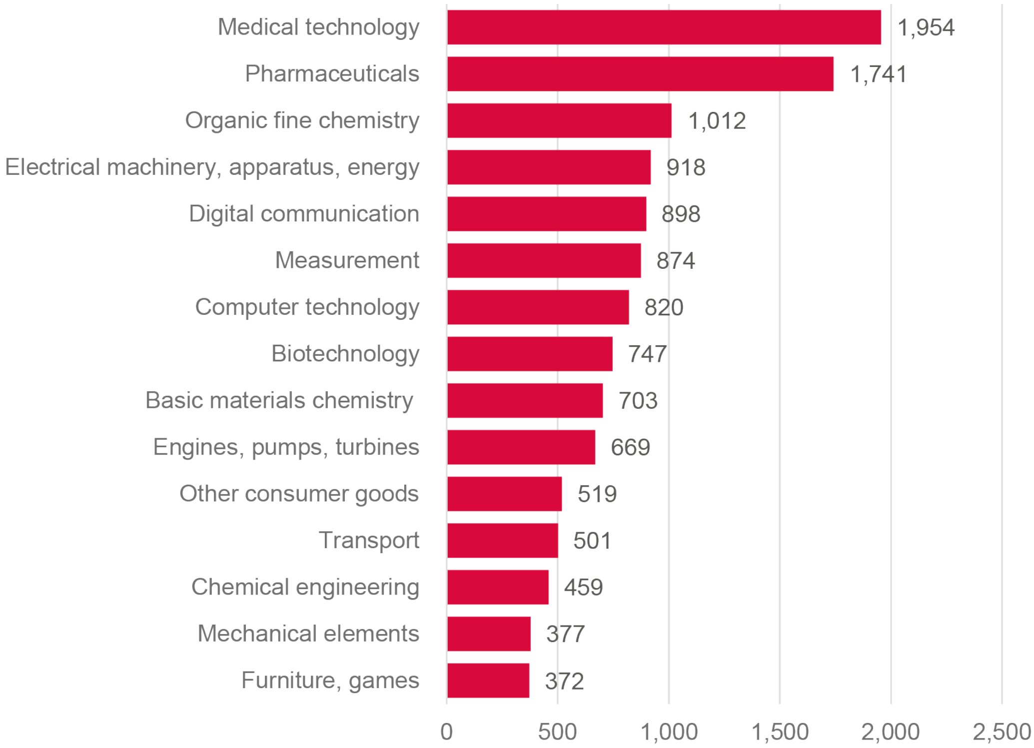
Source: Policy Links (2020). UK Innovation Report. University of Cambridge. Elaborated with data from ONS (2020). Business enterprise research and development.

In terms of innovation output, although it is difficult to define the boundaries of exactly which scientific and technological fields fall under manufacturing and materials, data on UK triadic patents by technology domain (as defined by the World Intellectual Property Organization – WIPO) shows a significant prevalence of patents in the medical technology and pharmaceuticals fields (Figure 3.3). Notable manufacturing and materials fields in this list include: electrical machinery, apparatus and energy; measurement; computer technology; basic materials chemistry; engines, pumps and turbines; and other consumer goods; among other categories.

The UK is internationally recognised for the research leadership and excellence of its scientific institutions. For example, the UK maintains its leadership as having one of the highest shares in the world's international publications, after China and the US. Furthermore, the UK's international publications are more likely to be highly cited compared to countries such as the US, Germany and the OECD average.[33]

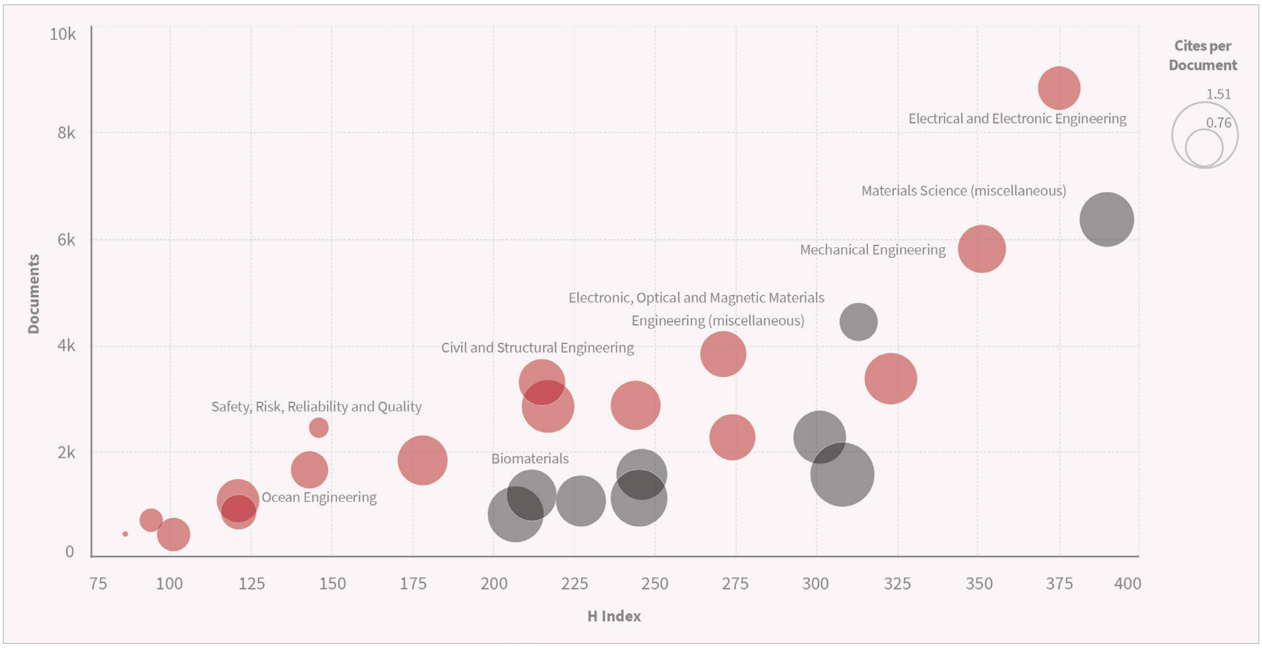
In terms of basic research output, data on UK scientific publications (2019–20), extracted from the Scopus database for the fields of engineering and materials science, shows a wide variety of specialisation areas, as shown in Figure 3.4. Whereas electrical and electronic engineering and (miscellaneous) materials science show the highest number of publications and h-index,[34] industrial and manufacturing engineering falls towards the middle of the chart, which can be simply interpreted as an area with lower scientific activity compared to other fields in the UK.

