HENRY ROYCE INSTITUTE

NATIONAL MATERIALS INNOVATION STRATEGY

UNLOCKING UK ECONOMIC GROWTH THROUGH MATERIALS INNOVATION

ROYCE

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Driven by Royce
Led by ScotChem Ltd

FOREWORD

Materials innovation lies at the heart of our future. It powers the advancements urgently required for our modern world and underpins our aspirations for a sustainable future.

From the emergence of a new hydrogen economy, fusion power and low-energy electronics to breakthroughs in bioelectronics, the transformative potential of materials science touches every aspect of our lives. In addition, the necessity of sustainability and resilience has added an essential new dimension to discovery and innovation processes.

The UK has a world-renowned depth of materials science expertise in academia and industry. It stands uniquely positioned to be a leader in this field. Innovation in materials drives tangible benefits for society and secures our place in the global science and technology landscape.

This National Materials Innovation Strategy represents a truly significant milestone. It is the output of extensive collaboration with the UK's strategic sectors. It brings together the insights of materials science, engineering researchers and innovators, policymakers, and industrial leaders in a unique manner - addressing national priorities and assimilating knowledge of markets in a top-down approach.

It was developed under the guidance of the Materials Innovation Leadership Group, and we would like to extend our utmost thanks to its members for their commitment. We also thank our partners ScotChem, who have genuinely mobilised the materials community, and Urban Foresight, who have been instrumental in supporting our approach.

The Strategy articulates a bold, new vision for harnessing the power of materials science to tackle the most pressing challenges of our time, from decarbonising energy systems and enhancing national resilience to revolutionising healthcare and boosting our circular economy.

Strikingly, this new strategy highlights the present contributions of the materials sector to the UK economy. The sector is the bedrock of a £45 billion economy employing over 635,000 people nationwide. Beyond its economic significance, the sector is a cornerstone of national resilience, underscoring areas such as defence, energy, infrastructure and telecommunications. It is clear, however, that if we are to maintain and extend our global leadership, we must address some of the longstanding barriers we face – including the persistent choke between research and commercialisation. This strategy sets out to do precisely that – creating pathways for accelerating the innovation journey from discovery to deployment. Significantly, it also highlights the opportunities and agility which will arise from the materials research community developing common frameworks and approaches to key technology differentiators such as digital transformation and sustainable futures.

When we embarked upon this process, we wanted to break down the traditional silos between industry sectors and foster partnerships across disciplines. This strategy represents the first phase of a huge national effort to speed up materials development cycles and unlock untapped potential in the UK. It has also begun building a national consensus around the key areas where public and private investment should focus – from R&D and scale-up facilities to skills development, regulatory frameworks, standards and, of course, digitisation.

Materials 4.0 will be a critical enabler, offering unprecedented opportunities to design, model, and optimise material solutions in ways that were unthinkable just a decade ago. The Strategy also aligns with the UK's ambitious commitments to sustainability and net zero goals by 2050.

As we face an increasingly complex global environment, the imperative to accelerate materials innovation has never been more pressing. This Framework for Action over the next 10 years is clear. It is paving the way for the UK to deliver cutting-edge materials technologies that advance society, strengthen our economy, and secure a more sustainable future.

The contribution from the materials community to this point has been fantastic. However, this must not pause. This is truly a "Call to Action" to continue working together to transform materials potential into materials progress and strengthen our position as the global leader in materials innovation.

Allan Cook CBE

Chair of the Materials Innovation Leadership Group

Professor David Knowles

CEO, The Henry Royce Institute

EXECUTIVE SUMMARY

Materials science and engineering is a cutting-edge technical discipline in which the UK is a world leader, with a track record of delivering substantial economic benefits to our economy. As the UK strives to be a healthier and more resilient nation operating in a prosperous net zero economy, it needs the backing of a specific, clear and standalone national strategy for materials innovation and technology translation. The Henry Royce Institute for Advanced Materials (Royce) has initiated the development of this National Materials Innovation Strategy (the Strategy) in response to that need – harnessing the collective knowledge of industry leaders, academic specialists and government experts.

The topic of materials is considerable in breadth and complexity, spanning a vast range of industries, historically working in clusters and constrained by specific industrial sectors. The challenge has been to break down elements of these historic barriers and establish priority impact areas determining how and where the UK should lead in discovering, developing, producing, commercialising, and deploying materials innovations at scale. This had to be addressed while also recognising the opportunities arising from emerging technologies, such as digital transformation, alongside constraints of sustainable use of our finite resources, commercial imperatives, and existing activity and initiatives, both nationally and internationally.

Over the last 18 months, the Materials Innovation Leadership Group, convened by Royce, has worked through these complex interdependencies and opportunities, producing a strategy to:

- Identify priorities for materials innovation, aligned with national priorities and economic imperatives, building on existing expertise, capabilities and investments, and filling ecosystem gaps.
- Identify the required enablers to deliver results for industry and the nation more broadly. These include commissioning research, developing and applying digital and artificial intelligence (AI) tools, delivering skills training, strengthening enabling regulatory frameworks, growing investment, and addressing scale-up barriers to innovation.
- Develop a set of preliminary priorities for materials and enabling innovations so that industry, academia, financiers, and the Government can work together to deliver on the Strategy progressively.

The approach has necessarily been top-down and challenge-led. It has benefited from input from over 2,000 industry, academic and government experts and end users across

271 organisations. They have identified the key national and global trends and drivers, informing the best opportunities for further exploration and development. The approach acknowledges that significant materials innovation activity exists within UK sectors and regions, with which the Strategy will align and complement. Further, it acknowledges that developing a strategy is just the start; the plans and actions need to be implemented if the identified outcomes are to be realised, balancing pragmatism and ambition to deliver useful, useable and lasting outcomes.

The priorities identified to date are not exhaustive but provide a starting point for the materials community to collaborate on delivering innovations and enabling ecosystems that will produce economic, environmental, and societal benefits for the UK and globally. They are not stand-alone priorities. Instead, they are a foundational element of a systems approach that cuts across disciplines, sectors, supply chains, and lifecycles. Horizontal and vertical integration are required to differing degrees across application areas, making a holistic, coordinated approach essential. The oversight of a focused Materials Innovation Leadership Group will be pivotal in ensuring timely, appropriate actions that align with Government needs and deliver maximum impact.

In summary, the Strategy has identified six Opportunity Themes which will deliver high-impact innovation into the UK economy, driving increased productivity, job creation and prosperity across the UK:

Energy Solutions
Rising to the net zero challenge

Future Healthcare
Delivering beyond biocompatibility for active medical solutions

Structural Innovations
Strengthening our infrastructure, built environment and transport systems

Advanced Surface Technologies
Enhancing product functionality, performance and lifetime

Next-Generation Electronics, Telecommunications & Sensors
Driving the future of high-performance connectivity and computing

Consumer products, packaging and specialist polymers
Paving the way for a greener tomorrow

Within these six themes, Opportunity Workstreams detail the pressing materials needs identified by industry, which in turn identify initial innovation priorities and interventions.

These will guide the Strategy's implementation, continuing to evolve as outcomes are delivered and new opportunities arise.

However, the truly distinct nature of this strategy lies in the openings it has uncovered related to enabling technologies and approaches required to transform the delivery and deployment of materials innovations spanning the whole sector. These are the Strategy's Cross-cutting Themes which convey the foundations for growth:

Materials 4.0
Embracing the digital revolution in materials discovery and translation

Sustainability and the circular economy
Embedding sustainability into materials innovations

Translation and manufacturing
Accelerating scale-up, commercialisation and adoption.

Skills
Nurturing a highly skilled workforce in high-value jobs

Policy, regulation and standards
Maximising ROI of innovation through an enabling regulatory environment

Of these, Materials 4.0[1] and Sustainability are truly cross-cutting, game-changing topics that have the potential to be trailblazing in their application across all the identified priorities. They demand an agile systems-thinking approach, embracing diverse technologies and methods to enable a step change in materials innovation delivery, adoption, and impact. Success alongside the other themes will improve the efficiency of the materials discovery and translation process, reduce cost and complexity, and increase industry competitiveness and economic prosperity.

With over 2,700 companies presently active in materials innovation and existing materials expertise, experience, and investment, the UK is poised to grow its leadership role in key materials-enabled industries. Successfully implementing this strategy will allow us to achieve our net zero targets, de-risk critical supply chains, add value to existing innovation infrastructure and capabilities, and grow economies (especially in electron-rich regions). The materials innovations unlocked will be foundational to the success of the UK's Industrial Strategy.

1 Materials 4.0 is an umbrella term for transitioning to a digitally enabled materials research and innovation environment. This will be underpinned by a materials informatics framework that combines capabilities in materials modelling, large data, AI/machine learning, digital twinning, in silico modelling, manufacturing informatics, and life-cycle simulation.

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1. BACKGROUND, AIMS AND OBJECTIVES

1.1 BACKGROUND

Materials innovation is key to economic growth and competitiveness in a national and global marketplace. It pervades society's technological challenges, from ensuring a healthy population to delivering ambitious net zero targets. Materials lie at the heart of the solutions to national challenges. They are also crucial to delivering commercially successful industries for the UK.

We have now reached the point where the UK cannot achieve its ambitions for a healthy and resilient nation operating in a prosperous net zero economy in the timescales demanded without the support of a specific, clear and standalone national strategy for materials innovation and technology translation. Critically, the Strategy must be sustained over the ten years needed to deliver this change.

The Henry Royce Institute for Advanced Materials (Royce) initiated the development of the National Materials Innovation Strategy (the Strategy) to harness the collective knowledge of industry leaders, academic specialists and government experts. The Strategy's outcome was to identify the materials innovation priorities that will drive economic growth in the UK. Without this, the UK's existing and future industrial sectors will not deliver the required growth nor be sustainable.

This strategy touches on almost every industrial sector in the UK, including a diverse range of nascent and emerging topics. It also spans a wide range of stakeholders whose requirements, ambitions and desired outcomes are clear on their immediate and future materials innovation needs. It anticipates requirements for developing an appropriately skilled UK workforce, implementing digital transition through Materials 4.0[2] to transform translation and deployment, and ensuring a coherent and joined-up innovation ecosystem and appropriate innovation and scale-up infrastructure to deliver new and refined materials. It recognises the importance of clarity and consistency in our policy and regulatory environment, supply chain autonomy and resilience in key sectors, and the fundamental importance of delivering sustainable industries (both environmentally and economically sustainable).

[2] Adopting Materials 4.0 principles will give the UK a competitive advantage across industrial sectors and supply chains. It will accelerate discovery and translation by embedding in-silico methods into design practice, reduce the cost of testing and component validation, and ensure quality assurance and traceability through digital fingerprinting methods.

It reflects the world-renowned strength of UK research in materials science, the UK's highly skilled and innovative materials industries, and the central role materials advances play in a truly innovative economy. It further recognises that the UK's strengths in materials research and innovation span many sectors. This is significant given the overwhelming need for effective cross-sector collaboration to drive the UK's economic growth, efficiency, and productivity.

The Strategy's implementation will prioritise and align national activities and endeavours, leveraging recognised strengths in our regions and growing our industrial productivity. It will ensure materials capability across the UK and deliver long-term benefits to regional and national economies, and our citizens. It is a pillar of sustained and sustainable manufacturing in the UK.

UK context: contribution of materials-dependent sectors to the UK economy

Materials are the bedrock of many of the UK's industrial sectors, from energy, transport and communications to defence. Materials innovation, therefore, is the foundation on which growth is based for many key UK sectors.

Hydrogen will be a critical component of our sustainable energy mix. The global market for green hydrogen is estimated to reach at least £475 billion by 2035.[3] This technology will only be enabled by developing new materials specifically designed for sustainable hydrogen production, transport, storage, and use.

Similarly, the bioelectronics market, a global growth area, relies entirely on materials innovation to advance. The UK bioelectronics market is worth between £132 million and £163 million. With materials innovations underpinning the UK sector, the projected UK market size is up to £442 million by 2035.[4] Materials innovation is, therefore, vital to maximising the UK's share of this high-value global market.

The UK's telecommunications industry is worth £32.4 billion and is estimated to rise to £50 billion by 2035, with a CAGR of 4.6%.[5] Materials innovations will drive the sector's future success.

[3] UK Hydrogen Strategy; Roots Analysis Green Hydrogen Market Analysis Report 2024-2035
[4] Materials for Bioelectronics in Healthcare Strategy and Action Plan 2024
[5] Mordor Intelligence UK Telecom Market Size Report 2024

Materials are (literally) the cornerstone of the construction sector. Critically, materials innovation also lies at the core of decarbonising the UK's construction industry and reducing the environmental impact of our infrastructure.

Materials fuel the manufacturing sector, which ranks 12th globally by output value.[6] The UK manufacturing sector accounts for over 9% of the total UK GVA, over 9% of employment (2.6 million people in 2024), and 45% of the value of all UK exports (2024).[7] It continues to be a vital driver of UK innovation, as evidenced by the amount it invests in R&D (spending more than any other industry). The sector accounts for 22% of all UK business R&D expenditure and over 40% of all UK business R&D activity (2024).[2,8]

Materials form the foundation of most of the UK's goods markets. These markets account for £393.5 billion of UK outputs, of which approximately £360 billion relies directly on materials.[9]

The vision

The vision is to implement a progressive national strategy for materials innovation at pace, delivering coherence across government and the industrial and academic materials community. This strategy will position the UK as a world leader in the rapidly expanding multi-billion-pound materials markets. The approach embraces the new challenges and opportunities presented by increased reliance on digital methods and demands for sustainable design. Success will significantly enhance the productivity and value of UK-based industries.

It will establish a dynamic, secure, connected, and inclusive materials ecosystem in the UK. This ecosystem will provide leadership in research, rapidly adopt innovations, and fast-track routes to market, all while ensuring we maintain a resilient and healthy economy and environment.

1.2 AIMS AND OBJECTIVES

The Strategy aims to provide the framework for delivering materials innovation, generating new and growing existing economic activity in the UK. It will also ensure

[6] MakeUK: UK Manufacturing; the Facts 2024

[7] Manufacturing Industries Economic Indicators January 2025; House of Commons Library Research Briefings

[8] Office for National Statistics: R&D Expenditure

[9] Office for National Statistics: Manufacturing Sector Data

resilience across an agile materials supply chain and direct efforts to align impact against the UK's most pressing challenges.

This industry-led strategy identifies industrial and societal imperatives that materials innovations and opportunities should enable. It builds on and expands multidisciplinary, cross-sector and international research collaborations spanning the UK's industrial sectors.

The objectives of the Strategy are to:

- Provide the framework to deliver a national approach to materials innovation for industry for the next decade. It will:
    - Identify and harness synergies across traditional sectors, promoting agility and stimulating technical development.
    - Create a collaborative materials innovation ecosystem in the UK.
    - Recognise transformational cross-sector priorities which will deliver increased productivity and international competitiveness required by UK industry.
    - Break down key barriers to innovation, respond to needs for national infrastructure, and deliver benefits from stimulating agile regulatory frameworks.
    - Deliver national resilience.
- Ensure optimum involvement and leadership of industry and other vital stakeholders in delivering UK materials research, development and translation by:
    - Stimulating the necessary partnerships, innovation, applications, and market opportunities in the UK and overseas, aligned with societal, environmental, and economic goals.
- Better coordinate and (re)allocate the portfolio of investments in materials innovation to:
    - Maximise ROI of existing investments.
    - Unlock nationwide opportunities for gearing international and national investment.
- Ensure a suitably skilled UK workforce is available and can benefit from materials innovation opportunities.

- Enable a strong foundation of capability and collaboration in the UK, supporting a leading global position and competitiveness for UK technology in the materials domain.

The Strategy systematically prioritises the needs and opportunities in a consultative and traceable way and provides clear and transparent evidence for interventions. To this end, it is essential that:

- Key government departments are aligned with the Strategy's implementation to ensure it maps across national government priorities and policies, international trading relations, regulatory policy, and current and future public sector investment.

Implementation of the Strategy will align with regional and devolved activities that draw on materials innovations to drive local economic prosperity and environmental and health priorities.

1.3 NATIONAL MATERIALS INNOVATION STRATEGY PROCESS

This strategy was developed under the oversight of an independent Materials Innovation Leadership Group. Royce stimulated, facilitated, and funded its creation based on the demand-led systematic approach outlined in the Framework for a National Materials Innovation Strategy[10], summarised in Figure 1.1. This was accompanied by an economic analysis of materials innovation in the UK (Appendix 1).[11]

Stakeholders were tasked with identifying industry-targeted opportunities covering two aspects:

- Opportunity Workstreams: key application and process developments to which materials innovation can contribute via value-creation opportunities (later grouped into Opportunity Themes).
- Cross-cutting Themes: pervasive national and industrial sector priorities, including trends, drivers and market needs.