FIGURE 3.3 UK TRIADIC PATENTS BY TECHNOLOGY DOMAIN (TOP 15, WIPO TECHNOLOGY FAMILIES, BY INVENTOR COUNTRY OF RESIDENCE, 2007–2016)



Note: A triadic patent family is defined as a set of patents registered at the European Patent Office (EPO), the Japan Patent Office (JPO) and the United States Patent and Trademark Office (USPTO).
Source: Policy Links (2020). UK Innovation Report. University of Cambridge. Elaborated with data from OECD (2020). Science, Technology and Patents database.

FIGURE 3.4 UK SCIENTIFIC PUBLICATIONS IN ENGINEERING (BLUE) AND MATERIALS SCIENCE (GREEN) (2019–2020, AS DEFINED IN SCOPUS DATABASE)



Source: Adapted from SCImago (n.d.). SJR — SCImago Journal & Country Rank [Portal]. Retrieved 9 February 2021, from http://www.scimagojr.com

3.1 Strengths in UK manufacturing and materials research and innovation

The manufacturing sector represents a key driver of innovation in the UK, covering a broad range of research and innovation sub-domains, including manufacturing technologies, materials engineering, chemical engineering, and optics, photonics and electronics engineering, among many others.

In order to identify potential opportunities for international research and innovation collaboration within this broad universe of technological areas, general insights from an extensive expert consultation and a review of specialised literature have been captured. These have been organised across three key themes defined by Innovate UK:[35]

- Net-zero manufacturing
- Industrial digitalisation
- Supply chain resilience

3.1.1 Key findings: net-zero manufacturing

Within net-zero manufacturing, UK strengths include a significant internal market, with a high percentage of renewable energy and world-leading net-zero targets and significant government financial support for development in this area. The UK is the fourth largest vehicle manufacturer in Europe, with a decade of experience in electric vehicle (EV) battery production, and existing R&I in high-energy battery technologies through the Faraday Battery Challenge and materials such as graphene.

In terms of technological capability, the UK is a global leader in lightweight technologies, particularly aluminium vehicle structure technologies, and in composite materials. The UK is a global leader in the aerospace, defence and motorsport industries. It has world-class engineering service providers and experience in manufacturing lower-power electric machine and power electronics. It has an advanced civil nuclear sector, from fuel production, generation, new build, to research through decommissioning, waste management and transportation and a world-class regulatory system.

3.1.2 Key findings: industrial digitalisation

Within industrial digitalisation, UK strengths include its universities, particularly in computer science, and world-class digital companies, start-ups and funding.

The UK has the strongest AI and machine learning market in Europe, with over two hundred SMEs, and a thriving ecosystem of researchers, developers and investors in AI. For example, the UK aerospace sector is already supporting the development and adoption of AM, AI, data analytics and virtual/augmented reality (VR/AR).

The UK has a very strong electech sector, which is essential to the future of automation and robotics, and the UK ecosystem offers capabilities in smart connectivity and autonomous systems.

The UK is a world leader in developing additive manufacturing (AM) and a pioneer of its commercialisation in medicine, aerospace and other industry sectors, with a well-established research community. It is a pioneer in the use of digital technology to enable servitisation of manufacturing, and the UK energy and pharmaceuticals businesses, in particular, are industry leaders in digitalisation.

The UK also has expertise in cyber-security, as well as strengths in regulations, codes and standards.

3.1.3 Key findings: supply chain resilience

Within the area of supply chain resilience, the UK supply chain has the ability to adapt and reconfigure when under stress. Catapults and the wider RTO base in the UK provide the ability to develop new technology solutions to be exploited across the supply chain, and the UK has a strong research base in decision sciences, including operational research. Regulators in the UK are internationally respected and they have significant legacy expertise.

Specifically, the UK also has strengths in end of life and decommissioning, in sectors such as aerospace and nuclear, as well as materials handling expertise. The UK is also a global leader in food safety and traceability systems. UK capabilities outside manufacturing in the digital tech sector could be leveraged to support supply chain resilience.

4. UK Technology Priorities

To identify key opportunities for international research and innovation cooperation, this report suggests that it is first necessary to map key areas of strategic value for various stakeholders across the national innovation system. A three-step approach has been followed to carry out this analysis, as depicted in Figure 4.1.

The analysis involved a combination of research, stakeholder consultations via interviews and an online workshop. This drew heavily upon a wide consultation with representatives from academia, industry and government, including research councils, Catapult centres, R&I funding programmes and industry associations, as well as a workshop that brought together a total of 27 participants from 17 different organisations.

FIGURE 4.1 PROJECT APPROACH TO IDENTIFY A LONGLIST OF UK TECHNOLOGY PRIORITIES IN M&M

Data Sources

a. Desk research review of selected reports, databases and websites;
b. Review of specialised literature;
c. Interviews and workshop consultation with relevant stakeholders from the UK innovation system (e.g. research councils, catapult centres, government agencies).

Step 1: Broad Map of UK Technology Priorities

- Stated priorities from selected funding institutions and programmes;
- Stated priorities from selected research and technology institutions;
- Technology priorities as perceived by consulted experts;
- Technology priorities extracted from specialised literature review;
- Technological scope of previous international collaborations.

~205 technology domains

Step 2: Quantitative Filter

- Technology domains most commonly found across the various sources of data from Step 1;
- Key technology domains put forward by consulted experts.