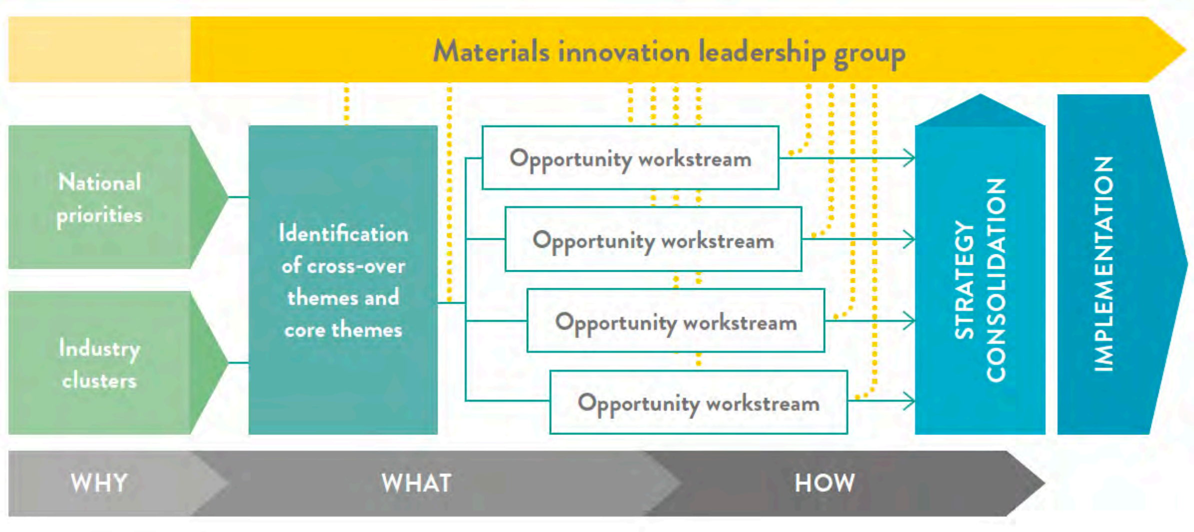
Following this initial task, Expert Working Groups (EWGs) were convened from across industry, academia, and government to consider and explore the workstreams and cross-cutting themes in detail. They identified materials innovation priorities that will have the

[10] https://www.royce.ac.uk/content/uploads/2023/04/Materials-Innovation-Strategy-Framework-Report-April-2023.pdf
[11] National Materials Innovation Strategy; Economic Evidence Bas. 10.5281/zenodo.12795155

most significant impact across the UK economy in the next ten years under three broad categories:

- Materials innovations to support industry growth opportunities
- Cross-sector collaboration priorities
- Non-technological supporting enablers

Figure 1.1 – Framework for a National Materials Innovation Strategy



The EWGs' overarching focus was to undertake the first review of value-creation opportunities and key material innovations that generate the most economic, societal, and environmental value for the UK. Promoting these will offer the greatest positive impact on national priorities. Discussions also captured the key associated gaps, barriers, enablers, and interfaces in technology translation and commercialisation.

The EWGs identified the current state of R&D gaps associated with each opportunity workstream, explored mechanisms for deeper collaboration, and highlighted investment opportunities. These have been consolidated into proposed Opportunity Sub-strategies (summarised in section 3 and provided in Appendix 2). The common goal is to accelerate specific materials innovations to solve industry-identified challenges that align with national priorities and drive industry growth.

Their efforts target information sharing, high-impact R&D, skills, infrastructure requirements, and rapid technology development and deployment.

The Strategy herein includes:

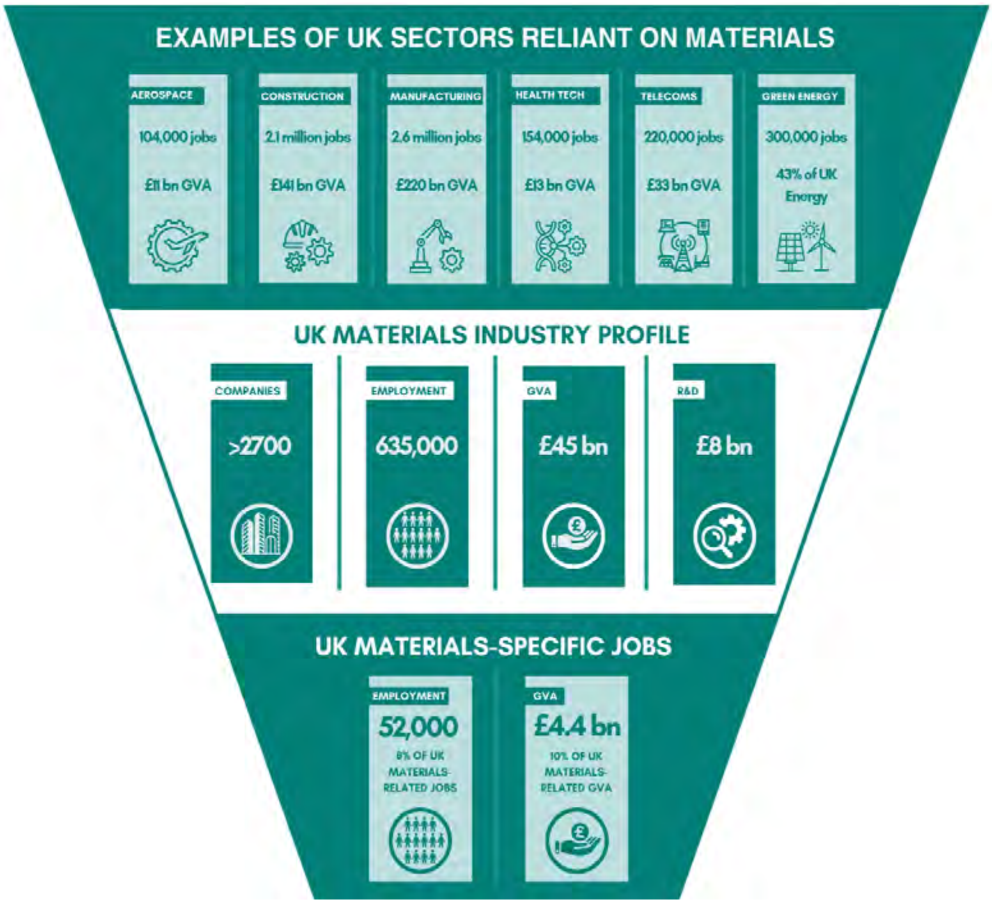
- A current economic analysis of materials innovation in the UK and its impact on the UK economy (Appendix 1).
- A summary of the opportunity workstreams, the extent of the community consultation, and the nature of the workshops and consultations.
- Grouping of the opportunity workstreams against common themes (Opportunity Themes) aligned with clear national priorities.
- Cross-cutting themes acting across the whole of the materials innovation ecosystem which, if addressed, will both dramatically accelerate innovation and bind together essential common processes, allowing the research community and industry to flourish and build agility.
- A commentary on the next steps required to deliver the Strategy in a government/industry partnership for maximum impact, leveraging on current infrastructure and investment, and making further inward private investment compelling.
- Appendix 2 details the initial opportunity workstream outputs, highlighting the priorities they address, the key interventions identified, the current ecosystem state, and the solutions they will deliver to industry.

2. ECONOMIC ANALYSIS

Clear evidence of the current economic impact of materials innovation is a prerequisite for developing a materials strategy. The analysis here focuses on companies engaged in materials innovation in the UK using a multi-source process.[12] Additionally, it identifies the sectors in which the companies operate (based on Standard Industrial Classification (SIC) codes), providing sectoral analysis, the number of specific materials innovation-related jobs, GVA, and growth predictions.

Economic analysis confirms that materials innovation is the bedrock of UK industry, particularly in manufacturing but also across many sectors, from health to energy (Figure 2.1). It is vital for strengthening and growing the UK economy.

Figure 2.1 – UK Industry and Materials Sector Profiles[13]



[12]Source: Perspective Economics; National Materials Innovation Strategy: Economic Evidence Base

[13]Financial indicators are per annum, based on 2024 data; Broad sectoral profile data is sourced from the Office for National Statistics reports. The Materials-specific data has been acquired through a commissioned economic analysis of companies active in materials innovation and their employment information.

2.1 MATERIALS INNOVATION SECTOR ECONOMIC IMPACT

The economic analysis has identified 2,768 companies in the UK active in materials innovation. They employ over 635,000 people,[14] contribute just under £45 billion p.a. to the UK economy,[15] and achieve a turnover of just under £1 trillion p.a. globally. In the last four years, they have secured more than £8 billion p.a. in external grants and funding for innovation activity within the UK.[16]

Seventy percent of the companies identified have registered offices outside London and the Southeast[17], contributing to regional prosperity.

Approximately three-quarters of the companies identified are micro or small-sized (between 1 and 49 employees). Sixteen percent are medium-sized companies (between 50 and 249 employees), and 10% are large companies (250 employees or more).[18]

A detailed analysis of employee data (Appendix 1) indicates between 35,500 and 52,000 materials-specific roles across these companies (out of 635,000 employees). Based on these figures, each materials-specific job facilitates up to 18 other jobs within UK materials innovation companies. The GVA associated with these materials-specific jobs is estimated to be between £3.1 and £4.4 billion.[19]

The average advertised salary for materials-specific roles is £33,595, above the national average wage of £29,664 and the average UK manufacturing wage (£30,049).[20] Since 2020, materials-specific salaries have increased by 28% in nominal terms and by almost 6% in real terms (above an inflation-adjusted figure),[21] well above the comparable average UK salary growth rates (20.8% and 2.2%, respectively).[22]

Based on annual trends, demand for materials-related jobs is estimated to increase between 5% and 10% annually. This suggests that the number of materials-specific jobs

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[14]Used to estimate UK employment within large companies: company accounts, annual reports, gender pay reports, economic impact reports, UK specific web-content and LinkedIn. Stated in order of priority i.e., LinkedIn data was only used where other sources did not provide specific UK employment figures. All employment within micro, small and medium sized companies is assumed to be UK specific.
[15]GVA per employee based on Office of National Statistics GVA reference tables (Regional Gross Value Added by Industry) and Employment by Industry, calculated at the level of SIC Sections.
[16]Based on UK employment figures
[17]Source: Glass.ai, Bureau van Dijk, Tussell, Beauhurst, Sector Experts
[18]Based on UK employment figures
[19]Perspective Economics. Economic Analysis of Materials Innovation companies and employment. 2024
[20]Office for National Statistics. Earnings and employment from Pay As You Earn real-time information; December 2024
[21]Source: Perspective Economics
[22]Office for National Statistics. Earnings and working hours reports

will at least double by 2035. A combination of existing capacity and capacity-building will meet this demand.

2.2 SECTOR CLASSIFICATION

The companies are registered under 217 unique SIC codes.[23] Of the top SIC codes identified, 50% of companies are in manufacturing, and 40% are in R&D.

However, it should be noted that SIC codes were limited in application. They did not lineate categories better suited to highlighting economic indicators specific to materials science.

Figure 2.2 indicates that the largest share of materials-specific employment occurs within companies involved in equipment manufacture and manufacturing engineering, foundation industries, transport, health and life sciences, aerospace, automotive, and defence.

Dependence on materials-specific employment is more acute within smaller companies. On average, 40% of all roles within micro-sized materials companies are materials-specific, and more than one-fifth (22%) of all roles within small companies are materials-specific. The average proportion of materials-specific roles within medium- and large-sized companies is 10% and 6%, respectively.

2.3 VALUE CHAIN ANALYSIS

Analysing descriptive information suggests that UK companies active in materials innovation span the entire value chain (Figure 2.3). However, over half of the companies identified are involved in materials processing, the production of intermediaries, or the production of materials parts and structures. Comparatively few companies have been classified as either materials producers or original equipment manufacturers (OEMs), pointing to potential value chain vulnerabilities at critical start and endpoints.

An analysis of company size by value chain segment shows (unsurprisingly) that the largest materials innovation companies are OEMs and that the materials producer and parts producer value chain segments also have notable shares of larger companies. However, overall, small and micro companies dominate the materials innovation industrial landscape across most of the value chain.

[23] Just over 1/3 of all UK Standard Industrial Classification (SIC) codes

Figure 2.2 – Materials-Specific Employment by Sector

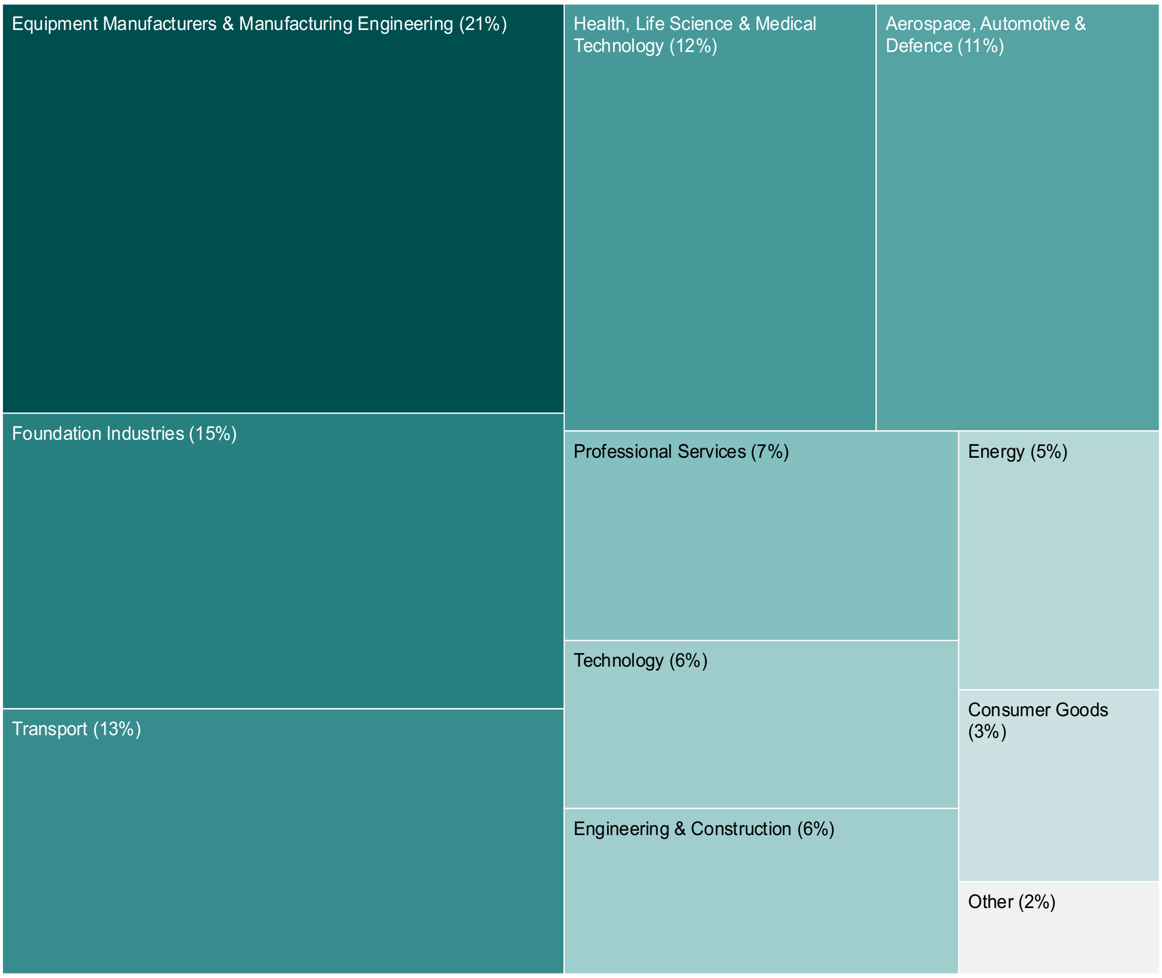
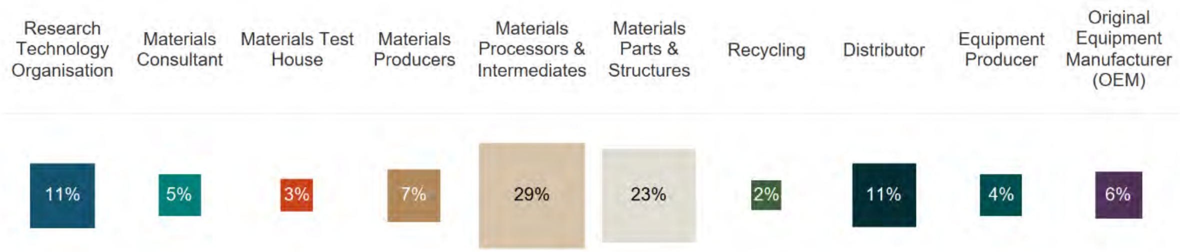


Figure 2.3– Value Chain Analysis of Companies Active in Materials Innovation



3. MATERIALS INNOVATION PRIORITIES

The cross-industry, academia, and government Materials Innovation Leadership Group has guided the process of identifying the most pressing and impactful materials innovations that will drive economic growth and deliver societal benefits in the UK, following the process detailed in section 1.3. The following sections note the level of engagement, and the opportunity groupings employed.