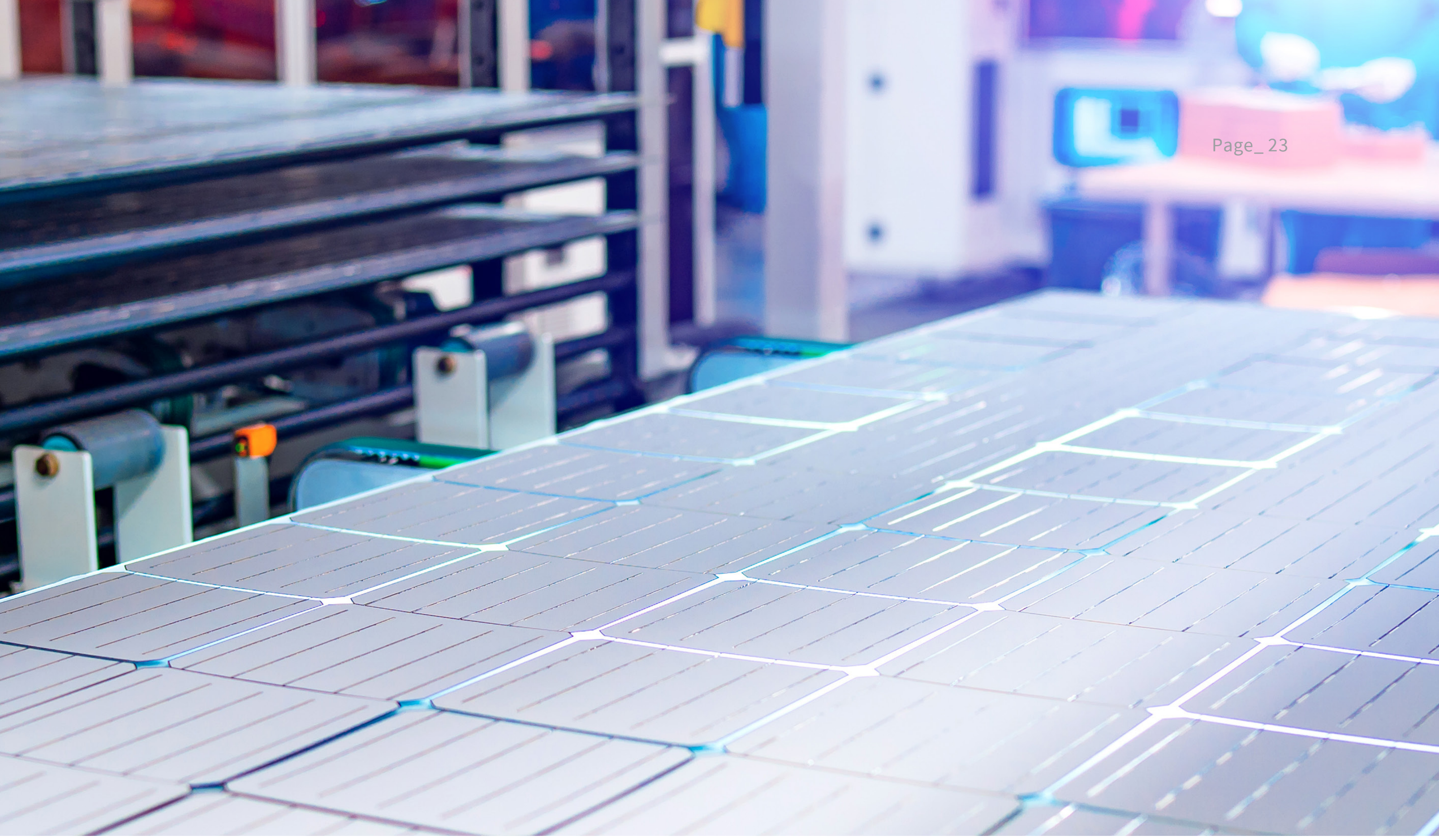
~48 technology domains

Step 3: Qualitative Filter

Prioritisation based on qualitative insights from stakeholder consultation and literature review (i.e. Section 3 SWOT analysis):

- Potential to enhance competitiveness of existing UK industries;
- Potential to support the development of future industries;
- Ability to support existing UK R&I strengths and/or address key weaknesses in the UK R&I landscape.

~33 technology domains



Through the workshop discussions, interviews and literature review, it became apparent that the value of specific technology domains for the UK was often framed around four key arguments by the different sources consulted, as follows:

Industrial competitiveness:

- The potential to enhance the competitiveness of existing UK industries; and
- The promise to support the development of future industries in the country.

Research and innovation excellence:

- The need to maintain current strengths in strategic UK research and innovation areas; and
- The possibility to address key weaknesses in strategic UK research and innovation areas.

Based on this framework, a total of 33 technology domains were selected to work as the basis for exploring potential international R&I collaboration, as shown in Table 4.1. The selected technology domains represent key areas showing strong alignment with UK national strategic development goals and where further R&I development efforts could lead to significant benefits for the country, according to the evidence collected in this report.

In doing this selection, it is necessary to consider that some technology domains can both enhance the competitiveness of existing sectors and represent future new sectors in their own right. For example, artificial intelligence (AI) applications in manufacturing are broadly considered to be fundamental enablers of Industry 4.0 toolkits and support programmes around the world. However, AI is also perceived as a nascent future sector in its own right, with applications expected to go beyond the manufacturing world and predicted to grow in complexity and value through increased research and development efforts.

The list of technology domains presented in Table 4.1 has been used as the basis to identify matching capabilities and priorities in advanced manufacturing and materials (M&M) in potential partner countries in the rest of this report.

TABLE 4.1 TECHNOLOGY DOMAINS SELECTED TO EXPLORE OPPORTUNITIES FOR INTERNATIONAL RESEARCH AND INNOVATION COOPERATION

Theme	Tech group	Technology domain (long name)	Technology domain (short name)	Selection rationale			
				INDUSTRIAL COMPETITIVENESS		RESEARCH & INNOVATION EXCELLENCE	
				Enhance competitiveness of existing UK industries	Support the development of future industries	Support current strength in strategic area	Address current weakness in strategic area
Net zero	(A) ENERGY STORAGE	Batteries for vehicles, consumer electronics, aviation and large-scale energy storage (lithium-ion, lithium-sulphur, lithium-metal, solid-state and non-lithium technologies) – improving battery lifespan and range, reuse, remanufacture and recycling	Batteries	✓	✓	✓	
Net zero	(B) CIRCULAR ECONOMY	Remanufacturing	Remanufacturing		✓		✓
Net zero	(B) CIRCULAR ECONOMY	Sustainable plastic packaging – design, production, supply, recovery and recycling of plastic packaging	Sustainable plastics	✓		✓	
Net zero	(C) FUTURE TRANSPORT	Connected and autonomous vehicles (CAV) – demonstration, safety validation, insurance and service models	Autonomous vehicles		✓		✓
Net zero	(D) GREENHOUSE-GAS REMOVAL (GGR) TECHNOLOGIES	Application of carbon capture, utilisation and storage (CCUS) in industry, as well as design and manufacturing of CCUS systems and infrastructure	CCUS	✓	✓	✓	
Net zero	(E) HYDROGEN	Development of combustor systems and fuel tanks to allow the conversion of current aircraft configurations to hydrogen-powered variants	Hydrogen: aerospace	✓			✓
Net zero	(E) HYDROGEN	Hydrogen fuel cells for transport (e.g. maritime, aerospace, rail, road vehicles, heavy-duty vehicles) and industrial applications	Hydrogen: fuel cells		✓		✓
Net zero	(E) HYDROGEN	Large-scale green hydrogen production, transport and use (e.g. from offshore wind surplus energy)	Green hydrogen production		✓		✓
Net zero	(F) LOW-CARBON TRANSPORT	Electric vehicles (and delivery of electric vehicle charging infrastructure)	Electric vehicles	✓		✓	
Net zero	(F) LOW-CARBON TRANSPORT	Hydrogen vehicles	Hydrogen vehicles		✓		✓
Net zero	(G) POWER ELECTRONICS	Power electronics, machines and drives (particularly in relation to the propulsion and electrification of transport)	Power electronics	✓	✓	✓	
	(H) ADVANCED MATERIALS	Materials informatics (e.g. machine learning and small-scale high-throughput experiments and testing, computational materials, virtual design, modelling and simulation of materials, processes and the interfaces between models)	Materials informatics	✓		✓	

Industrial digitalisation and supply chain resilience	(I) ARTIFICIAL INTELLIGENCE	Artificial intelligence and machine learning -– programming and application	AI and ML	✓	✓	✓	
	(J) AUTOMATION	Bespoke automation and machine-building	Automation and machine-building	✓			✓
		Robotics (including low-cost robotics)	Robotics	✓		✓	
	(K) DATA SCIENCE	(Big) data analytics and visualisation	Data science and sensors	✓		✓	
		Data science and database management (and data governance)	Data science and sensors	✓		✓	
		Data capture, management and sensors	Data science and sensors	✓		✓	
	(L) DIGITAL	Augmented reality/virtual reality for manufacturing applications	AR and VR	✓	✓	✓	
		Cyber-security technologies	Industrial cyber-security	✓	✓	✓	
		Digital twins and virtual testing of facilities and processes to optimise future designs or current states	Digital twins	✓	✓		✓
		Internet of things (IoT) and industrial Internet of things (IIoT)	IoT and IIoT	✓	✓	✓	
	(M) SYSTEM INTEGRATION	Digital systems integration and interoperability (including integration with legacy systems)	Digital systems integration	✓			✓
		Digital end-to-end supply chain integration (digital thread)	End-to-end SC integration	✓			✓
	(N) SYSTEMS ENGINEERING	Predictive, self-reconfiguring system	Predictive systems	✓	✓	✓	
Other M&M thematic priorities	(O) BIOTECH	Bio-derived materials, including biomedical materials ("smart" biomaterials that improve health and well-being)	Bio-derived materials manufacturing	✓	✓		✓
		Bio-refinery, including circular waste solutions	Bio-refinery processes	✓		✓	
		Synthetic biology manufacturing	Synthetic biology manufacturing	✓		✓	
	(P) HIGH-PERFORMANCE COMPUTING	High-performance computing	High-performance computing	✓		✓	
		Quantum computing (quantum-scale engineering) for new products and services of sectors, including automotive, healthcare, infrastructure, telecommunications, cyber-security and defence	Quantum systems manufacturing		✓	✓	
	(Q) PRODUCTION TECHNOLOGY	Additive manufacturing (approved and right-first-time solutions)	Additive manufacturing	✓		✓	
		Laser-based manufacturing processes	Laser-based processes	✓		✓	
	(R) ADVANCED MATERIALS	Graphene and other 2D materials (atomic thickness materials) for applications such as membranes for filtration and coatings, energy storage and functional composites	Graphene and 2D materials		✓	✓	

5 International Review of Research and Innovation Priorities

The first step to identifying UK priority partner countries involved the analysis of stated and observed priorities from strategic documents and funding databases. In addition to this desk-based analysis, consultations were conducted with key stakeholders in the UK from government, academia and industry to identify potential future priorities. Table 5.1 (below) shows the main sources of information reviewed, as well as the list of consulted stakeholders. The qualitative analysis led to the identification of a longlist of 45 priority countries for international collaboration with the UK.

TABLE 5.1 QUALITATIVE ANALYSIS – SOURCES OF EVIDENCE CONSULTED TO SELECT KEY UK INTERNATIONAL PARTNERS

Qualitative analysis	Stated and observed priorities	**Sources examined include:** • Secretary of State for Foreign and Commonwealth Affairs • Department for International Trade • Fund for International Collaboration • Innovate UK • Science and Innovation Network • Engineering and Physical Sciences Research Council • European Commission's funding databases; Newton Fund • Global Research Challenges Fund • Studies on manufacturing research collaboration
	Stakeholder consultation	**Key stakeholders consulted include:** • ADS Group; Advanced Manufacturing Research Centre (AMRC); Department for Business; Energy and Industrial Strategy (BEIS); Department for International Trade (DIT); Centre for Process Innovation (CPI); East Anglian Motor Auctions (EAMA); Food and Drink Federation (FDF); High Value Manufacturing Catapult (HVMC); Hyde Aero; Innovate UK; Institute for Manufacturing; Industrial Strategy Challenge Fund (ISCF) – Faraday Challenge; ISCF – Transformation Foundation Industries; ISCF – Smart sustainable plastic packaging; Knowledge Transfer Network (KTN); Made Smarter; Manufacturing Technology Centre (MTC); National Composites Centre (NCC); National Manufacturing Institute Scotland (NMIS); Queens University of Belfast; Science and Innovation Network; Society of Motor Manufacturers and Traders Ltd (SMMT); University of Sheffield Advanced Manufacturing Research Centre (AMRC); and the University of Nottingham.

The second step to identifying UK priority partner countries involved the analysis of quantitative indicators about international industrial competitiveness, research and innovation (Table 5.2). For each indicator, a cross-country comparison was conducted to highlight the main strengths and weaknesses of the world's leading countries to select the candidates with the highest potential to meet the principles of win–win collaboration established in Section 2.

TABLE 5.2 QUANTITATIVE ANALYSIS – INDUSTRIAL AND INNOVATION INDICATORS REVIEWED

Quantitative analysis	Industrial activity	**Indicators analysed:** • Manufacturing value added (MVA), growth • Manufacturing exports, growth • UK trade partners
	Innovation activity	**Indicators analysed:** • R&D expenditure, growth • Number of publications, growth, and publications by field • Co-publications with the UK • Triadic patent families • Triadic patent families by field • Co-patents with the UK • Unicorns

The findings of the quantitative analysis were matched with the longlist of priority countries identified through the qualitative analysis. This process led to the selection of 13 countries/territories as having the potential for effective international research and innovation collaboration with the UK in advanced manufacturing and materials. The final selection also reflects, however, the consulting team's interpretation of the evidence and therefore involves an element of judgement.

The following table summarises the conclusions of the analysis that led to the selection of UK priority countries for collaboration in advanced manufacturing and materials and highlights the key criteria used to justify the selection of each country.

Consultations were conducted with key stakeholders in the UK from government, academia and industry to identify potential future priorities.