3.1 MATERIALS INNOVATION OPPORTUNITIES ENGAGEMENT

The Strategy benefits from extensive engagement across industry, academia, and government sectors. It draws upon expert input from over 2,000 contributors from over 270 companies and organisations. The Strategy has identified key challenges and opportunities for materials innovation to provide solutions or be a key enabler.

In doing this, industry (across all sectors) has come together with academia and government through nine industry clusters and twenty-one EWG meetings to provide input to **Opportunity Themes** that will be enabled by materials innovation.

The industry clusters and expert working groups also identified five **Cross-Cutting Themes** that will be critical in enabling materials innovations across all sectors (Section 3.3).

3.2 OPPORTUNITY THEMES

Materials innovations as enablers for industry growth have been grouped under six opportunity themes:

Energy Solutions
Rising to the net zero challenge

Future Healthcare
Delivering beyond biocompatibility for active medical solutions

Structural Innovations
Strengthening our infrastructure, built environment and transport systems

Advanced Surface Technologies
Enhancing product functionality, performance and lifetime

Next-Generation Electronics, Telecommunications & Sensors
Driving the future of high-performance connectivity and computing

Consumer Products, Packaging and Specialist Polymers
Paving the way for a greener tomorrow

3.2.1 Opportunity workstreams and priority innovations

Each opportunity theme comprises groupings of opportunity workstreams identified through the EWGs. Currently, there are nineteen application and materials-specific opportunity workstreams (Table 3.1), each with a dedicated sub-strategy (Appendix 2).

The sub-strategies outline forty-three innovation priorities, which are summarised in Table 3.1. These priorities are set to enable the translation and adoption of materials innovation.

For each innovation priority, initial interventions have been proposed to meet immediate and emerging industry needs. The sub-strategies list these proposals.

The opportunity themes, underlying workstreams, and innovation priorities will form the basis for discussions on initial materials innovation programmes.

They do not constitute an exhaustive list of materials innovation priorities. However, they are a starting point for delivering the materials innovations industry needs to achieve its commercial and national goals.

Table 3.1 Summary of Opportunity Themes, Opportunity Workstreams and Innovation Priorities

Opportunity Theme		
Opportunity Workstreams		
	Innovation Priorities (within each opportunity workstream)	
1.	**Energy Solutions: *Rising to the net zero challenge***	
1.1	**Materials for battery energy storage**	
	1.	Development and translation of next-generation battery chemistries/materials to improve performance and diversify supply chains.
	2.	Strengthening the UK's capability in battery technology translation, scale-up, and manufacturing, meeting national and international regulatory standards.
1.2	**Materials for large-scale electrochemical energy generation and conversion (including hydrogen)**	
	1.	Development and refinement of electrode, catalysis and membrane materials to improve performance and reduce environmental impacts.
	2.	Application-driven, digital design-led manufacturing processing and trial procedures to allow rapid deployment of electrochemical system components, alongside improved sustainability and recyclability.
1.3	**Materials for hydrogen transport, storage and use**	
	1.	Delivering materials solutions critical to widescale hydrogen deployment, including barriers and coatings, materials to enable deployment in extreme environments, and materials to enable hydrogen to X.
	2.	Coordinating scale-up and test capabilities to fast-track materials solutions from concept through prototype to commercialisation.
1.4	**Materials for heat exchange, heat storage and waste heat recovery**	
	1.	Developing and translating materials for industrial heat exchange, recovery and storage solutions.
	2.	Developing and translating materials for domestic-scale heat exchange and storage systems.
	3.	Reviewing thermal energy provision and delivery of a translation, scale-up, manufacturing and integration capability.
1.5	**Materials for energy harvesting**	
	1.	Developing and deploying materials for higher-efficiency solar PV and specialist energy harvesting applications, including health, battery-less mobile electronic devices, and sensors.
	2.	Accelerating scale-up and manufacturing of energy-harvesting materials and devices to support resilient supply chains and generate new economic opportunities.
1.6	**Materials for advanced nuclear fuels and nuclear test capability**	
	1.	Developing nuclear fuel options for industry based on agreed technologies.
	2.	Delivering test, scale-up and manufacturing capabilities to fast-track technology development, supported by a skills programme to enable technology development and deployment.

Table 3.1 continued	
Opportunity Theme	
Opportunity Workstreams	
	Innovation Priorities (within each opportunity workstream)
2.	**Future Healthcare:** ***Delivering beyond biocompatibility for active medical solutions***
2.1	**Biocompatible materials**
	1. Developing biocompatible materials with specific properties for targeted therapies (including structural/scaffolding, porous, conductivity, patient-derived, injectable, 3-D printable, patient-specific, and drug-eluting) to meet clinical demand.
	2. Harmonising regulatory pathways, including reinvigorating a national clinical trials capability aligned with national and international regulatory requirements.
2.2	**Materials for bioelectronics**
	1. Delivering an industry-driven programme to develop bioelectronic materials with a specific focus on: • Long-term (>10 years) implantable materials. • Electrically conducting, biocompatible materials with mechanical properties similar to tissue for interfacing electronics with the body. • Materials which improve sensor performance in vivo (elimination of biofouling or inflammatory responses).
	2. Elevating the skills and investing in new facilities to achieve the standards required by this highly controlled sector.

Table 3.1 continued	
Opportunity Theme	
Opportunity Workstreams	
	Innovation Priorities (within each opportunity workstream)
3.	Structural Innovations: *Strengthening our infrastructure, built environment and transport*
3.1	Materials for low-carbon construction
	1. Decarbonising cement and concrete within five years.
	2. Delivering tested and standardised construction materials for improved energy efficiency and improved occupier health in homes and extending performance in the in-use life of infrastructure.
	3. Developing policy, regulations and standards (including testing and characterisation) to enable rapid adoption and deployment of new construction materials.
3.2	Materials for sustainable structural systems – composites
	1. Developing more sustainable composites designed and optimised for multiple applications, longer lifecycles, recycling and re-use. Some composite innovations will also support sustainability goals by enabling other sustainable technologies.
	2. Securing more robust and resilient supply chains supporting growth and resilience in existing markets and new circular economies.
3.3	Metallic materials
	1. Developing high-volume metallic materials that are strong, durable, and compatible with circular economy principles, as well as enhanced performance and tailored properties for the application of new and emerging technologies.
	2. Securing the supply chain for high-volume metals (particularly steel and aluminium) through circularity and performance improvement: innovation in manufacture, repair, processing, and end-of-life solutions for sustainable metallic materials through technologies that reduce energy consumption, minimise emissions and optimise resource utilisation.
	3. Developing speciality, high-performance metallic materials to enable capability in key UK priority technologies such as clean energy and health, including critical supply chain and end-of-life considerations.
3.4	Ceramic materials
	1. Developing a portfolio of advanced ceramics for a diverse range of applications.
	2. Improving manufacturing and processing capabilities for ceramics.

Table 3.1 continued		
Opportunity Theme		
Opportunity Workstreams		
	Innovation Priorities (within each opportunity workstream)	
4.	Advanced Surface Technologies and Materials Durability: *Enhancing product safety, performance and lifetime*	
4.1	Materials and modelling for surface engineering and tribology	
	1.	Improving the performance of surface protection materials and tribology solutions to extend technology/infrastructure lifetime.
	2.	Improving materials design and deployment through enhanced modelling, characterisation, testing and certification.
4.2	Surface treatments and materials for demanding environments	
	1.	Developing and refining material systems and functional materials for specific extreme conditions, especially thermal and radiation extremes, as well as multi-extreme environments.
	2.	Advancing the UK's capability in autonomous design, enabling rapid development and test capability fused with materials 4.0 methods to accelerate development and deployment across the supply chain.

Table 3.1 continued	
Opportunity Theme	
Opportunity Workstreams	
	Innovation Priorities (within each opportunity workstream)
5.	Next-Generation Electronics, Telecommunications & Sensors: *Driving the future of high-performance connectivity and computing*
5.1	Materials for power electronics
	1. Developing and integrating wide- and ultra-wide bandgap materials aligned to a national skills provision for power electronics.
	2. Strengthening the UK wide band gap semiconductor supply chain.
5.2	Materials for quantum technologies
	1. Developing and maintaining world-leading characterisation capability for quantum platforms and metrology.
	2. Developing and facilitating access to micro, nanofabrication and integration capabilities: • Delivering the spatial control of functionality and interfaces for solid-state quantum technologies. • Allowing efficient integration of solid-state quantum devices with photonic networks.
5.3	Materials for connectivity & telecommunications
	1. Developing a portfolio of materials for higher efficiency communication systems (5G, optical, RF, IR, RADAR, etc).
	2. Coordinating and integrating capabilities for application-based translation and manufacturing of materials and components for telecommunications to facilitate faster translation underpinned by standardised testing, validation and scale-up.

Table 3.1 continued	
Opportunity Theme	
Opportunity Workstreams	
	Innovation Priorities (within each opportunity workstream)
6.	Consumer Products, Packaging & Specialist Polymers: *Paving the way for a greener tomorrow*
6.1	Materials for sustainable packaging
	1. Development and translation of bulk sustainable plastic packaging processing and manufacturing.
	2. Development of bio-based, biodegradable, sustainable packaging based on agreed environmental parameters.
	3. Ensuring an enabling policy/regulatory environment to facilitate Priorities 1 and 2 (Whilst this is not materials innovation *per se*, it will be critical as an enabler to deploying the materials innovations from priorities 1 and 2).
6.2	Speciality polymers: sustainable elastomers
	1. Delivering high-value, specialist elastomeric materials to support high-growth sectors.
	2. Improving sustainability through extended in-life service, end-of-life processing and recyclability of high-volume elastomeric materials.

3.3 CROSS-CUTTING THEMES

The EWGs across all opportunity workstreams highlighted that an appropriately connected, coherent, standardised, and agile materials innovation ecosystem will accelerate future technology development and ensure the UK remains a global leader in this field.

Whereas the six opportunity themes focus on improving products, this domain addresses broader challenges, highlighting topics and interventions which will enable and underpin the opportunity themes.

Five cross-cutting themes that genuinely span the entire materials sector and bring common approaches and methodologies have been identified to deliver this. However, inconsistent approaches, significant technical gaps, and a lack of a common framework impair these cross-cutting themes to varying degrees. Addressing these issues offers the greatest opportunity for the strategy's impact. They will bind the community, create agile and transferrable skills solutions, and enable faster commercialisation routes and greater growth opportunities; together, they will make the UK an easier place to do business.

Materials 4.0

The most significant enabler for the materials sector is embracing the digital revolution in materials discovery and scale-up. Interfacing existing materials manufacturing infrastructure with Materials 4.0 will naturally draw together diverse groups across the community to develop common working methods.

Sustainability and the circular economy

Embedding sustainability and sustainable by design principles into materials innovations is a genuinely global issue that must be implicit in new technologies. Designing materials for sustainable products and outcomes (for increased in-use life, recycling, reuse, and recovery or driving decarbonisation) scores at or near the top priority across all sectors.

Translation and manufacturing

Creating a connected and agile scale-up and manufacturing ecosystem with investments, technologies, and infrastructure (including advanced machinery, equipment, instrumentation, rapid testing, and scale-up capabilities) is essential to materials innovation and will accelerate scale-up, commercialisation and adoption.

Skills

Nurturing a highly skilled workforce in high-value jobs to deliver materials innovations is a fundamental requirement across all materials innovation areas. Identifying current and future skills gaps and gap-filling solutions, as well as opportunities for re-skilling, up-skilling, and developing new skills and capabilities for specific opportunity themes or workstreams, will be critical. The materials community can also collaborate to coordinate outreach better and build a broader understanding of the opportunities afforded by materials and materials-related jobs.

Policy, regulation and standards

Addressing this theme will support an enabling regulatory environment where materials innovation can flourish, barriers to innovation are minimised, and the ROI in innovation is maximised. Close collaboration with the Regulatory Innovation Office will be paramount.

The two cross-cutting themes requiring a true ecosystem approach are the application of Materials 4.0 and Sustainability. Notably:

- There is no coherent ecosystem-level framework or common lexicon for interacting data, digital tools, and processes to optimise materials design, manufacture, and performance.
- The inconsistent application of methodologies and trusted data for sustainability assessment must be addressed.

These two topics alone represent massive barriers to delivering materials innovation at scale across sectors and applications.

The EWGs have identified key innovation priorities under these two themes, summarised in the sub-strategies in Appendix 3.

With dedicated funding, specialist steering groups should drive two national programmes in these areas. The cross-cutting nature, breadth, and scale of the activities would stimulate cross-sectoral collaboration, translate best practices, bring agility to the innovation supply chain, and unlock opportunities across all sectors and material innovation areas, positioning the UK at the forefront of materials innovation globally.

The three other priority areas should be addressed at the Opportunity Theme level to deliver:

- Accelerated translation and manufacturing:
    - Reviewing the landscape for scale-up capability across the theme – identifying requirements to join up existing capabilities, and gaps and solutions to address them.
    - Ensuring seamless access to national capabilities/facilities for scale-up and translation, supplemented with targeted investments in essential national research infrastructure.
    - Derisking investment and encouraging UK-based, industrially led research and translation.
- The necessary skilled workforce to support both nascent and more traditional materials:
    - Highlighting skills deficits/opportunities and working across themes to secure common outcomes.
- Agile regulatory systems for materials across different sectors, along with contemporary standards which can respond to emerging markets and new innovation:

- Identifying regulatory barriers to innovation and making recommendations for solutions

Enablers to address these cross-cutting opportunities should be embedded into demonstrator programmes to provide focus. Successful implementation will deliver an integrated end-to-end innovation approach with clear pathways to existing funding, access to necessary infrastructure, and more agile scale-up ecosystems relevant to material classes, supported by enabling policies.

The consolidated information should be used at the opportunity theme level, for example, to report to the new Regulatory Innovation Office or steer national needs for specific infrastructure against tangible materials innovation priorities. It can also be passed to a materials leadership body. It will take an overarching view of requirements and direct changes needed across all the materials cross-cutting and opportunity themes.

4. A ROUTE TO IMPLEMENTATION

The Strategy has highlighted the need to coordinate a range of proposed interventions in materials innovation, which would deliver significant economic and societal impact – positive action, at pace, will stimulate our economy, resilience, and sustainability. The Strategy should, therefore, transition quickly to the establishment of a detailed plan and supporting case developed with the Government. With ongoing alignment to key government objectives, an implementation plan will articulate the delivery model and the necessary steps to pivot, coordinate, and (re)allocate the existing and future portfolio of investments in materials innovation.

Based on the input from the work to date, Figure 4.1 summarises an initial strategy-led recommendation for an implementation structure.

To gain national traction, industry and the government would need to work in partnership. This would require the appointment of a representative group or team with the remit and mandate to deliver change and input to spending and investment decisions on behalf of all the major stakeholders.

- The Materials Innovation Leadership Group was established to develop the Strategy. This team, with its balance of government, industry, and academic members, is committed to providing support, engaging senior colleagues across the materials sector to implement the Strategy, and providing the necessary oversight and linkages among senior stakeholders while monitoring the strategy's overall progress.
- Industry/research-led steering groups should take responsibility for the respective opportunity themes. They will need the experience and resources to:
    - Coordinate and drive activities.
    - Monitor and review the progress and success of developed programmes and, where appropriate, refine goals, deliverables and timelines.
    - Identify future gaps in programmes and infrastructure.
    - Recommend investment requirements.
    - Anticipate future needs to develop an agile ecosystem.
    - Make recommendations on broader issues, such as regulatory changes.
    - Identify skills requirements.

Materials 4.0 and sustainability are the sector's absolute cross-cutting priorities. They should be considered the priority themes to draw common threads across the Strategy's activities with their own steering groups and programme development.

The remaining cross-cutting priority areas can be embedded into the individual opportunity themes as required.

Figure 4.1 – Implementation Structure

5. NEXT STEPS & CALL TO ACTION

The production of this strategy has garnered far-reaching support from stakeholders in industry, academia, and government. A rapid transition to action is essential to maintaining momentum from these efforts and delivering materials-related opportunities that promote industry growth.

5.1 NEXT STEPS

The Strategy has now been developed to the extent that the next steps require government input and insight. This should support the development of a detailed implementation phase, leveraging industry and government leadership to drive outcomes. Royce and the Materials Innovation Leadership Group are ready to work with government, industry and academia to develop the required options to support a business case and suggest that the following would be a central tenant of an implementation plan:

- Develop an outline business case, implementation plan and timetable for the Strategy.
- Ensure a clear mechanism to coordinate materials innovation activity across current government investment and regional initiatives.
- A national materials innovation leadership group with the mandate and funding to develop and drive the implementation plan.
- Identify ways to better connect national research and innovation infrastructure, creating a joined-up, coherent, and accessible ecosystem with simplified, cost-effective, and efficient mechanisms for access by the materials innovation community.
- Assess needs for infrastructure investment based on gaps and ecosystem priorities focusing on translation, scale-up and manufacturing.
- Optimise international cooperation to address specific infrastructure gaps.
- Analyse investment levels and access routes to unlock funding for commercialising and translating materials capabilities, technologies, and know-how, accelerating the commercialisation cycle.
- Review incentives for companies to invest in innovation and adopt new materials, including tax credits, grants, and other forms of financial support to help offset research and development costs.

- Establish clear, mission-focused, high-impact programmes:
  - Prioritise activating broad programmes for Materials 4.0 and Sustainability themes.
  - Test and refine the ideas captured and summarised in the materials innovation priority sub-strategies (Appendix 2).
  - Align opportunity themes and workstreams with current investment commitments and identify gaps in high-priority areas; these should include materials-specific interventions, associated skills provision, scale-up capabilities, and regulatory and policy enablers.
  - Signal emerging areas of materials research to existing funding bodies.

5.2 OUTCOMES

Implementing the Strategy is essential to amplify the impact of what is already a powerhouse behind the UK economy. It will establish a rejuvenated community with a clear and common purpose: rapidly delivering cutting-edge materials technology.

Key outcomes will include:

- A step change in economic impact through the provision of focus – ongoing prioritisation of high-value innovation requirements aligned with UK and industrial priorities, continually monitored at a national level.
- A demonstration of effective partnership between government, industry and the wider investment community fuelling the growth in materials innovation and supporting the national industrial strategy.
- A shift in design and innovation to embrace the two imperatives which bind together the materials community and will deliver agility in the marketplace.
- Exploiting the potential of Materials 4.0 and embedding it into everyday methods.
- Sustainability by design entrained into all innovation.
- Linking and leveraging capabilities in our universities, research organisations and industry to provide world-leading access to well-resourced, state-of-the-art research and scale-up infrastructure across the country.
- A growing pool of homegrown, highly productive teams and the pulling power to attract the best talent from overseas

In summary, delivering the Strategy will unite industry, government, and the materials research community nationwide to collaborate and cooperate for shared outcomes. It will connect the UK innovation ecosystem in a new way to derisk and accelerate the translation of materials innovations to commercial markets and provide a unified approach to international partnerships.

Enabling the Strategy will put the UK at the forefront of materials innovation globally, assist our industries in rising to sustainability challenges, boost our economy and competitiveness, and provide new opportunities for our citizens.

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FOR MORE INFORMATION

APPENDIX 1

Estimates of Employment in Materials-Related Roles

The study team automated a search for people with publicly accessible employment profiles that referenced the word "materials."

Web data was gathered for three-quarters of the companies identified in the National Materials Innovation Strategy dataset.[24] Several iterations of the automated script were tested to seek the closest possible alignment to the results obtained from manual web searching, including different iterations of the key terms being used to search for materials-related employment and searching within different numbers of fields (for example, position, about, experience, etc.). The final version of the script searches for the word 'materials' within four potentially relevant fields, namely position, about, experience and education. The study team reviewed results for the top 10 largest employers to test the accuracy of the automated search. In all cases, variances in the proportion of materials-related employment returned for these top 10 companies fell within +/- 2%, as illustrated in Table A1 below.

Table A1 – Automation vs Manual Materials Employment Results (top 10 largest employers)[25]

company_id	script_proportion	web_proportion	variance
01	0.71%	1.45%	0.74%
02	4.02%	3.25%	-0.77%
03	1.12%	0.45%	-0.67%
04	3.19%	3.13%	-0.05%
05	5.94%	4.82%	-1.13%
06	3.72%	2.23%	-1.50%
07	3.21%	2.75%	-0.46%
08	1.10%	0.73%	-0.37%
09	3.49%	3.47%	-0.02%
10	2.97%	3.16%	0.19%

[24] 1,909 of 2,574 companies

[25] Source: Perspective Economics

Where data for larger companies was not returned via the automated search, the study team filled data gaps for any blanks (companies) with more than 200 employees. This was done by manually searching for the number of UK employees who refer to the word materials within descriptive information.

Final estimates regarding the proportion of materials-related employment derived from automated and manual searches were applied to 1,248 companies, including most companies with more than 200 employees. These proportions were then used to create averages by company size. These averages filled gaps where web-based estimates were either not available or were deemed not to provide a reasonable representation of overall employment (for example, web data for some large manufacturing companies is significantly lower than the level of employment reported in annual accounts).

Applying this experimental approach to estimating materials-specific employment in the UK suggests that:

- An estimated 35,500 to 50,000 people are in materials-specific roles across the companies in the materials innovation dataset – between 5% and 7% of the total UK materials innovation employment figure. In other words, every material-specific job facilitates between 13 and 18 other jobs within UK materials innovation companies.
- The GVA associated with these jobs is estimated to be in the region of £3.1 billion to £4.4 billion.[26]
- Dependence on materials-specific employment is more acute within smaller companies. On average, 40% of all roles within micro-sized materials companies are materials-specific, and more than one-fifth (22%) of all roles within small companies are materials-specific. The average proportion of materials-specific roles within medium- and large-sized companies is 10% and 6%, respectively.
- Jaguar Land Rover, Morgan Advanced Materials, Altrad, Rolls-Royce, Element Materials Technology, BAE Systems, Babcock International, Heidelberg Materials, BT, and Tata Steel are among the top employers of people in materials-specific roles.

[26]Assuming that all these jobs are 'professional, scientific and technical', they could contribute between £2.4bn and £3.4bn in GVA (35,500 and 50,000 x £67k using ONS 2023 output per job). Assuming they're all manufacturing jobs, they could contribute between £3.1bn and £4.4bn (manufacturing output per job = £87,150).

The largest share of materials-specific employment occurs within companies involved in manufacturing engineering and equipment manufacture, foundation industries, transport, health and life sciences, aerospace, automotive, and defence.

APPENDIX 2

Opportunity Theme Sub-strategies

The sub-strategies presented below are based on the input of experts across industry, academia and government. From materials' discovery to their end use, initial priorities and potential solutions have been captured.

These represent a starting point for delivering the UK's priority materials innovations over the next ten years. It is not an exhaustive list. These suggested priorities must be tested, refined, and allowed to evolve as materials innovation progresses and new opportunities and technologies arise.

A2 – 1 ENERGY SOLUTIONS

A2 – 1.1 Materials for battery energy storage

Overall opportunity

As we transition to decarbonised energy systems, applying and developing electrochemical energy storage technologies is critical for supporting the widescale deployment of renewable energy sources. From balancing peak demand and grid flexibility to the widespread adoption of electric vehicles and as an enabling technology for other clean energy solutions, innovation in battery storage is essential. Such innovation depends on new and refined materials to maximise efficiency, safety and applicability.

The UK battery market was valued at £2.7 billion in 2022 and is expected to reach over £14 billion by 2035, with a CAGR of 17.9%.[27] The Faraday Institution predicts that by 2035, the UK alone will need the equivalent of eight gigafactories, each producing 20 GWh of battery storage capacity per year.

As global demand for energy storage grows, continued innovation in high-performance materials for battery use is essential. For battery chemistries, the overarching priorities include increasing energy density, improving safety, and reducing reliance on toxic or scarce raw materials without increasing cost. Whilst Lithium-ion (Li-ion) technologies are the pre-dominant technology in the short- (and likely medium-) term, there is a significant opportunity to accelerate the development and deployment of a portfolio of battery chemistries, including post-Li-ion (for example, sodium ion, solid state, lithium-sulphur), as well as large scale flow batteries. There is also scope for developing bespoke materials systems to unlock local production based on local natural resources. This portfolio approach collectively provides greater flexibility and resilience – leveraging the existing significant UK research base with substantial arising commercial opportunities.

The UK Faraday Institution brings together significant electrochemical energy storage research, skills development, market analysis, and early-stage commercialisation. It has also completed significant road-mapping activities highlighting crucial needs for the UK and global battery sectors.[28] Focusing on critical materials gaps would significantly strengthen the nation's community of practice in battery technology, scale-up, and

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[27] UK Battery Strategy, 2023

[28] The Faraday Institution Technology Roadmaps; https://www.faraday.ac.uk/research/scientific-publications/

deployment and allow the industry to capitalise on the UK's existing strengths and capabilities.

The industry's issue with scaling up synthesis and processes remains, and this is particularly acute for next-generation battery chemistries. Access to scaling-up engineering capabilities, such as dry coating, is also a priority. As in other sectors, specialist testing, characterisation, validation, performance prediction, and improved quality control are essential enablers.

Opportunity Priorities

Two key priority areas in materials for battery energy storage have been identified as key areas of focus for the UK:

Priority 1: Next-generation battery chemistries/materials to improve performance and diversify supply chains.

Benefits to the UK:

(i) Enabling balanced renewable energy supply and demand underpinned by robust UK battery industries.
(ii) Increasing national resilience with different chemistries, making the UK less exposed to global constraints.
(iii) Aligned testing, characterisation and validation methodologies, tools and data
(iv) Improved return on investment in battery technologies.

Priority 2: Strengthening the UK's capability in battery technology translation, materials scale-up, and manufacturing, meeting national and international regulatory standards.

Benefits to the UK:

(i) Meeting battery demand at all scales across renewable energy supplies.
(ii) Sustainable and ethical battery supply chains.
(iii) Improved ROI in current and new capabilities by streamlining processes with agreed standards.
(iv) Increased domestic and international investment.
(v) Compliance with international legislation (such as, the EU Critical Raw Materials Act [29]).

[29] Critical Raw Materials Act, 2024
https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L_202401252

(i) High-skill, high-value manufacturing jobs onshored

What we need to do in the UK to realise the opportunities in this area

MATERIALS FOR BATTERY ENERGY STORAGE PRIORITY 1: Next generation battery chemistries/materials to improve performance	
Outcomes	Rapid translation of application-ready battery technologies.
	Streamlined translation of new battery materials through early identification of battery technology "winners" in terms of performance and scalability, thereby increasing ROI.
	Reduced costs and environmental impacts.
Enabled by	**Key interventions**
	A cross-industry-academia working group to agree and deliver the next 10-year priorities in battery materials innovation (led by the Faraday Institution) for varied scale of batteries (micro, on chip, cylindrical, prismatic), serving different energy requirements.
	Battery chemistries: A thorough socioeconomic and sustainability benchmarking of any identified new chemistries required (with data on performance, formulations and applications) compiled into a curated database with appropriate tools to allow technoeconomic and sustainability analysis.
	A flow battery materials programme, including: • Sustainable electrolytes (focussing on organic electrolytes for flow batteries and sustainable electrolytes compatible with new battery chemistries) utilising computational screening and experimental validation. • Membranes including development and scale up for flow battery membranes. • Membrane-less technology such as immiscible liquids.
	Improving access to a UK capability in rapid testing, characterisation and validation for battery materials.
	Review of requirements and establishment of an open access facility to support synthesis at scale.
	Battery material development as part of a wider UK strategy for 'materials 4.0' predictive capability to accelerate material design.
Underpinned by	**An enabling ecosystem**
	Existing UK expertise and capabilities such as the Faraday Battery Challenge, Advanced Materials Battery Industrialisation Centre, and Northeast Battery Alliance.
	Existing skills and facilities, including the UK Battery Taskforce.
	UK Battery Strategy.
Providing solutions to	**Solve industry challenges**
	Sourcing validated state-of-the-art battery materials in scale-up quantities.
	Lack of bespoke engineering capabilities for testing new processing technologies at an industrial scale.
	Improved efficiencies and yields.
	Speeding up procurement of equipment.

MATERIALS FOR BATTERY ENERGY STORAGE PRIORITY 2: Rapid and efficient battery scale-up and manufacturing	
Outcomes	A connected translation and scale-up battery pipeline.
	A community of practice with inter-changeable skills, ensuring national critical infrastructure requirements are met.
	Alignment with key strategies and legislation (UK and international) for example, Faraday Battery Challenge, Battery 2030 (EU) and JCESR (US).
	Improved ROI by building on existing funding programmes.
Enabled by	**Key interventions**
	Comprehensive review of the UK materials (system) manufacturing capability and assessment of all current pilot scale capabilities for battery materials development to identify and address gaps and solutions. For example, this may include: • Cell line for solid state batteries (some of which require very protected environments during manufacture). • Na-ion capability. • LiS pilot line >10s MWh (S is not always compatible with other chemistries). • Li metal protection capability at scale for next-generation chemistries. • Facilities to enable dry coating at scale. • Flexible scale, prototyping/demonstration capability, building on the cell-scale flexible industrial line at UKBIC with associated materials synthesis across a range of chemistry TRLs.
	Identify a public-private solution to address the funding gap between the Faraday Battery Challenge and Advanced Propulsion Centre TRL levels for pilot line capabilities.
	Improved quality control for battery materials technologies based on agreed cross-industry standards, providing a significant opportunity to UK plc to (i) differentiate domestic manufacturing and (ii) develop tools/methods which can be exported.
	Programme to develop improved recycling and reuse capability in line with national and international legislation and create a circular economy for the battery supply chain, enabled by battery passports.
	A national structure to deliver competencies and skills in manufacturing and across the full vertical supply chain.
Underpinned by	**An enabling ecosystem**
	Existing UK capabilities (for example, Faraday Battery Challenge, Faraday Institution, Royce, NPL, UKBIC, AMBIC and Advanced Propulsion Centre).
Providing solutions to	**Solve industry challenges**
	Access to a pipeline of scale-up facilities and funding across all TRL levels (gap-filling).
	Clarity from cross-industry standards.
	Responding to incoming battery regulation which will require CO_2 reporting and UK/EU rules of origin.

A2 – 1.2 Materials for large-scale electrochemical energy generation and conversion

Overall opportunity

Electrochemical cells and systems are vital in various industry sectors, including automotive, heavy-duty transport, maritime, and defence. These devices, which enable energy conversion through an intermediate such as hydrogen, are also critical enabling technologies for renewable energy, energy management, conservation and storage, pollution control/monitoring, and greenhouse gas reduction.

Traditional electrochemical energy technology systems continue to be optimised for cost, lifetime, and performance, leading to their continued expansion into existing and emerging market sectors. There is also increasing global demand for hybrid systems, including new electrochemical energy generation solutions to overcome the performance limitations of single power generation (for example, response time and power capacity). Many electrochemical energy technologies are expected to be critical in such hybrid solutions.

Technologies, such as fuel cells, electrochemical reactors, ion transport membranes, and supercapacitors, will substantially influence how we produce energy and improve its environmental impact. Their evolution is critical to reaching net zero targets and requires innovative materials for more efficient electrochemical energy generation. They also present new opportunities for distributed energy systems, with local manufacture and energy production, reducing the need for storage, transportation and large-scale infrastructure investment.

They also present a substantial economic opportunity for the UK. The value of the global fuel cell market alone is currently estimated at £7.5 billion with an estimated CAGR of 27.1% through to 2035.[30] The value of the global electrolyser market is presently estimated at £765 million with a CAGR of 95.2%through to 2035.[31] The demand for green hydrogen is primarily driving this growth.[30]

The UK has a world-leading research base and several globally active companies in this field. To capitalise on this and capture the economic benefits of the growing renewable energy economy, the UK must have the technology supply chains and skills to deliver

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[30]Grandview Research Fuel Cell Market Size, Share, Growth, Industry Report
[31]Grandview Research Electrolyser Market Size, Share & Trends Analysis Report

predicted domestic demand and capitalise on the significant export opportunities. Materials innovations are urgently needed as enabling technology.

Opportunity priorities

Two key priority areas in materials for electrochemical energy generation are key for the UK:

Priority 1: Developing and refining cost-effective electrode, catalysis and membrane materials to improve performance and reduce environmental impacts.

Benefits to the UK:

(i) Reaching net zero targets.
(ii) Supporting strategic net zero technology (growth) markets, including the green hydrogen market.
(iii) Increasing competitiveness and supporting other industry sectors through spillover benefits from hydrogen production materials research; for example:
(iv) Improved catalysts for electrolysis will reduce the use of rare metallics.
(v) The development of thinner, more robust membranes for electrolysis.
(vi) Removing dependency on forever polymers such as PFASs (per- and polyfluoroalkyl substances) and other synthetic organofluorine chemicals.

Priority 2: Application-driven, digital design-led manufacturing processing and trial procedures to allow rapid deployment of electrochemical system components, alongside improved sustainability and recyclability.

Benefits to the UK:

(i) Growing an advanced, sustainable manufacturing sector with high-skill, high-value jobs.
(ii) Securing a leading global position in advanced sustainable manufacturing.
(iii) Intellectual property-driven investments.
(iv) Developing supply chains for critical components for the energy transition.
(v) Creating new circular economies.
(vi) Supply chain security for critical materials/minerals.