TABLE 5.3 OVERVIEW OF SELECTED PRIORITY COUNTRIES/TERRITORIES

Country/ territory	Selection criteria
Australia	Stated and observed priority country; consultation
	Top UK partner for international publications
	Leading country in patent applications in selected advanced manufacturing technologies
	Top UK partner for patent applications
Canada	Stated and observed priority country; consultation
	Leading manufacturing country by share of world manufacturing value added
	Leading manufacturing country by share of world manufacturing exports
	Main UK trade partner
	Leading country by share of world international publications
	Top UK collaborative partner for patent applications
	Leading country in patent applications in selected advanced manufacturing technologies
China	Leading manufacturing country by share of world manufacturing value added
	Leading manufacturing country by share of world manufacturing exports
	Main UK trade partner
	Leading country by share of world international publications
	Top UK partner for international publications
	Leading country in patent applications
	Top UK partner for patent applications
	Leading country by number of unicorns
The EU	Five countries as leading manufacturing country by share of world manufacturing value added
	Six countries leading manufacturing country by share of world manufacturing exports
	Main UK trade partner
	Nine countries as leading countries for R&D expenditure
	Thirteen countries among top UK partners for international publications
	Leading countries in patent applications
	Eleven countries among top UK partners for patent applications
Germany	Stated and observed priority country; consultation
	Leading manufacturing country by share of world manufacturing value added
	Leading manufacturing country by share of world manufacturing exports
	Main UK trade partner
	Leading country for R&D expenditure
	Leading country by share of world international publications
	Top UK partner for international publications
	Top UK partner for patent applications
	Leading country in patent applications
	Leading country by number of unicorns
India	Stated and observed priority country; consultation
	Leading manufacturing country by share of world manufacturing exports
	Leading country by share of world international publications
	Leading country in patent applications in selected advanced manufacturing technologies
	Leading country by number of unicorns
Israel	Leading country for R&D expenditure
	Leading country in patent applications in selected advanced manufacturing technologies
	Top UK partner for patent applications
	Leading country by number of unicorns
Japan	Stated and observed priority country; consultation
	Leading manufacturing country by share of world manufacturing value added
	Leading manufacturing country by share of world manufacturing exports
	Main UK trade partner
	Top 10 for R&D spending
	Leading country by share of world international publications
	Leading country in patent applications
	Top UK partner for patent applications
South Korea	Stated and observed priority country; consultation
	Leading manufacturing country by share of world manufacturing value added
	Leading manufacturing country by share of world manufacturing exports
	Main UK trade partner
	Leading country for R&D expenditure
	Leading country by share of world international publications
	Top UK partner for international publications
	Top UK partner for patent applications
	Leading country in patent applications
	Leading country by number of unicorns
Singapore	Stated and observed priority country; consultation
	Main UK trade partner
	Leading country in patent applications in selected advanced manufacturing technologies
	Top UK partner for patent applications

Switzerland	Leading manufacturing country by share of world manufacturing value added
	Leading manufacturing country by share of world manufacturing exports
	Main UK trade partner
	Leading country for R&D expenditure
	Top UK partner for international publications
	Leading country in patent applications
	Top UK partner for patent applications
Taiwan	Leading manufacturing territory by share of world manufacturing exports
	Leading territory for R&D expenditure
	Leading territory in patent applications in selected advanced manufacturing technologies
The US	Stated and observed priority country; consultation
	Leading manufacturing country by share of world manufacturing value added
	Leading manufacturing country by share of world manufacturing exports
	Main UK trade partner
	Leading country for R&D expenditure
	Leading country by share of world international publications
	Top UK partner for international publications
	Leading country in patent applications
	Top UK partner for patent applications
	Leading country by number of unicorns

The selected 13 countries/territories were then further analysed to identify their technology priorities in advanced manufacturing and materials (M&M). Based on publicly available information, a country or territory is deemed to be prioritising a technology when it: (a) references the technology explicitly in national strategic documents; (b) includes the technology as a field of focus by designated research and technology centres; (c) creates specific initiatives and programmes surrounding the technology; and (d) has existing or planned international collaboration for the technology.[36] When strengths are stated – either by national governments or industry/trade organisations – the information is also captured.

The identified priorities were sorted into the thematic areas of net-zero manufacturing, industrial digitalisation, supply chain resilience and other/general advanced manufacturing and materials (Figure 5.1). While the best efforts have been made to provide a useful snapshot of countries' technology priorities, the review is not exhaustive, given the diversity of fields covered and the ever-changing innovation landscape in each country. The results from this analysis were used to identify key opportunities for international research and innovation collaboration, as explained in the following section.

FIGURE 5.1 INTERNATIONAL REVIEW OF TECHNOLOGY PRIORITIES FOR 12 ECONOMIES AND THE EU

6 Opportunities for International Research and Innovation Collaboration

To produce a final list of opportunities for international research and innovation collaboration in advanced manufacturing and materials, the insights from the technology analysis (Section 4) and international review of partner countries (Section 5) were combined. Additional prioritisation criteria were required in this process. For the longlisting exercise, top priority was given to the countries that meet all of the following requirements:

To produce a final list of opportunities for international research and innovation collaboration in advanced manufacturing and materials, the insights from the technology analysis (Section 4) and international review of partner countries (Section 5) were combined. Additional prioritisation criteria were required in this process. For the longlisting exercise, top priority was given to the countries that meet all of the following requirements:

- The specific UK technology domain under analysis represents a national priority in the partner country;
- The specific UK technology domain under analysis represents a research priority in the partner country;
- The partner country counts with national innovation initiatives in the specific technology domain under consideration;
- The partner country is already running international collaboration programmes in such technological areas;
- The partner country has a track record of previous collaboration with the UK in this or related technology areas.

The results of this analysis are summarised in Table 6.1. To agree on a shortlisted selection of opportunities, a second workshop was conducted to bring together a combination of stakeholders from government, industry and academia to assess and discuss the longlist of opportunities for international R&I collaboration.

- The outcome of this process led to the shortlisting of 16 opportunities for international research and innovation collaboration, which are summarised in Table 6.2. Overall, the following considerations were included in this selection:
- The list of technologies covered cannot be comprehensive given the diversity of fields analysed and their changing nature;
- This does not imply that some technologies are more important than others. Rather, these represent an initial selection considering the boundaries of this study (further work could look at other technologies);
- A variety of considerations exist when selecting potential countries for collaboration: not only "strengths" but also track record, national priorities, and so on;
- Looking at "UK plc" as a whole, not just individual institutions;
- Sought to come up with a "balanced" portfolio beyond the traditional list of countries already collaborating with the UK.

It should be noted that the results of this analysis only represent evidence that may feed into Innovate UK's decision-making, and this does not imply that Innovate UK will only seek to collaborate with these countries or around these technologies. It also does not guarantee a future call for proposals within these specific technology–country pairings.