What we need to do in the UK to realise the opportunities in this area

ELECTROCHEMICAL ENERGY GENERATION AND CONVERSION PRIORITY 1:
Development and refinement of cost-effective electrode, catalysis and membrane materials to improve performance and reduce environmental impacts

Outcomes

- Coordinated cross-industry-academia community, with priority programmes delivering immediate, near and long-term materials innovations.
- Industry-driven, application-based research outputs.
- Suite of ready-to-deploy sustainable, high-performance materials designed for specific industry applications.

Enabled by

Key interventions

Cross-industry-academia opportunity workstream to:

- Identify specific materials priorities, gaps and solutions.
- Review and assess all current pilot scale capabilities for electrochemical. materials development and identify gaps and solutions.
- Drive delivery of identified solutions.

Integrated programme to develop and refine electrochemistry materials:

- Electrode materials.
- Membranes (including a capability to develop and scale up new flow battery membranes).
- Thrifting or elimination of Platinum Group Metals (PGMs) in catalysts (durable, stable, high-activity, self-supporting, higher Faradaic efficiency, suitable for multiple fuels, reduced metal).

Underpinned by

An enabling ecosystem

- National expertise in fuel cell technology which is applicable to energy conversion and areas such as hydrogen generation.
- UK membrane R&D expertise.
- Existing capabilities and networks such as, UK Catalysis Hub, EaSI-CAT, CRITICAT.

Providing solutions to

Solve industry challenges

- Improved connectedness between industry and academia, setting research priorities and supporting adoption of application-specific research outputs.
- Access to scale-up and pilot-line facilities.
- Addressing the lack of confidence in materials testing for applications such as hydrogen.
- Better prediction of critical components that will deliver the desired performance, reducing costs and time to deployment.

ELECTROCHEMICAL ENERGY GENERATION AND CONVERSION PRIORITY 2: Application-driven, digital design-led, rapid, multi-scale electrochemical component manufacturing to allow rapid deployment of electrochemical system components, incorporating reducing waste and improving recycling	
Outcomes	Coordinated approach for the electrochemical advanced manufacturing sector.
	Rapid and lower-cost deployment of technologies in real-world applications.
	Embedded circularity in materials design.
	Workforce skilled in advanced, multi-material manufacturing.
	National approach to validation and certification of components.
Enabled by	**Key interventions**
	Comprehensive review of manufacturing capability across the UK and creation of a community of practice to build and learn from industry successes.
	Programme to develop scalable, high-speed, multi-materials, mass-production manufacturing of all materials related to Fuel Cell and electrolyser assemblies/systems and designed for rapid assembly/automatic assembly of components or component housings.
	Embedded sustainable manufacturing practices to include inherent recyclability (including critical material PGMs) and the development of circularity methods for each material with systems designed for second-life use.
	Improved modelling, and the application of Materials 4.0 to: • Allow lifetime predictions particularly under cycling conditions and higher temperature operation. • Accelerate materials discovery.
	Access to national test capabilities for new materials and generating trusted data for industry (providing standard protocols and clear targets).
	Review and align the regulations and validation and certification process for components.
	Review standards and regulations across national boundaries and build knowledge of these into the development of new materials/refinement of existing materials.
	Skills focus on multi-method manufacturing.
Underpinned by	**An enabling ecosystem**
	Digital manufacturing techniques.
	Digital design tools and materials designed for second-life use.
	Industry success in early-stage discovery and translation into commercial application.
Delivering solutions to	**Solve industry challenges**
	Decreasing bottlenecks in technology supply through rapid translation to market.
	Reducing manufacturing costs through simpler component assemblies.
	Improving trust in certified products, suitable for domestic and export markets.
	Attaining sustainability goals, including improved recycling.
	Accessing a skilled workforce.

A2 – 1.3 Materials for hydrogen transport, storage & use

Overall opportunity

Ninety-five percent of the world's current hydrogen production comes from fossil fuels. By 2050, 75% is expected to be produced through electrolysis and will be an integral part of a future resilient and renewable energy system.

Since 1975, global demand for hydrogen has grown more than threefold, and it is estimated to reach 300 MtH_2 by 2050. Within the same timeframe, the demand for hydrogen energy in the EU and the UK is expected to be around 2,750 TWh. The global size of the hydrogen economy was estimated to be £136 billion in 2023 and is expected to rise to at least £2 trillion by 2050.[32,33]

With its sizeable renewable energy generation resource, the UK is ideally placed to exploit hydrogen as an energy storage option for curtailed wind and as part of its integrated net zero energy objectives. It is also in a strong position to utilise hydrogen further to decarbonise hard-to-abate areas, including aviation, heavy-duty transport, and marine, as well as energy-intensive industries such as the foundation industries – glass, cement, concrete, ceramics, and steel. However, global hydrogen business opportunities will only be realised through technological innovations in accelerated materials development and translation. Such innovations are needed urgently to deliver materials solutions at critical points across the hydrogen supply chain.

Once produced, hydrogen must be stored and transported, requiring material systems and coatings that provide low permeability and the sensing capability to monitor any potential hydrogen loss. Hydrogen state (gaseous or liquid) and purification requirements vary by end-use, and the pressure (up to 800 atmospheres gaseous) and temperature ranges (-253°C to >1000°C) present significant challenges to be addressed by a combination of innovative materials design and function.

Therefore, the technical materials challenges across the hydrogen supply chain must be addressed:

Make it – using electrolysis to produce low-cost green hydrogen at scale, enabled by significant improvements in electrolyser technology.[34]

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[32]McKinsey & Co; Global Energy Perspective 2023: Hydrogen outlook

[33]International Energy Agency; Global Hydrogen Review 2023

[34]Materials innovations required to enable hydrogen production are covered in the sub-strategy on Electrochemical Energy Generation

Move it – developing coatings, novel material systems and sensors to enable storage and widescale hydrogen distribution, including supporting national hydrogen infrastructure needs.

Use it – new materials solutions for gas and liquid storage in fixed and mobile applications, purification at the point of use, and downstream issues associated with hydrogen use and degradation, such as corrosion.

The UK is primed to lead the development of the hydrogen supply chain. We have the materials research and innovation expertise to develop the innovative solutions required, and we have key industrial players capable of developing, piloting, demonstrating, and deploying innovative materials-based solutions. The need is pressing because there is significant UK Original Equipment Manufacturer (OEM) application demand for hydrogen materials innovation.

Opportunity Priorities

Two key priority areas in materials for hydrogen transport, storage and use have been identified as game-changing for the UK:

Priority 1: National hydrogen materials challenge programme to identify and fast-track hydrogen energy-enabling technologies for widescale deployment, including:

- Barriers and coatings
- Materials to enable deployment in extreme environments
- Materials to enable hydrogen to X

Priority 2: Coordinated scale-up, test and commercialisation capabilities to accelerate investment-ready hydrogen technologies.

This will include new modelling and testing methodologies and capabilities (from virtual to large-scale, in-use testing), technology prototyping and demonstration, and investment mechanisms. It will be supported by complementary agile, fast-track regulatory frameworks to enable materials development and adoption at pace and scale based on national standards, as well as a focused skills development programme to support widescale deployment.

Benefits to the UK from delivering the above priorities:

(i) Meeting the Government Mission to make Britain a clean energy superpower.

(ii) Securing opportunities in an existing £170 billion global hydrogen sector.

(iii) Improving supply chain autonomy and resilience and national security.

(iv) Delivering more high-value jobs and supporting the growth of a hydrogen-based industry.

(v) Through spillover benefits from hydrogen materials research, competitiveness will increase, and other industry sectors will be supported. For example, improved catalysts for electrolysis will reduce the use of rare metallics, and the development of thinner, more robust membranes for electrolysis will reduce operating costs and remove dependency on forever polymers such as PFASs (per- and poly-fluoroalkyl substances) and other synthetic organofluorine chemicals.

(vi) Offering the potential to re-purpose much of the UK's natural gas network using low permeability materials to provide an extensive hydrogen supply network and storage.

(vii) Capitalising on and maximising the ROI of the UK's offshore wind infrastructure.

(viii) Providing local energy supply and resilience.

What we need to do in the UK to realise the opportunities in this area

HYDROGEN TRANSPORT, STORAGE & USE PRIORITY 1: Delivering materials solutions critical to widescale hydrogen deployment - design, discovery and translation for hydrogen technologies	
Outcomes	Portfolio of application-based materials delivered through a nationally coordinated approach to development and translation of materials for hydrogen technologies, building on industry demand, and existing capabilities and investments.
	Maximising the ROI of existing programmes and infrastructure (for example, research infrastructure, and re-purposing of existing energy infrastructure).
Enabled by	**Key interventions**
	National hydrogen materials challenge programme to identify and fast-track hydrogen energy-enabling technologies, co-designed and led by industry, academia and government and including a focus on coatings, barriers, alloys and ceramics.
	Developing an integrated UK hydrogen technologies roadmap.
	Developing and deploying UK expertise in application of materials 4.0, including physics-based modelling, virtual testing and AI to hydrogen technologies.
	Hydrogen materials accelerator – driving investment to support rapid technology translation to commercial application.
Underpinned by	**An enabling ecosystem**
	Existing UK programmes and capabilities including Hy-RES and HI-ACT programmes, the Hydrogen Innovation Initiative (HII), various hydrogen demonstrators (such as HyNET and the Rolls Royce Hydrogen Demonstrator), sector-specific groups such as the ATI Hydrogen Capabilities Network, and research and translation capabilities such as the Royce Hydrogen Accelerator, and the Defence Materials Centre of Excellence (DMEx).
	OEM application demand.
	Energy infrastructure including gas and renewables (wind).
Providing solutions to	**Solve industry challenges**
	Access to urgently needed hydrogen technologies.
	Supporting SME developers.
	Demand quantification for supply chain actors.

HYDROGEN TRANSPORT, STORAGE & USE PRIORITY 2: Scale-up, test and commercialisation capabilities for hydrogen technologies	
Outcomes	Vastly accelerated translation of hydrogen materials research.
	Coordinated cross-discipline community of practice for hydrogen (including metallics, composites, ceramics, infrastructure (construction) and health and safety).
	Materials 4.0 skilled community (which can translate across sectors/disciplines).
Enabled by	**Key interventions**
	Materials Hydrogen opportunity workstream drawn from industry and academia to oversee and leverage investment in existing programmes and address gaps in UK scale up capabilities to accelerate technology out of the lab into investable propositions for deployment.
	Coordination and gap analysis of national testing and scale-up capability.
	Review of existing regulations, identifying gaps and developing a clear regulatory framework (including measurement & technical standards) to qualify materials and verify technologies (for example, for aerospace applications), aligned with international standards (to facilitate export of technologies).
Underpinned by	**An enabling ecosystem**
	Current regulations (such as those for automotive) as a starting point for regulatory framework revision.
	Existing UK programmes and capabilities including Hy-RES and HI-ACT programmes, the Hydrogen Innovation Initiative (HII), various hydrogen demonstrators, sector-specific groups such as the ATI Hydrogen Capabilities Network, and research and translation capabilities such as the Royce Hydrogen Accelerator, and DMEx.
Providing solutions to	**Solve industry challenges**
	Access to validated hydrogen compliant/certified materials.
	Negating having to send samples overseas for testing and subject to long waiting times and the loss of embryonic supply chains which typically cluster and develop around such facilities.
	De-risking investments in hydrogen technologies and infrastructure.
	Working in an ecosystem of established common standards and regulatory clarity.

A2 – 1.4 Materials for heat exchange, storage & heat recovery

Overall opportunity

Thermal energy, including domestic and industrial heating and cooling, accounts for more than 5% of the UK's energy consumption.

UK household energy use is estimated to account for around 25% of UK greenhouse gas emissions. 75% of domestic energy consumption is for space and water heating.[35] On average, UK homes lose between 25-30% of their domestic heat, and at a rate three times faster than the equivalent stock in the EU. This is mainly due to the age of our housing stock and less emphasis on retrofitting anti-heat-loss technology to improve the thermal envelope efficiency.[36] This is estimated at up to 33 million kWh/year in lost thermal energy. Further development of higher-performance materials designed to recover, transport, and store domestic waste heat more efficiently offers a massive opportunity for energy savings. This would enable the UK to meet its 2050 targets for domestic heat decarbonisation and significantly reduce heat poverty.

Electronics generate significant amounts of heat during operation, resulting in substantial energy loss in domestic and industrial settings. For example, industry-specific electronic components (such as in data centres and steel production facilities) and ubiquitous electronic devices (such as lighting, HVAC systems, and appliances) convert most of the electricity they consume into heat. Technologies can reduce overall energy consumption: from heat batteries, thermoelectric coolers or heat pipes to building-integrated systems such as steam generators, absorption chillers, heat exchangers and heat recovery ventilation. All rely on materials innovation to improve system efficiency at multiple scales and expand systems and application areas.

The UK's industrial sector suffers from relatively high energy prices but also generates a substantial amount of waste heat from industrial processes, estimated at over 300,000 GWh per year,[37] spread across low-, medium-, and high-temperature waste. As much as 80% of this heat could be cost-effectively recovered and reused, partially offsetting emissions. However, currently available methods are not always cost-effective or do not recover heat in a usable form.

[35] Watson, Lomas & Buswell. Decarbonising Domestic Heating: What is the peak GB demand? Energy Policy. 2019
[36] Tado Domestic Heat Loss Report. 2020
[37] Waste heat mapping: A UK study – ScienceDirect. 2019

To decarbonise and remain globally competitive, UK foundation industries need improved methods of managing the heat used (energy efficiency) and decarbonised heating methods, avoiding using fossil fuels. Without this capability, there is a risk of offshoring production to carbon-intensive producers (on a cost basis) or those with cheap renewable energy sources. If the UK is to retain core manufacturing for national security and economic growth, solutions need to be developed for heat energy efficiency; new materials development is critical to such solutions, and step change materials innovation could lead to new disruptive technologies, such as low capex electricity recovery from waste heat or improved heat storage.

The UK has clear strengths in this broad area. It could lead global energy efficiency solutions, underscore its national commitment to environmental sustainability, and generate widespread economic benefits. Innovation in this domain will benefit a wide range of energy sectors and applications and can also transform other industries, such as transport, construction, manufacturing and telecommunications. Thermal energy solutions can also work with other energy technologies to help balance supply and demand.

Industry engagement highlighted some clear priority areas, including energy conversion (large-scale power), improved heat exchange energy and power systems (with lighter weight for transport applications) and more efficient energy conversion from one form to another for both small-scale and large-scale energy conversion systems.

Opportunity priorities

Three key priority areas in materials for heat exchange and recovery have been identified as game-changing for the UK:

Priority 1: Developing and translating materials for industrial-scale heat exchange, recovery and storage solutions.

Benefits to the UK:

(i) Retaining key UK *manufacturing and process* industries by reducing energy costs and enabling efficient off-peak energy usage.

(ii) Meeting industrial decarbonisation targets.

(iii) Grid-balancing and solving intermittency issues of electrification (renewables).

(iv) Supporting new industries/sectors, such as electrified aircraft or biomaterials.

(v) Enabling the use of waste heat in alternative settings by transportable thermal storage.

Priority 2: Developing and translating materials for domestic-scale heat exchange and storage systems.

Benefits to the UK:

(i) Addressing heat poverty by reducing domestic heat loss.

(ii) Achieving the UK's 2050 targets for domestic heat decarbonisation.

(iii) Cementing the UK's position as a heat exchange and recovery technology leader.

Priority 3: Reviewing thermal energy provision and delivery of a translation, scale-up, manufacturing and integration capability.

Benefits to the UK:

(i) Retaining key UK industries (globally competitive Foundation Industries) through improved ROI.

(ii) Solving intermittency issues of electrification (renewables).

(iii) Making use of electrical heat systems more cost-competitive.

(iv) Decarbonising industry and meeting 2050 targets.

(v) Reducing heat poverty by increasing the utilisation of industry waste heat in domestic settings.

(vi) New economic opportunities through the development and transfer of technologies.

(vii) Retaining core industries for national security.

What we need to do in the UK to realise the opportunities in this area

HEAT EXCHANGE, HEAT STORAGE & WASTE HEAT RECOVERY PRIORITY 1: Development and translation of materials for industrial-scale heat exchange, recovery and storage systems	
Outcomes	UK as a leader in industrial scale heat exchange and recovery.
	National energy infrastructure innovation. For example, Super Energy Infrastructure (SEI) based on current petrol stations, providing charging functions to EVs, cold chain transportation, etc, using waste heat, natural energy and renewable heat.
	Recover/re-use heat from high thermal energy producers such as data centres.
Enabled by	ISO standardised energy management (including Thermoelectric Generators).
	Key interventions
	Cross-industry working group to oversee the development of a database of Industry challenges and a corresponding database of materials solutions, and to share knowledge and learning between different sectors, for example, aerospace, nuclear, concentrated solar power.
	Programme to develop targeted materials for heat transfer and storage, delivering for example: • New, efficient heat battery materials. • Thermal storage or recovery materials (or other new materials) using waste heat streams. • Structural power batteries (for example, using multifunction thermal materials for aircraft skin cooling, etc). • Caloric materials development, including improving energy recovery, efficient delivery of the driving field and durability (including lifecycles), barocaloric materials with increased thermal conductivity that can work below 300 bar, reducing hysteresis, mechanical breakdown and fatigue in elastocaloric materials, and reducing the quantity of permanent magnet required for magnetocaloric systems. • Development of phase change storage materials and thermoelectric materials to address specific challenges and opportunities. • Bi-polymer systems for waste heat recovery. • Pipes/ducts technology for air-cooled/evaporative vapour-cooled systems. • High-efficiency heat exchangers.
	Focussed programme for specialist materials integration in key technologies such as solar-thermal systems, heat batteries, implantable and/or wearable devices and transport components.
	Provide solutions for device engineering and real-world validation of materials performance (including accelerated lifetime testing), pilot lines and scale-up across higher TRL levels.