TABLE 6.1 DISTRIBUTION OF LONGLISTED OPPORTUNITIES BY COUNTRY/TERRITORY

LONGLIST – Opportunities by Country and Technology			
Country/territory	**Net-zero manufacturing**	**Industrial digitalisation and supply chain resilience**	**Other/general**
Australia	• Green hydrogen production		
Canada	• Sustainable plastics	• Data science and sensors • End-to-end supply chain integration	• Quantum systems manufacturing
China	• **Batteries** • **Electric vehicles**	• Robotics	• Bio-refinery processes • Additive manufacturing
The EU	• **Hydrogen – aerospace** • **Power electronics**		
Germany	• **Batteries** • **CCUS** • **Hydrogen – fuel cells**	• Materials informatics • IoT and IIoT • Digital systems integration • Predictive systems	• High-performance computing • Graphene and 2D materials
India		• Digital twins	• Synthetic biology manufacturing
Israel		• Industrial cyber-security	• Quantum systems manufacturing
Japan	• Sustainable plastics • CCUS • Green hydrogen production	• AI and machine learning • Augmented and virtual reality • Predictive systems	• Bio-derived materials manufacturing
South Korea	• Electric vehicles	• Automation machine-building • Digital twins	• Bio-refinery processes • High-performance computing • Graphene and 2D materials
Singapore		• AI and machine learning • Robotics • End-to-end supply chain integration	• Synthetic biology manufacturing
Switzerland		• Automation machine-building • Augmented and virtual reality	
Taiwan		• Data science and sensors • IoT and IIoT	
The US	• Hydrogen – aerospace • Hydrogen – fuel cells • Power electronics	• Materials informatics • Industrial cyber-security • Digital systems integration	• Bio-derived materials manufacturing • Additive manufacturing

TABLE 6.1 DISTRIBUTION OF LONGLISTED OPPORTUNITIES BY COUNTRY/TERRITORY

SHORTLIST – Opportunities by Theme and Technology			
Theme	Shortlisted technologies	Countries and territories shortlist	Rationale – technology highlights
Net zero	**Electric machines** Including power electronics, machines and drives (particularly in relation to propulsion and electrification of transport)	The EU, the US, Canada, Germany, the Netherlands, Singapore, India, Taiwan, Japan, South Korea, Scandinavian countries	• Considered both an important enabler to support competitiveness in existing UK industries and an important sector to support the development of future industries. • Numerous UK companies conducting electric traction machines and power-electronics-related research and development, including many SMEs. • The UK counts with world-class engineering service providers and experience in manufacturing lower-power electric machine and power electronics. • Irrespective of whether fuel-cell, plug-in-hybrid or battery electric vehicles dominate in the future, electric machine and power electronics will be required to convert their stored energy into motion. • All vehicle manufacturers are seeking gains from next-generation power electronics systems.
	Hydrogen: aerospace Development of combustor systems and fuel tanks to allow the conversion of current aircraft configurations to hydrogen-powered variants	The EU (France, Germany), Switzerland, Japan, South Korea	• Considered an important technology domain to support the future competitiveness of the UK aviation sector: the UK aviation sector runs the risk of losing competitiveness if it does not adapt to new sustainable fuels, hydrogen and electrification trends. • Opportunity to strengthen the UK's R&I capabilities in this area, in which other countries are leading. • Hydrogen and electrified aviation to transform mobility is gaining momentum, and electrification is the most significant contributor to IP growth. • By 2030 entirely new aviation markets will emerge, exploiting electrification and autonomy in the urban and sub-regional airspace.
	Hydrogen: fuel cells Hydrogen fuel cells for transport (e.g. maritime, aerospace, rail, road vehicles, heavy-duty vehicles) and industrial applications	Germany, the US, Japan	• Considered an important future industry where the UK has an opportunity to establish itself early on if R&I gaps are addressed appropriately. • Three-quarters of the electrical energy storage and fuel-cell-related projects are being supported by external funding, which highlights the immaturity of the technology and the supply chain in the UK (BEIS – Advanced Propulsion Centre UK, Low Carbon Automotive Propulsion Technologies (2016)).
	Batteries Batteries for vehicles, consumer electronics, aviation and large-scale energy storage (lithium-ion, lithium-sulphur, lithium-metal, solid-state and non-lithium technologies) – improving battery lifespan and range, reuse, remanufacture and recycling	Germany, Canada, India, Israel, Switzerland, China, Australia, the US, Finland, Japan	• Considered an important nascent industry with multiple applications in both transport electrification and energy system storage. • The UK has strong R&I in high-energy battery technologies, and batteries for EVs (e.g. Faraday Battery Challenge). • The UK's track record of attracting FDI in high-volume vehicle assembly plants serving the European market positions the UK strongly to attract vehicle-manufacturer-led traction battery system assembly as its mainstream products migrate to electrified powertrains.
	Carbon capture, utilisation and storage (CCUS) Application of carbon capture, utilisation and storage (CCUS) in industry, as well as design and manufacturing of CCUS systems and infrastructure	Germany, Japan, Australia, Finland, the US, China	• Considered both an important enabler of competitiveness in existing industries (by applying CCU to meet their carbon targets) and an important future sector in its own right, where the UK has strong R&I investments and capabilities. • Potential for the UK to be a world leader in CCUS, supporting long-term competitiveness, as a result of its accelerating progress. • A number of CCUS strategic projects already running in the UK supported by the BEIS.

Industrial digitalisation and supply chain resilience	**AI and machine learning** Artificial intelligence and machine learning -– programming and application	Singapore, Japan, Australia, Canada, Israel, Switzerland, China, Germany, South Korea, the US, Taiwan	• Considered a key enabling technology for industrial digitalisation and a future sector with multiple applications beyond just manufacturing. • The UK has the strongest AI and machine learning market in Europe, with over 200 SMEs in the field (compared to just 81 in Germany and 50 in both the Nordics and France) (Made Smarter Review, 2017). • The application of AI in industry offers £198.7 billion in value at stake to the UK economy between 2017 and 2027 (Made Smarter Review, 2017). • Thriving ecosystem of researchers, developers and investors in AI (Made Smarter Review, 2017).
Industrial digitalisation and supply chain resilience	**Augmented reality and virtual reality (AR/VR)** Augmented reality/virtual reality for manufacturing applications	Switzerland, Japan, Singapore, Germany, South Korea	• Considered a key enabler of industrial digitalisation and an area in which the UK has strong R&I capabilities. • The UK hosts a number of notable companies in the industrial VR/AR field, including Autodesk, Virtalis and Eon Reality, and it is this sector in which much of the future industrial value lies (Made Smarter Review, 2017).
Industrial digitalisation and supply chain resilience	**Data science and sensors** (Big) data analytics and visualisation Data science and database management (and data governance) Data capture, management and sensors	Taiwan, Canada, Australia, Switzerland, Germany, Japan, South Korea	• Considered a key element of industrial digitalisation in existing sectors and an area where the UK has strong R&I capabilities. • Strongly related to AI and ML learning opportunity
Industrial digitalisation and supply chain resilience	**Digital twins** Digital twins and virtual testing of facilities and processes to optimise future designs or current states	India, the US, Singapore, Taiwan, France, Germany, Japan, South Korea, Estonia	• Considered a key element of industrial digitalisation in existing sectors and an area where the UK has strong R&I capabilities. • The UK has a strong combination of cutting-edge R&D and a number of high-performing sectors in the application of digitalisation in design, manufacturing and servitisation. • Computer technology is the second top technology field in the UK patent publications of UK applicants for 2012–17.
Industrial digitalisation and supply chain resilience	**End-to-end supply chain integration** Digital end-to-end supply chain integration (digital thread)	Singapore, Canada, Australia, India, the US, Taiwan, Germany, Japan, South Korea, Estonia	• Considered a key enabler of industrial digitalisation in existing manufacturing sectors and an area where the UK could learn from other countries to strengthen its R&I capabilities.
Industrial digitalisation and supply chain resilience	**Industrial cyber-security** Cyber-security technologies	Israel, the US, Australia, Canada, Switzerland, Germany, Japan, Singapore, Estonia, China	• Key enabler of digital manufacturing (and potential barrier for adoption) in existing sectors, as well as being a large future sector in itself. • The UK perceived as a leading country in cyber-security R&I.
	Additive manufacturing Additive manufacturing (approved and right-first-time solutions)	The US, China, India, Switzerland, Australia, Germany, France, the Netherlands, Japan, Singapore	• Considered a key area to support the competitiveness of existing manufacturing sectors and one in which the UK has strong R&I capabilities that can be leveraged to find complementary partners. • Alignment with the UK's national strategy for developing the UK's additive manufacturing industry. • The UK is a world leader in developing additive manufacturing (AM) and a pioneer of its commercialisation in medicine, aerospace and other industry sectors, with a well-established research community and manufacturing capability.

Other advanced manufacturing and materials thematic priorities	**Bio-derived materials** Bio-derived materials, including biomedical materials (“smart” biomaterials that improve health and well-being)	The US, Japan, India, France	• Considered a key emerging area for manufacturing in which the UK needs to build stronger R&I capabilities and a critical mass of innovative businesses. • The UK ranked fourth in the h-index for materials science generally, and specifically for biomaterials and nanoscience and nanotechnology, compared to its international peers, topped by the US, China and Germany, during 1996–2019. • The UK exports biomaterials, composites and electronic and magnetic materials at a higher level than 50% turnover (Innovate UK, Materials landscaping study, 2018). • However, biomaterials are among the weakest of the UK sub-sectors in terms of the number of companies, number of employees and turnover (Innovate UK, Materials landscaping study, 2018).
	Graphene and 2D materials Graphene and other 2D materials (atomic thickness materials) for applications such as membranes for filtration and coatings, energy storage and functional composites	Germany, South Korea, Australia, Switzerland, China, the US, Denmark, Spain	• Considered a key future area, with potential applications in multiple sectors where the UK is a trailblazer. • Strong current government investment in graphene for applications such as improved energy storage in batteries and supercapacitors.
	Quantum systems manufacturing Quantum computing (quantum-scale engineering) for new products and services of sectors, including automotive, healthcare, infrastructure, telecommunications, cyber-security and defence	Canada, Israel, Germany, Singapore, the US	• Considered a key future industry, where the UK is in a good position to establish global leadership in developing innovative applications. • UK universities have done groundbreaking work in quantum physics. • The UK is one of the world’s major investors in quantum research (i.e. ESPRC). • Quantum technologies are expected to have a big impact on the world’s largest markets, such as the £305.6-billion global semi-conductor industry and the £1.3-trillion oil and gas industry.
	Synthetic biology manufacturing Processes to support applications in biopharma, carbon recycling, fashion and fabric, cosmetics, and food ingredients, among others	Singapore, India, Taiwan, the US, Israel, Japan, the EU	• Considered a key emerging manufacturing sector, where the UK needs to strengthen its R&I position. • Perceived need to invest in advanced bio-products manufacturing research translating breakthroughs in biology and synthetic biology.

The results obtained from the shortlisting exercise were validated in meetings with the Steering Group of the project and the High-Value Manufacturing Catapult CTOs. Overall, the general consensus was that the technologies selected in this study are all relevant to supporting the competitiveness of existing industries and capturing value from future sectors, and therefore the list could be adopted by Innovate UK without further modifications. A few suggestions were made regarding technologies that could also be prioritised in the future, including:

- Low-cost nuclear – small modular reactor design, manufacturing and operation;
- Legacy systems’ integration and interoperability, including manufacturing system-level integration between information technologies (IT) and operational technology (OT);
- Large-scale hydrogen production, transport and use (including green hydrogen from offshore wind surplus energy);
- Hydrogen distribution systems, transport and storage;
- Smart grids for electricity distribution;
- Bespoke automation and machine-building;
- Sustainable materials beyond composites.

7 Informing the Selection and Funding of International R&I Collaboration

This section discusses the key observations emerging from this study that are relevant to the selection and funding of international R&I collaboration. The information contained in this section is intended to inform the development of future calls for proposals and provide suggestions of evidence that could be requested from applicants to ensure that collaboration leads to the intended benefits. A brief discussion of how international collaboration opportunities for the UK could be identified more systematically in the future is presented..

7.1 STEM graduate levels between countries

International R&I collaboration is expected to contribute to more effective and efficient use of resources, while strengthening the capabilities of all of the countries involved. During the course of the project a recurrent theme identified by the stakeholders consulted is the need to ensure that investments in international R&I collaboration do in fact lead to value capture for the UK. In particular, there was emphasis on the potential risk that UK know-how may be exploited elsewhere. This will occur, for example, if the scale-up of technologies developed in the UK (and the manufacture of products based on those technologies) takes place elsewhere, intellectual property agreements are not clearly defined or adhered to, or project outcomes benefit industries and firms in partner countries more than in the UK.

With this in mind, there is value in future calls for a proposal to challenge bidders to demonstrate how the UK has the potential to capture significant value from proposed international collaboration and how potential risks such as the ones discussed earlier in the report are to be mitigated. As part of this, bidders could be asked to provide information on how working with the proposed international R&I partners offers the possibility of mutually beneficial outcomes. This might also include reflection on how the project could benefit broader industrial capabilities in both countries, considering differences in the levels of maturity and supply chain specialisation.

7.2 Moving beyond value creation to ensure value capture

There is a need to move beyond value creation to ensure long-term UK value capture from international R&I collaboration. A number of barriers related to technology, manufacturability, supply chain and skills need to be addressed as part of the innovation journey. However, too often policies and programmes focus on the value-creation aspect of this journey, while overlooking what is required to ensure that the country is able to capture value from them.[37] Building on this categorisation of barriers (discussed in more detail in Section 2), it is possible to distinguish between activities leading to value creation and those leading to value capture (Figure 2.1). An overarching question in discussions around value capture is whether R&I collaboration can ultimately lead to increased competitiveness of the UK as an industrial location.