Underpinned by	**An enabling ecosystem**
	Existing expertise and capability in institutes such as Faraday.
	UK heat transfer technologies expertise.
Delivering solutions to	Power electronics - control system capability.
	Solve industry challenges
	Decarbonisation.
	Reducing costs through resource recovery and re-use.
	Hydrogen management (for example, in aircraft).
	Supporting emerging technology translation such as bioelectronics.

HEAT EXCHANGE, HEAT STORAGE & WASTE HEAT RECOVERY PRIORITY 2: Development and translation of materials for domestic-scale heat exchange and storage systems	
Outcomes	Reduced domestic heat loss.
	Improving the UK's housing stock thermal efficiency, making it net zero compliant.
	A suit of certified technologies designed for domestic retrofit applications.
Enabled by	New technologies for more efficient, net zero domestic heating.
	Key interventions
	Cross-industry working group to identify priority materials gaps and drive key technology innovations, including: • Review of current technology to identify value-add opportunities. • Expand opportunities for heat storage beyond hot water and space heating.
	Establishment of thermal management/insulation cluster to deliver key materials innovation needed for domestic applications. For example: • Improved materials for heat batteries (for domestic space heating). • High-thermal conductivity thermoelectrics for active cooling.
Underpinned by	Addressing the lack of clarity in regulations for deploying new materials into homes (for example, combustibility, toxicity) and issues of aesthetics for retrofitting housing stock.
	An enabling ecosystem
	Existing UK expertise in thermal management/insulation materials at lower TRL levels.
Providing solutions to	UK expertise in heat technologies such as phase change materials and ground heat exchangers.
	Solve industry challenges
	Certified, cost-effective materials and thermal energy systems that can be deployed in both new housing and retrofitted to older housing stock.

HEAT EXCHANGE, HEAT STORAGE & WASTE HEAT RECOVERY PRIORITY 3: Thermal energy review and translation, scale-up, manufacturing and integration capability	
Outcomes	An enabled industry-research ecosystem to support rapid translation and deployment of integrated thermal energy solutions.
	Inclusion of a "heat strategy" as part of an overarching energy/electricity generation strategy.
Enabled by	**Key interventions**
	Comprehensive review of current pilot and testing capability across the UK, identifying gaps and solutions to underpin a thermal energy strategy.
	Establish a coherent national innovation translation and scale-up capability and creation of a community of practice to: • Provide access to materials testing, characterisation and validation capability, including stress-testing materials and devices at a small scale. • Incorporate new promising materials into devices for testing. • Enable close integration of components. For example, for transferring heat from a heat store to processes need. • Develop methods to manufacture the materials themselves that lead to low-cost manufacturing. • Better tools/capabilities for LCA that can reliably demonstrate benefits. • Employ additive manufacturing for multifunctional materials for heat and mass transfer.
	A programme to improve the fundamental understanding and hence mitigation of high-temperature degradation (corrosion and mechanical damage), associated with operation at very high temperatures or over extended time periods.
	Embedding of materials 4.0, circularity and advanced manufacturing skills into the programme objectives.
	Regulatory review to incentivise uptake of improved heat use/waste heat use.
Underpinned by	**An enabling ecosystem**
	Existing industry expertise and capability in heat exchange and recovery in residential, small commercial and large industrial applications (including, HRV, ERV, thermal wheel recovery, heat pipe, closed loop coil and integrated heat recovery systems.
	Existing grant support programmes such as the Industrial Heat Recovery Scheme (IHRS).
Delivering solutions to	**Solve industry challenges**
	Accelerated lifetime testing.
	Allowing real world operation simultaneously alongside accelerated lifetime testing.
	Ensure compatibility with national infrastructure for example, cryogenic H_2 enabling large-scale LH_2 infrastructure for aviation and beyond.

A2 – 1.5 Materials for energy harvesting

Overall opportunity

Reaching net zero will require various energy solutions, including energy harvesting. Solar photovoltaic (PV) will be pivotal to the energy transition and will likely become the dominant global power source by 2050.[38] Energy harvesting is also crucial to delivering battery-less and mobile power sources for mobile electronic devices (for example, micro-generation), sensor network systems and the Internet of Things (IoT). These and other high-impact specialist applications (such as thermoelectric dressings, wound healing accelerators, caloric heaters and coolers, and piezoelectric sensors, transducers and actuators) rely on materials innovation.

Energy harvesting constitutes a substantial global market. In 2024, the UK solar energy sector's market size was 17 GW and is expected to exceed 50 GW by 2035, with a CAGR between 11% and 23%. The sector currently employs almost 14,000 people but could support at least 60,000 jobs by 2035.[39]

Solar power used in our homes will be essential to the overall push to reduce UK greenhouse gas (GHG) emissions and is one of the most effective ways to reduce energy costs, thereby decreasing heat poverty. It is already a popular form of low-maintenance domestic energy in the UK, with nearly one million homes benefiting from solar photovoltaics (PV) for electricity and 100,000 solar thermal for hot water.[40] The UK has over 16 GW of solar capacity, accounting for around 7% of the UK's energy mix. Achieving the solar roadmap target of 70GW by 2035 requires significantly accelerated deployment of more efficient systems.

Agrivoltaics—integrating PV and agriculture so that crop growth is not impeded and, in some cases, is enhanced—is a significant growth opportunity for PV. It also provides a measure of resolution to concerns over PV competing with agriculture for land use.

China remains the dominant global supplier of solar PV cells. However, there is an immediate need for discovery and integration of new, more efficient energy harvesting materials to meet our net zero targets, reduce energy poverty, and present new domestic and global economic opportunities across various sectors.

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[38]Nature Communications
[39]Mordor Intelligence UK Solar Power Market Report 2024
[40]Solar Energy UK

The rapid increase and dependency on specialist materials for energy harvesting from environmental sources, including mechanical vibrations, magnetic fields, heat, and light, have become highly relevant for implementing the IoT vision, which requires self-powered wireless sensor networks. These include piezoelectric materials, magnetoelectrics, and thermoelectrics, emphasising the flexibility of energy harvesters.

The UK has clear strengths in this broad area. It could lead in the global energy sector, underscore its national commitment to environmental sustainability, and generate widespread economic benefits. Innovation in this domain will benefit many sectors, including energy, construction, health, and agriculture.

Opportunity priorities

Two key priority areas in materials for energy harvesting have been identified for the UK:

Priority 1: Develop and deploy materials for higher-efficiency solar PV and specialist energy harvesting applications, including health, battery-less mobile electronic devices, and sensors.

Benefits to the UK:

(i) UK leading materials discovery for new PV.
(ii) Increasing renewable energy use, decreasing GHG emissions and reaching net zero targets.
(iii) Developing a world-leading, global capability in specialist energy-harvesting materials.
(iv) Enabling new economic opportunities in high-value markets.

Priority 2: Accelerate scale-up and manufacturing of energy-harvesting materials and devices to support resilient supply chains and generate new economic opportunities.

Benefits to the UK:

(i) Growing the UK's solar PV market.
(ii) Diversifying the UK's energy mix and enhancing energy system resilience.
(iii) Improving energy security by generating electricity locally and reducing dependence on imported fuels.
(iv) Improving supply chain security for critical components.
(v) Promoting sustainable land use through the regeneration of brownfield sites or former industrial areas.
(vi) Growing and supplying new high-value markets in technologies that require battery-less energy supply or self-powered wireless sensor networks for sectors such as health

(including wearables and implantables), construction (sustainable buildings sensors) and the IoT.

(vii) Creating new high-skill, high-value jobs, stimulating local economies, and supporting rural development.

What we need to do in the UK to realise the opportunities in this area

ENERGY HARVESTING PRIORITY 1: Develop and deploy materials for higher-efficiency solar PV and specialist energy harvesting applications, including health, battery-less mobile electronic devices, and sensors	
Outcomes	National solar PV capability supplying cross-sector needs through an accelerated, targeted programme.
	World-leading, global capability in specialist energy-harvesting materials.
	New industry opportunities in specialist energy harvesting devices (for example, IoT, health, sustainable buildings).
Enabled by	**Key interventions**
	Cross-industry-academia-government task force (expanding beyond the current task force supply chain focus) to: • Identify new application areas (including space, aerospace and agrivoltaics, and local net zero solutions) and energy harvesting solutions (including perovskites). • Oversee a national Solar PV programme for priority materials development and translation such as tandem systems, light-weight PV, flexible PV, thin film solar layers, PV coatings, organic photovoltaics. • Oversee a national programme for development of materials and devices for specialist energy harvesting applications (including, piezoelectric materials, magnetoelectrics, and thermoelectrics).
	Deployment of Material 4.0 methods aligned with rapid throughput and high fidelity testing to accelerate material discovery.
	Review and alignment of standards for PV and other energy harvesting applications to underpin state-of-the-art testing protocols for new materials and device evaluation, agreed and implemented by industry and academia.
Underpinned by	**An enabling ecosystem**
	Existing national expertise in PV materials and systems development.
	Existing expertise in specialist materials and in specialist sectors (for example, bioelectronics).
Providing solutions to	**Solve industry challenges**
	Accelerated access to a portfolio of more efficient energy-harvesting materials, tested and verified against agreed standards.
	Unified standards to allow rapid deployment.
	New sectors supplied with PV solutions (for example, space and aerospace).
	New specialist sector opportunities identified (for example health).
	Access to a skilled workforce.

ENERGY HARVESTING PRIORITY 2: Accelerated scale-up and manufacturing of energy-harvesting materials and devices to support resilient supply chains and generate new economic opportunities	
Outcomes	Achieve the solar roadmap target of 70GW by 2035.
	Enhanced solar PV system integration.
	Local PV systems deployed.
	New market opportunities in specialist energy harvesting technologies.
Enabled by	**Key interventions**
	Access to national pilot, scale-up and integration facility with: • A focus on higher TRLs and lowering production costs. • Oversight of a national programme for system integration of PV with energy conversion and storage systems such as electrocatalysis/photo-electrocatalysis. • New high-value device testing, pilot and manufacturing capability to accelerate time to market.
	Centralised or coordinated regulations and standards advisory capability.
	Access to clinical trials capability to enable novel energy-generating materials in devices for health applications.
Underpinned by	**An enabling ecosystem**
	Dispersed SME expertise in energy materials and systems development.
	Experience from Faraday Battery Challenge.
Providing solutions to	**Solve industry challenges**
	Filling the current scale-up gap.
	Simplified, clarified and aligned standards with access to centralised advice on standards and regulations.
	Development of new market opportunities.
	Supported supply chain with improved security and resilience.

A2 – 1.6 Materials for advanced nuclear fuels and nuclear test capability

Overall opportunity

Nuclear energy will be a critical component of the UK's (and global) net zero ambitions. Eleven percent of electricity globally is produced from nuclear energy in a £1.5+ trillion nuclear market across an extensive supply chain. The UK has nine reactors across five nuclear sites, providing around 14% of the country's electricity from 5.9 GW of capacity. Of the current nuclear fleet, only Sizewell B will be online after 2028, while Hinkley Point C is due to come online between 2029 and 2031. Accelerated development of GW-scale and small modular reactors (SMRs) is required if the UK is to meet its future energy needs and the ever-increasing needs of the large-scale technology sector.[41]

The UK has a long history in nuclear fusion energy and vast expertise across the nuclear lifecycle, from fuel production, generation, new construction, and research to decommissioning, waste management, and transportation. It also has a world-class regulatory system.

The UK's civil nuclear sector's economic footprint provides around 60,000 highly skilled jobs, many in the northwest and southwest of England. With the required sector expansion, this number will likely double over the next 20 years, with further job creation in the defence nuclear sector and diverse regions across the UK.

This outlook is strengthened by the recently signed UK-US civil nuclear agreement and ongoing discussions between the UK and Canada to speed up the delivery of advanced nuclear technologies. Further international collaborations, such as with Europe and Japan, will also accelerate innovation in nuclear materials.

These priorities will also be pivotal in supporting the UK's ambition to establish a leading position in manufacturing and supplying new generations of nuclear reactors, including advanced modular reactors and small modular reactors.

Developing secure and cost-effective nuclear fuel supplies and other nuclear-related materials will expand nuclear power provision and bring significant economic value to the UK by hosting part of the nuclear supply chain. It will help the UK meet its domestic needs for nuclear energy solutions (quadrupling its output by 2050) and improve national security and resilience through onshored large-scale fabrication of nuclear fuels and other nuclear components. The approach will need defined targets, sufficient budget, be

[41] The Role of Nuclear in the UK's Energy Supply. 2023. House of Lords Library

built from collaborations and have access to surrogate/active R&D, scale-up and pilot facilities.

This must be underpinned by the growth of a highly skilled workforce developing and deploying a globally unique stock of technologies that will also benefit other industries and services and have significant potential in overseas markets.

Opportunity priorities

Two key priority areas in materials for nuclear fuels have been identified as key for the UK:

Priority 1: Developing and translating nuclear fuel options for industry based on agreed technologies.

Benefits to the UK:

(i) Industry access to a portfolio of nuclear fuels for deployment in priority nuclear systems.
(ii) Enhanced national security through nuclear supply chain sovereignty and resilience.
(iii) Directly supporting the transition to net zero.
(iv) Indirectly supporting the wider transition to net zero (for example, enabling green hydrogen production).
(v) Realisation of co-generation opportunities.
(vi) Potential for reduced nuclear waste.
(vii) Securing a portion of the global nuclear fuels market.
(viii) Retaining IP in the UK.
(ix) Economic returns, including highly skilled jobs in diverse regions across the UK.

Priority 2: Delivering test, scale-up and manufacturing capabilities to fast-track technology development, supported by a skills programme to enable technology development and deployment.

Benefits to the UK:

(i) Sovereign capability strengthening national security and resilience.
(ii) Accelerated materials translation and deployment.
(iii) Collaboration across civil and defence sectors providing economies of scale and sharing expertise.
(iv) Highly skilled workforce supporting the growth of the UK's nuclear sector.

What we need to do in the UK to realise the opportunities in this area

ADVANCED NUCLEAR FUELS AND NUCLEAR TEST CAPABILITY PRIORITY 1: Development and translation of nuclear fuel options for industry based on agreed technologies	
Outcomes	Clear, agreed priorities for UK nuclear technology development.
	Agile fuel design iteration based on functional requirements definition (i.e. capable of meeting needs, available and reliable) which also reduce decommissioning costs.
	More competitive supply chain; more UK companies using advanced manufacturing methods and entering domestic and export markets for nuclear goods and services.
Enabled by	**Key interventions**
	Cross industry-academia working group to identify and shortlist (within three years) new fuel types and other materials of interest which may realistically be ready for post-irradiation examination (PIE) within 10 years, with a focus on industrially relevant/near to market concepts.
	National programmes (with oversight from the Nuclear Innovation Research Office; NIRO) complimenting exiting National Nuclear Laboratory (NNL) programmes to: • Refine existing fuel technologies. • Better understand behaviours under different conditions (such as sintering, high burn-up, environmental factors), gaps in irradiation performance, degradation, corrosion, fragmentation, relocation and dispersal. • Develop materials to enable new technologies with a focus on near to market technologies such as accident tolerant fuel (ATF) concepts (specifically Cr coated clad/Cr_2O_3 doped UO_2) and HTGR (for example, DRAGON fuel availability, TRISO matrix graphite fabrication and characterisation).
	Coordinated approach to producing, curating and accessing data through collaboration (for example, a UK-led OECD-NEA type collaboration) - a key link to Materials 4.0.
	Establishment of a UK database and archive of active/irradiated materials for nuclear applications.
	Training Programme in materials science processing with an emphasis on larger (practical) scales based on a skills gap analysis for the sector.
Underpinned by	**An enabling ecosystem**
	Expertise, breadth of technology and global reputation of the UK's civil nuclear industry.
	Coordination through existing mechanisms including NNL, NIRO, UK Fuel Forum and Nuclear Industry Association.
	Existing programmes and facilities such as AMR RD&D, AFCP, UK-CPF, Hitachi helium reactor with molten salt storage, TRISO use in SMRs/AMRs for transportation (for example, space exploration), materials expertise from other sectors (for example in CMCs).
Providing solutions to	**Solve industry challenges**
	Accelerated access to safe nuclear materials.
	Supply chain sovereignty and resilience.
	Access to a highly skilled workforce.