TABLE 7.1 VALUE CREATION AND CAPTURE FROM RESEARCH AND INNOVATION

Innovation journey/ perspective	Value creation	Value capture
Workforce/skills	• Skills development in new technologies • Lifelong STEM education	• Effective industry application of new technology • Increased competitiveness as industrial location
Supply chain	• Cooperation between innovators, suppliers of input (materials, components, sub-systems) and equipment/tool vendors	• Adoption of new technologies across the supply chain • Enabling domestic development of new products, processes and business models • Generation of industrial jobs • "Stickiness" in local economy • Contribution to trade balance
Manufacturing process	• Pushing manufacturing readiness levels (MRLs) up • Demonstration of production technology functionality, applicability and cost-effectiveness at required production volumes and realistic environments • Systems integration (new technologies into existing processes)	• New know-how embedded in production processes • Manufacturing intellectual property creation • Increased production efficiency and sustainability • Economies of scale and scope, enabling industrial jobs in a high-wage economy • Standards adoption and regulatory compliance
Technology	• Pushing technology readiness levels (TRLs) up across the "valley of death" • Turning lab prototype into demonstrators with the potential for full-scale production • Technology convergence/integration	• Technology patenting and licensing • Generation of R&D jobs

Source: Policy Links, IfM Engage, University of Cambridge.

These categories were discussed with the stakeholders consulted, some of whom put particular emphasis on the importance of considering the "stickiness" of manufacturing activity related to R&I activities in the country. A particular concern was the potential risk that international R&I collaboration enables knowledge flows through which the know-how created during the collaboration results in manufacturing activity in other countries and not in the UK. In other words, most of the value created by the R&I collaboration is captured by the international partner.

There was broad consensus on the importance of considering how international collaboration can support the adoption of new technologies across UK supply chains (and help to address disparities in productivity). Indeed, the "capacity of [the] UK industrial base to absorb and deploy technology/process" has been identified as the main factor affecting national value capture from international manufacturing research collaboration. Even if funding for international R&I collaboration is not used to support programmes solely focused on technology adoption, calls for proposals could challenge applicants to think beyond value-creation metrics and describe specific pathways to value capture from a UK industry standpoint.

The creation of manufacturing intellectual property (in addition to technology intellectual property) was also highlighted as a particularly valuable activity that should be among the considerations when attempting to distinguish which projects may have the potential to capture domestic value. To some stakeholders, this seems particularly relevant when considering perceived gaps of production equipment vendors in the UK base compared to other competitors.

Other aspects that warrant particular consideration include the potential for international R&I collaboration to support the development of new workforce skills (and their application in UK industry) and the domestic manufacture of next-generation products (and development of related business models).

7.3 Variety of manufacturing-related R&D domains

In considering the potential of value-capture, as well as value-creation, opportunities, portfolio managers may choose to prioritise different technology domains for investment. Previous studies have suggested that consideration should be given to framing future calls for proposals in terms of a mix of relevant R&D categories,[38] including: production technology R&D; manufacturability R&D for key emerging application technologies; challenge-led manufacturing R&D (manufacturing technology-related contributions to grand challenges); and manufacturing-enabling technology R&D (e.g. metrology, simulation, modelling).

In particular, there is merit in considering cross-cutting R&D efforts that might not naturally fit into the thematic priorities considered by this project (digital, net zero, supply chain, other). Topics such as metrology, simulation and modelling might need to be incorporated into portfolios of international collaborative projects given their enabling and cross-cutting nature. Similarly, the importance of systems integration, engineering design and virtual product development and validation – which have the potential to underpin advances across manufacturing technology domains and sectors – was highlighted during the consultations.

The need to consider supporting projects, including elements of business model innovation, and the incorporation of social science perspectives, was also identified.

7.4 National contexts and alignment

A clear message emerging from this project is the importance of trust among partners and a track record of collaboration when it comes to project prioritisation. There was broad agreement that collaboration is more likely to be successful when the complexities of working with overseas partners in different contexts are understood. This applies for both funding agencies and firms.

This suggests the need to consider, as part of the management of international collaboration portfolios, directing efforts at better understanding the institutions, competitive dynamics, industrial context and cultural dynamics in partner countries. International missions were highlighted during consultations as a particularly effective mechanism to do this. At institutional level, gaining visibility over the funding mechanisms in other countries and their investment cycles for particular technologies can help to align investments.

There is also a need to go beyond high-level descriptions of technology priorities to better understand the extent to which funding agencies invest in projects at TRL levels of interest to Innovate UK and at the scale required by the technological challenges being addressed.

7.5. Towards a systemic approach to international R&I collaboration

This project has attempted to inform the identification and prioritisation of international collaboration with the potential to lead to value capture in the UK. This has required the structured analysis of various sources of qualitative and quantitative information and the gathering of key stakeholder views. The results should be seen as a step in a long-term process.

Opportunities exist to develop a more institutionalised approach to informing the funding of international R&I partnerships with other nations. In other countries, specialised technical units provide governments with analysis of technologies on a regular basis. Examples include Japan's Centre for Research and Development Strategy and the European Commission's Joint Research Centre. Studies provided by such units include, for example, an expert assessment of the relative strengths of partner countries in specific technology domains, from both R&D and industrial perspectives.

Similarly, some evidence-gathering mechanisms are able to collect, on behalf of the government, evidence "hidden" within disperse technology communities. An example is the United States' MForesight: Alliance for Manufacturing Foresight, a non-profit organisation that works to convene diverse stakeholders in manufacturing to forecast and develop recommendations for advanced manufacturing technologies.[39]

In the UK, opportunities exist to more systematically leverage technological expertise in public research and technology organisations (particularly the High Value Manufacturing Catapult network); industrial perspectives from business organisations (including SME and technology-based firm organisations); and insights into international science and technology trends (such as those captured by the Science and Innovation Network (SIN)).

Finally, there is little evidence on the actual impact of international R&I collaboration. Publicly available evaluations are scarce. Monitoring and evaluation of these initiatives are necessary in order to learn from good practices and avoid those that are less effective. Conducting baseline surveys as part of the application process may provide useful and timely input for evaluations. More generally, some of the principles outlined in this report (particularly Sections 2 and 7) can inform the design of evaluations of international R&I collaboration.

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35. Although only three themes are used in this section, the rest of this report introduces a fourth theme, labelled "other", to accommodate findings that cannot directly be classified using the themes shown here.
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