ADVANCED NUCLEAR FUELS AND NUCLEAR TEST CAPABILITY PRIORITY 2: Test, scale-up and manufacturing capabilities to fast-track technology development, supported by a skills programme to enable technology development and deployment	
Outcomes	Sovereign test, scale-up and pilot capability for nuclear materials, across civil and defence applications.
	Accelerated path to market for new technologies.
	IP retained in the UK.
	Skilled nuclear workforce supporting and growing the sector, with skills transferrable to other sectors.
Enabled by	**Key interventions**
	Review of requirements for test and scale-up facilities, including access to a materials test reactor, PIE, HTGR demonstrator, uranics research facility.
	Develop a model for international collaboration (for example UK-Canada collaboration) and access to facilities in parallel to recapitalisation of UK infrastructure, retaining sovereignty through UK thought leadership and specific materials domain knowledge retention.
	Develop large scale modelling capabilities combined with testing capabilities to test models across all operating parameters; proof of methodology against archived materials which underpin current regulatory acceptance.
	Access to large scale computation and fission-fusion collaboration on nuclear materials model validation approaches related to irradiation.
	Skills (manufacturing & operating) licence & design based on International Atomic Energy Agency (IAEA) specifications and cross-sector learning.
Underpinned by	**An enabling ecosystem**
	Existing expertise and facilities (for example, NNL), industry-academia collaborations and access to international facilities for academics (for example, through UK-Canada collaboration).
	IAEA specifications for skills needs and utilisation of IAEA Nuclear Education Network (NET) programme for UK students.
Providing solutions to	**Solve industry challenges**
	Access to secure supply chain of verified nuclear materials and fuels.
	Growing the global market share in nuclear technologies.
	Access to a skilled workforce.

A2 – 2 MATERIALS FOR FUTURE HEALTHCARE

A2 – 2.1 Biocompatible materials

Overall opportunity

Biocompatible materials, often engineered with surface treatments, are integral to the success of medical implants, devices, and prosthetics. These materials must meet rigorous safety standards, ensuring they perform their intended functions without causing adverse immune reactions, infections, or toxicity. They require constant innovation to improve their properties and, hence, the performance and longevity of the end products, delivering enhanced benefits to the end user/patient.

While the UK market in biocompatible materials is relatively small, the global market is significant. In 2024, its estimated value was £150 million and is expected to reach £349 million by 2035, growing at a CAGR of 8.8%, with the US and China being the two largest individual markets. The UK holds around an 8% share of the global market and is particularly strong in areas supported by its robust healthcare system.[42]

The growth in the biocompatible materials market is driven by several factors, including technological advancements that allow for the development of more sophisticated and effective products, the growing global disease burden (especially in ageing populations) and government support and regulations promoting sustainable practices and materials. Moreover, regulatory support for biocompatible materials in emerging markets is expanding access to novel medical technologies, further stimulating growth in the industry. These factors collectively ensure that the demand for biocompatible materials continues to grow, providing essential solutions for a wide range of medical applications and offering opportunities for the UK to capitalise on its research and translation expertise in biocompatible materials (and materials more broadly) and its regulatory systems.

While biocompatible materials have transformative potential, their clinical application has several challenges. The complexity of human biology means that predicting how materials will behave inside the body can be incredibly complex. Immune response, bio-corrosion, and long-term stability are among the significant issues that researchers must address. Furthermore, the cost of developing and testing new materials can be prohibitively high, often necessitating extensive preclinical and clinical trials to ensure they meet safety and efficacy standards (for example, ISO13485 compliance). These

[42] Persistence Market Research Biocompatible Materials Market Report

challenges require ongoing research and collaboration between material scientists and medical professionals to ensure that new developments can be safely and effectively translated into clinical practice.

Materials development, characterisation, and validation for medical use are fundamental requirements for the biocompatible materials opportunity. Building on current systems and processes will support the development of innovative biocompatible materials which can feed into global markets. Key areas in which biocompatible materials innovation is required include 3-D fabricated advanced materials, defined-porosity materials, biosynthetic hybrid materials, conductive materials, tailored mechanical metamaterials, patient-specific materials, externally controlled implantable materials, infection-reducing surfaces, coatings and drug release, bone and cartilage regenerative solutions, and shape memory materials.

It is critical to scale up and provide market-ready trial materials to meet the required regulatory standard. Streamlining access to capabilities in universities and innovation centres, as well as materials and device registrations and approvals, would accelerate the translation and commercialisation of biocompatible components and devices. The approach should also consider centres spanning traditional disciplines/boundaries so that it is led by innovation needs.

Clinical trials are vital for any product entering the healthcare medical device sector. Any new materials or changes in material that form part of an end product will require approvals, which initiate the clinical trial process. The national health service offers a unique opportunity for the UK to regain its position as a global leader and provider of clinical trials that align with regulations and standards required by other markets (such as the US, Australia and Europe). This would give our materials innovators access to international markets and create additional economic opportunities through clinical trial services.

Opportunity priorities

Two key priority areas in biocompatible materials innovations have been identified as game-changing for the UK:

Priority 1: Developing biocompatible materials with specific properties for targeted therapies (including structural/scaffolding, porous, conductivity, patient-derived, injectable, 3-D printable, patient-specific, and drug-eluting) to meet clinical demand.

Benefits to the UK:

(i) Improved patient outcomes.
(ii) UK healthcare system with access to state-of-the-art clinical tools and products.
(iii) Economic opportunities in commercialising/licencing high-value products.
(iv) International recognition of UK sector expertise in biocompatible materials.
(v) New employment opportunities in high-skill, high-value jobs.

Priority 2: Enabling a harmonised regulatory and clinical trials ecosystem aligned with international standards, regulations and protocols to accelerate the translation of biocompatible materials and devices into markets (both domestic and international).

Benefits to the UK:

(i) UK leading fast-track, harmonised tech transfer across UK/EU/US/AU.
(ii) Unlocking trade barriers and improving market accessibility (making it easy to trade with the UK).
(iii) Economic opportunities as a globally competitive environment for translation of biocompatible materials innovation.
(iv) Harnessing the power of the NHS, improving patient care and reducing public costs.
(v) Economic and social returns through clinical trials delivery for international customers.
(vi) New employment opportunities in high-skill, high-value jobs.

What we need to do in the UK to realise the opportunities in this area

BIOCOMPATIBLE MATERIALS PRIORITY 1: Development of biocompatible materials with specific properties for targeted therapies	
Outcomes	Portfolio of new, tested and verified materials with application-specific properties for targeted therapies (targeting international markets).
	Growth for the UK-based, high-value biomaterials sector with enhanced access to international markets.
Enabled by	**Key interventions**
	Cross-academia-clinical-government working group to facilitate collaboration, identify and drive priority areas for materials challenges and medical device development, and ensure alignment with key international market requirements.
	Industry-driven programme to develop biocompatible materials with specific properties for targeted therapies.
	Embedded skills delivery linked to the materials discovery and translation programmes.
	Directly supported by priority 2 – regulatory pathway harmonisation and clinical trials system (to bring products to market more swiftly and aligned with key international market regulations and standards).
Underpinned by	**An enabling ecosystem**
	Existing biomaterials expertise.
	National capabilities including NPL, NHS, catapults, advanced manufacturing.
Delivering solutions to	**Solve industry challenges**
	Next-generation materials available for patient-specific needs.
	Addressing skills and workforce gaps.
	Growth in the biocompatible materials sector.

BIOCOMPATIBLE MATERIALS PRIORITY 2: Regulatory pathway harmonisation, including reinvigorating a national clinical trials capability aligned with national and international regulatory requirements			
Outcomes	Enhanced patient/end-user outcomes.		
	De-risked investment strategies.		
	Accelerated biocompatible materials and device commercialisation.		
	UK leading the global clinical trials market.		
Enabled by	Enhanced clinician career opportunities improving talent attraction and retention.		
	Key interventions		
	Harmonising regulatory systems for materials to allow innovations to reach go/no-go points faster. For example, streamlined regulatory feedback on pre-clinical testing/validation plans and Medicines and Healthcare products Regulatory Agency and Human Tissue Authority guidance to manufacturers and sponsors.		
	Harmonising UK/EU/US/AU product regulatory approvals (including comparison to the Food and Drug Administration regulatory consultation mechanism "Q-Sub process" to determine if an analogous approach is applicable).		
	Review of mechanisms to derisk investment support to get new materials not currently FDA-approved through regulations.		
	A national capability in predictive clinical outcomes (in-silico, ex-vivo, in -vitro), including modelling as an alternative to first-in-human trials-based interventions (including ethics and regulatory trial approval).		
	National clinical trials service.		
Underpinned by	Need for accessible testing facilities (CROs, large animal) to move through TRLs towards clinical trial.		
		An enabling ecosystem	
		Medicines and Healthcare products Regulatory Agency and Human Tissue Authority.	
Delivering solutions to		NHS systems and patient cohorts provide a unique foundation on which to build a world-leading clinical trials system that is accessible globally.	
			Solve industry challenges
			Prioritising application-led innovations.
			De-risk developing and adopting new materials for medical applications.
			Streamlined regulatory environments facilitating innovation adoption.
			Access to a coordinated clinical trials system that is compatible across regulatory jurisdictions.
			Inability to recruit required skills base and reducing loss of clinical research talent from the research and translation pool.

A2 – 2.2 Materials for bioelectronics

Overall opportunity

Bioelectronics is the electronic monitoring and control of biological systems for applications in medicine, agriculture, industry, and the environment. It includes the use of devices, and the application of materials that establish and use synergies and the interface between electronics and biology. In healthcare, bioelectronic systems directly interface with biological systems (in vivo or in vitro) to prevent, diagnose, monitor, treat, and cure disease and to rehabilitate patients.

Pacemakers, blood glucose monitors, and cochlear implants are examples of established bioelectronic healthcare solutions, as are a wide range of emerging neurotechnology and regenerative medicine solutions.

The estimated global market size for bioelectronics is between £7.8 billion and £17.6 billion. By 2035, it is estimated to grow between £33 billion and £45 billion, with a CAGR between 6% and 14%. The estimated market size for the bioelectronics sector in the UK is between £132 million and £163 million. Based on a CAGR of 10.5%, the projected UK market size is up to £442 million by 2035.[43]

The UK's strengths in bioelectronics include the international reach of its research outputs, a well-networked community, and a competitive development environment.

There are 56 businesses active in bioelectronics innovation in the UK, 55% of which are micro or small businesses. The UK's active bioelectronics research sector supports them. Twenty-two UK universities are actively researching bioelectronics; a third have a dedicated group or institute. They produce around 11% of scientific papers globally and 2.64% of all bioelectronics patent applications – the highest percentage of any European country.

Materials innovation is fundamental in supplying safe, responsible and disruptive bioelectronic healthcare solutions. However, the sector is being held back by its poor definition, access to funding, awareness of industry and clinical needs, availability of data about materials, appropriate supply of materials, capability to scale up, and accessibility of high-standard testing, fabrication and prototyping facilities.

In addressing these issues, the UK bioelectronics sector is well-positioned to grow its global market share.

[43] Materials for Bioelectronics in Healthcare Strategy and Action Plan (2024)

Innovation Priorities

Two priority areas in bioelectronic materials innovations have been identified as key for the UK:

Priority 1: Develop a suite of electrically conducting materials with mechanical properties similar to human tissue for interfacing electronics with the body to improve sensor performance in vivo, and increase implantation life (> 10 years).

Benefits to the UK:

(i) Improved patient outcomes.
(ii) UK healthcare system with access to state-of-the-art clinical products.
(iii) Economic opportunities in commercialising/licencing high-value products.
(iv) International recognition of UK sector expertise in bioelectronics.
(v) New employment opportunities in high-skill, high-value jobs.

Priority 2: Creating a highly connected and efficient bioelectronics ecosystem based on agreed standards, skills and facilities.

Benefits to the UK:

(i) Highly functioning bioelectronics ecosystem.
(ii) Accelerating commercialisation/licencing of high-value products.
(iii) New employment opportunities in high-skill, high-value jobs.

What we need to do in the UK to realise the opportunities in this area

BIOELECTRONICS PRIORITY 1: Develop a suite of bioelectronic materials with application-specific properties	
Outcomes	Portfolio of new, tested and verified materials with application-specific properties for targeted bioelectronic therapies.
	Growth for the UK-based, high-value bioelectronics sector with enhanced access to international markets.
Enabled by	**Key interventions**
	Cross-academia-clinical-government working group to facilitate collaboration, identify and drive priority areas for bioelectronic materials challenges and medical device development, and ensure alignment with key international market requirements.
	Industry-driven programme to develop bioelectronic materials with specific focus on: • Long-term (>10 years) implantable materials. • Electrically conducting, biocompatible materials with mechanical properties similar to tissue for interfacing electronics with the body. • Materials which improve sensor performance in vivo (elimination of biofouling or inflammatory responses).
Underpinned by	**An enabling ecosystem**
	Existing biomaterials expertise.
	National capabilities including bioelectronic institutes.
Delivering solutions to	**Solve industry challenges**
	Next-generation materials available for patient-specific needs.
	Growth in the biocompatible materials sector.

BIOELECTRONICS PRIORITY 2: **Creating a highly connected and efficient bioelectronics ecosystem based on agreed standards, skills and facilities**	
Outcomes	Highly connected bioelectronics ecosystem based on agreed standards.
	Growth for the UK-based, high-value bioelectronics sector supported by skills and facilities that meet rigorous bioelectronics standards.
	Highly skilled bioelectronics workforce.
Enabled by	**Key interventions**
	Cross-academia-clinical-government (Medicines and Healthcare products Regulatory Agency) working group to facilitate collaboration, identify and drive priority areas for bioelectronic materials challenges and medical device development, and ensure alignment with key international market requirements.
	Establish a standard for material biocompatibility data and create a database or other data sharing service for material biocompatibility data.
	Create digital and AI toolkits for materials computational modelling and predictive testing.
	Create a network of testing, prototyping and fabrication facilities available to those working in bioelectronics that meet the required standards.
Underpinned by	**An enabling ecosystem**
	Existing biomaterials expertise (research and commercialisation).
	Medicines and Healthcare products Regulatory Agency.
Delivering solutions to	**Solve industry challenges**
	Next-generation materials designed and developed for specific clinical needs.
	Accelerating timescales and lowering development costs of bioelectronic materials and devices.
	Addressing skills and workforce gaps.
	Growth in the biocompatible materials sector.

The Materials for Bioelectronics in Healthcare Strategy and Action Plan (2024) provides further details on specific interventions.[44]

[44]Materials for Bioelectronics in Healthcare Strategy and Action Plan. Royce. 2024. https://www.royce.ac.uk/collaborate/roadmapping-landscaping/materials-for-bioelectronics-in-healthcare/

A2 – 3 STRUCTURAL INNOVATIONS

A2 – 3.1 Materials for low-carbon construction

Overall opportunity

Construction is fundamental to our economy and society. From domestic housing and industrial-scale buildings to national transport and energy infrastructure, it is, literally, the foundation.

The UK construction market was valued at £384 billion in 2023, contributing £37 billion in GVA. It is predicted to achieve a CAGR of more than 2% from 2025 to 2028.[45] More than 2.2 million workers are employed in the construction sectors.[46]

Construction sectors are high-volume material users, with construction materials estimated to account for 55% of yearly global material extraction.[47] There is widespread agreement that most current, high-volume construction materials must be more sustainable.

For example, concrete is the most used material in the UK (and the world). Embodied carbon in buildings accounts for 11% of our national total emissions, with concrete accounting for 8-10%.[48] In addition, current concrete recycling practices devalue it dramatically. The estimated value of the UK's precast concrete sector is £3.7 billion, growing at around 5% per year, while the UK ready-mixed concrete sector is worth over £3 billion. There are over 1,900 concrete plants in the UK supporting 29,000 employees.[49] As a carbon-intensive material, developing sustainable (low-carbon emissions) concrete is a top priority in decarbonising the construction industry and achieving net zero. This is a global opportunity for the UK.

The sector also typically sees high volumes of wastage. For example, it is estimated that around 1.3 million tons of plasterboard waste is generated annually within the new-build and refurbishment sectors. Despite legislation requiring that gypsum-based materials not go to landfills but be recycled, significant quantities are still not recycled. The opportunity to adopt new materials that generate less waste and can be more easily re-

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[45]Global Data Construction Market Analysis (June 2024)

[46]Office of National Statistics; Construction statistics (November 2023)

[47]Krausmann et al., 2017

[48]World Green Building Council

[49]IBIS Concrete Construction Product Manufacturing in the UK - Market Size, Industry Analysis, Trends and Forecasts Report

used or cost-effectively recycled is urgently needed. In addition, the UK market for gypsum-based products is considerable, and currently, all of them are imported.

The construction sector has further opportunity to contribute to the UK's net zero targets by improving energy efficiencies, especially in the UK housing stock (30 million homes). It is valued at over £8 trillion[50] and is one of Western Europe's oldest and leakiest housing stocks. Twenty percent of our housing stock was built before 1919, and a further 34% before 1964 – yet 80% of buildings in use today will still be inhabited by 2050. They are responsible for 48% of carbon emissions from the built environment and 21% of the UK's total carbon emissions.[51]

The built environment's impact on human health and wellness is also an essential consideration in the industry. Mounting evidence indicates a direct correlation between health and the materials used in homes.[52] It is long-established that construction materials are also critical in maintaining safe drinking water supplies. All these factors require the right materials applied in the right way. Interventional measures using new materials technologies are much more cost-effective than clinical treatment of illness, reducing the overall burden on national healthcare costs. To address this, we need alternative, high-performance, more recyclable construction materials that extend the life of assets and provide vastly improved energy efficiencies in the UK housing stock.

Many construction companies are willing and ready to implement new materials. However, their adoption can be delayed by a lack of standards, regulatory clarity, and insurance concerns. Predictable, long-term regulation is necessary in the construction sector to ensure successful investment business cases. The regulation also needs to be responsive and fit for purpose. The UK needs to lead on agile regulations for new materials to bring cost-effective, sustainable solutions to the market.

By harnessing innovation in critical construction materials, the UK can lead the global race towards cleaner economic growth, reach its net zero targets and deliver a truly sustainable industry within 20 years.

Opportunity Priorities

Three key priority areas in materials for low-carbon construction have been identified, driven by a cross-industry leadership group:

[50]Bank of England
[51]Energy Savings Trust (November 2021)
[52]Nokulu & Acun Ozgunler, GU J Sci, 2019

Priority 1: Decarbonising cement and concrete within five years.

Priority 2: Develop and deploy tested and standardised construction materials to improve energy efficiency, improve occupier health in homes, and extend the performance of infrastructure in its in-use life.

Priority 3: Develop policy, regulations and standards (including testing and characterisation) to enable rapid adoption and deployment of new construction materials.

Together, these priorities will deliver significant benefits to the UK:

(i) Meeting net zero targets through decarbonisation of the construction industry.

(ii) Meeting the Government Missions: Kickstart economic growth, Make Britain a clean energy superpower and Build an NHS fit for the future.

(iii) Securing an industry as a leader in delivering economic growth with minimal environmental impact.

(iv) Attracting and growing a new demographic skills base.

(v) Enhanced resilience of the UK supply chain from diversification of resources.

(vi) Decreased reliance on virgin materials within the industry.

(vii) Improved reputation for the cement, concrete, and infrastructure sector.

(viii) Improving the health and well-being of building occupiers.

(ix) More agile construction sector (across all scales).

(x) Improved return on investment in materials research by enabling rapid adoption of new technologies.

(xi) More agile and responsive regulatory environment and improved compliance.

What we need to do in the UK to realise the opportunities in this area

LOW-CARBON CONSTRUCTION PRIORITY 1: Decarbonising cement and concrete within five years	
Outcomes	Reducing UK CO_2 emissions by at least 8%.
	Reducing waste to landfill and creating new circular economy opportunities.
Delivered by	**Key interventions**
	Development of faster-curing, low-carbon concrete suitable for use across the built environment.
	Recovery of cement through efficient recycling of waste concrete (a decarbonised source of calcium that could be used across multiple applications including cement recycling and CO_2 mineralisation).
Underpinned by	**An enabling ecosystem**
	UK-based calcined clay production (expected to grow from < 10Mt/yr today, to 375 Mt/yr by 2050.
	Skilled workforce.
Delivering solutions to	**Solve industry challenges**
	Decarbonising the construction industry within 20 years.
	Improve sector profitability through circular economy opportunities, reduced waste and more cost-effective materials systems.
	Addressing the shortage of ground granulated blast furnace slag (GGBS), which limits our ability to decarbonise concrete.

LOW-CARBON CONSTRUCTION PRIORITY 2: Tested and standardised construction materials for improved energy efficiency and improved occupier health in homes and extending performance in the in-use life of infrastructure	
Outcomes	Improving the health of building occupiers.
	All homes achieving an Energy Performance Certificate (EPC) rating of 'C' or above by 2050.
	Highly skilled workforce in developing, manufacturing and installing next-generation products.
Delivered by	**Key interventions**
	Sustainable materials hub to focus development of construction materials to: • Reduce the carbon footprint of buildings (e.g., improved thermal insulation (internal retrofit insulation, construction boards from recycled glass fibre-reinforced polymer composites). • Build healthier homes (e.g., bio-based alternatives, reduced volatile organic compound alternative to polymeric foam). • Extend in-use life (e.g., alkali-activated cementitious material (ACCM), fibre-reinforced concrete, geopolymer coatings, improved cathodic protection systems).
	Directory of independently tested and validated materials.
	A construction "skills academy" approach linking apprenticeships, colleges and universities and to the implementation of new materials to create a skilled and agile workforce able to design, construct and install the new materials.
Underpinned by	**An enabling ecosystem**
	Existing training programmes, better linked across the skills pipeline.
	Research expertise in structural materials.
	Willingness of industry to adopt new practices.
Delivering solutions to	**Solve industry challenges**
	Resolve the GG Blast Furnace Shortage.
	Dramatic reduction of reliance on imported high-VOC materials.
	Access to an appropriately skilled workforce.

LOW-CARBON CONSTRUCTION PRIORITY 3: Policy, regulations and standards (including testing and characterisation) to enable rapid adoption and deployment of new construction materials	
Outcomes	Rapid deployment of new technologies.
	Sector compliance facilitated (especially for SMEs).
Delivered by	Greater efficiency in the regulatory and compliance systems.
	Key interventions
	Develop an advanced market commitments framework for the UK, building on and increasing return on investment.
	Cross-industry-regulators working group to identify areas of improvement across the regulatory pathway, prioritising/supported by the following:
	Standards • Development of complimentary technology-specific standards for designing new materials (new design models required). • Machine readable standards and calibration formats to allow traceability of testing results.
	Testing • Rapid, independent testing in line with approved standards (durability, corrosion, performance).
	Certification • Certification loan for SMEs (currently IUK funding does not cover regulatory stages). • Accelerating the agreement certificate through a new approach to early engagement of British Board of Agreement (BBA) for rapid and more relevant product certification (out with the British Standards Institute (BSEN) structures).
	Verification • Access to independent validation/verification capabilities for new materials/processing.
	Policy • Consider accelerating the phasing out of Portland cement. • Decision to be made by the UK Government as to whether product certification and approvals bodies need to be UKAS accredited (post-Brexit).
Underpinned by	Training focused on regulatory regime, so stakeholders (manufacturers) understand compliance requirements.
	An enabling ecosystem
Delivering solutions to	Materials 4.0 – AI, data-sharing, predictive modelling and new technologies for application in real-world durability testing.
	Solve industry challenges
	Improved compliance through a more standardised framework.
	Risk-reduction (and improving access to insurance).
	Achieving sustainability goals within 10 years.

A2 – 3.2 Materials for sustainable structural systems - composites

Overall opportunity

Composites are system-level advanced materials that provide essential lightweight, durable, and high-performance structural solutions across multiple sectors (including aerospace, space, energy, marine, automotive, construction and defence), from high-value applications in aerospace and defence to high-volume, durable applications in renewable energy and transportation.

They cover a wide range of systems (from polymers to ceramic matrix composites) with a wide range of maturities. By their very nature, composites are joined into systems that need related capabilities, requiring innovation in joining and coating technologies. For example, glass fibre-reinforced plastic on turbine blades, carbon-reinforced composites in advanced airframes, and ceramic matrix composites in fusion and heat engine technologies.

Composites[53] enable strategic advantages for UK manufacturing, are critical to the defence sector (improving performance and reducing costs) and strengthen demand for chemicals and other materials. For example, increased blade length for wind turbines, high-pressure storage systems (hydrogen), increased range and reduced fuel consumption in all forms of transportation, modular build opportunities with reduced cost and social burden, and highly durable, environmentally resistant subsea structures are all applications that require innovation in composites.

For the sizeable construction market, the need exists for materials with more modest, or at least nuanced, performance. They also need to be net-zero or carbon-negative and highly circular (for example, utilising valorised waste streams and offering very low-impact end-of-life treatments such as composting (where it is not practicable to design for reuse or repurposing of components and sub-components). Major client bodies such as local authorities require this, and their supply chains are now driving this through specification.

In other sectors, the transition to net zero and the need for resilient and enhanced defence platforms demand enhanced composite materials.

The UK composite materials sector, which includes 400+ companies and 30,000 jobs, is currently worth £4 billion and has a CAGR of 6 to 9%. This will increase further if the UK

[53] Includes polymer matrix composites (PMCs), ceramic matrix composites, (CMCs), reinforcement and layup. Metal Matrix Composites (MMCs) are covered by Expert Working Group 18B.

can secure the materials and production market for aerospace (wing), wind (blades), hydrogen (storage), and defence (high temperature, extreme performance). At the same time, it must meet the high-volume, low-cost needs of sectors such as construction.

Opportunity priorities

Two key priority areas in composites' innovations have been identified as game-changing for the UK:

Priority 1: Developing more sustainable composites designed and optimised for multiple applications, longer lifecycles, recycling, and reuse. Some composite innovations will also support sustainability goals by enabling other sustainable technologies.

Benefits to the UK:

(i) Reaching net zero targets.

(ii) Reducing costs and increasing competitiveness.

(iii) Supporting key sectors from construction and transport to defence.

Priority 2: Securing a more robust and resilient composite materials supply chain, supporting growth and resilience in existing markets and new circular economies.

Benefits to the UK:

(i) Securing growth opportunities in the domestic composites market, feeding 400,000+ jobs in the UK's manufacturing sector.

(ii) Creating a more competitive UK materials proposition could capture an increased proportion of the £76 billion global market.

(iii) Improving supply chain autonomy and resilience: There are only a limited number of UK raw material suppliers. Raw material demand is import-driven despite the potential for 3–6 times value creation from materials to end-part manufacturing.

(iv) Improving national security by reducing the defence sector's reliance on imported carbon fibre composites and ceramic matrix composites, which are subject to tight international controls (for example, International Traffic in Arms Regulations). This represents a £1.5 billion direct materials opportunity.

(v) Improving environmental impact through infrastructure and innovation in processes, such as enabling new chemicals/materials and products from recyclate, creates a strategic advantage in net zero composites and products, reducing the significant social and environmental burden, and developing new circular economies (with associated economic returns).

What we need to do in the UK to realise this opportunity

SUSTAINABLE SYSTEMS – COMPOSITES PRIORITY 1: More sustainable composites designed/optimised for multiple applications, longer lifecycles, recycling and re-use	
Outcomes	Enable resilient UK production and application of high-performance composites with reduced dependency on insecure and high GWP imports.
	Improve the sustainability of composites, reducing embedded carbon, improving recyclability and contributing to net zero targets through improved resins/adhesives.
Enabled by	**Key interventions**
	Incentivised industry-research collaborations, emphasising industry grand challenges, to rapidly bring new/refined composites (fibre and resins) and processes to market readiness for industrial applications.
	National programme in sustainable fibre and matrix development: • High-performance, low-global warming potential fibres. • Polymer matrix composites for construction. • Fibre coating chemistries (especially for glass fibre).
	Cross industry development of enhanced life assessment technologies and capabilities to extend and optimise the life of composite assets (covering application of methods, sensors and large data analysis).
	Scale emerging materials, process technologies and recycling concepts across the maturity scale to enable the exploitation of underpinning technology developments and de-risk industry investment.
Underpinned by	**An enabling ecosystem**
	World-class UK composite materials research and manufacturing institutes across academia, catapults and research and technology organisations.
	Existing, untapped supply of bio-waste resources.
	Key UK Original Equipment Manufacturer application demand for composite material innovation.
Delivering Solutions to	**Solve industry challenges**
	Lack of end-use focussed composites solutions.
	Improved waste management/valorisation.
	Improved economic outcomes through new circular economies and supply chains.
	The in-life application benefits of composites for net zero are so significant industry and UK targets are focused on delivering product performance, creating a void in funding and opportunities to capitalise on UK innovation in new sustainable materials and their supply chains.
	Lack of scale-up opportunities and capabilities (TRL 3–5 infrastructure) for key fibres and resins to reach investable uptake within the UK.

SUSTAINABLE SYSTEMS – COMPOSITES PRIORITY 2: More robust and resilient supply chains for composites	
Outcomes	Strengthened domestic composites production and recycling.
	Meeting net zero targets by re-defining composite manufacturing processes to improve efficiency, reduce energy and improve composite performance.
Delivered by	**Key interventions**
	Consolidation of access routes to composites technology scale-up and recycling research infrastructure – accompanied by gap analysis.
	Development of targeted programme(s) to take the materials innovation from production through to production and recycling.
	Establishment of UK composite network and capabilities for tooling, design and manufacture.
Underpinned by	**An enabling ecosystem**
	Filling the gap between industrial scale and existing demonstrator capabilities and creating true end-to-end discovery, translation and production.
Delivering solutions to	**Solve industry challenges**
	Lack of UK supply chain in critical composite classes.
	Current reliance on imported materials with high global warming potential.
	Lack of appropriate recycling infrastructure at pilot scale.

A2 – 3.3 Metallic materials

Overall opportunity

Metallic materials (pure metals and alloys) are essential across a wide range of sectors, from transport, energy and electronics to construction and health.

The UK metals sector has a long history, evolving over centuries and driven by constantly changing demands. In the latter half of the 20th century, the decline of traditional manufacturing industries, overseas competition, economic recessions and privatisations led to the restructuring of the sector. In recent decades, the emphasis has shifted towards high-value products, recycling, and reducing carbon emissions. Companies have invested in advanced technologies and research to remain competitive and environmentally responsible. Today, the UK's metals sector remains critical to domestic GDP. It supports various industries, from aerospace and automotive to construction, medical and renewable energies. The UK metallics market value is £15.6 billion in 2024, ranking 3rd in Europe.[54]

Innovation in metallic materials is critical to reaching net zero targets, moving high-volume industries onto a sustainable footing and securing national resilience for a class of materials of unparalleled strategic importance to the UK. The priority is developing metal technologies to enhance their current applications and enable key emerging technologies and commercial opportunities.

Further advances in metallic materials processing (including recovery, recycling, repurposing, remanufacturing, refurbishing, repairing, reusing, reducing, rethinking, and refusing) are critical to transforming our associated manufacturing technologies and providing tailored material designs. Specifically, they will ensure sovereign capability, realise the UK competitive advantage, and provide the opportunity for international leadership in metals circularity, essentially re-vitalising the UK supply chain and re-invigorating UK manufacturing.

They will be fundamental to securing a sustainable and resilient future, particularly in the energy, transport, construction, defence, and packaging sectors. They are essential for developing new technologies and economies in areas such as energy infrastructure. They remain the backbone of the transport (automotive, rail, shipping, and aerospace), civil infrastructure, defence, and energy (oil and gas, renewable, nuclear) sectors. They are also crucial to emerging, disruptive technologies.

[54] Office of National Statistics

Cross-sectoral collaboration is required to maximise the return on investment on existing capabilities and ensure systems are fit for current and future purposes.

Opportunity priorities

Three key priority areas in metallic materials have been identified as game-changing for the UK:

Priority 1: Developing high-volume metallic materials with improved performance and increased application range, compatible with circular economy principles, as well as enhanced performance and tailored properties for applying to new and emerging technologies.

Benefits to the UK:

(i) Industry can take advantage of new economic opportunities through enhanced processing capability in a circular economy and applications for new demanding technologies and sectors (for example, energy, defence and transport and establishing sustainable manufacturing in the UK based on secondary rather than primary resources).

(ii) Critical to achieving national and global net zero targets and industry sustainability goals, primarily through new energy solutions and greater energy and resource efficiencies.

(iii) National resilience and sovereign capability for major industrial sectors, from defence to the UK's wider national infrastructure, depend on critical metallic materials resources.

(iv) Enhancing the UK skills base by applying digitalisation tools and machine learning methods (applicable across many sectors and disciplines).

(v) Securing new, high-value jobs across the whole of the supply chain.

Priority 2: Sustainable metallic materials manufacture, processing and end-of-life solutions, securing the supply chain for high-volume metals (particularly steel and aluminium), and reducing energy consumption, minimising emissions and optimising resource utilisation.

Benefits to the UK:

(i) Reaching net zero targets.

(ii) Economic returns through new circular economies and resource efficiency.

(iii) Supply chain security.

(iv) Global leadership in closed-loop metallics recycling.

Priority 3: Developing speciality, high-performance metallic materials to enable capability in key UK priority technologies such as clean energy and health, including critical supply chain and end-of-life considerations.

Benefits to the UK:

(i) Enabling key industries across transport, defence, energy and health to deliver new technology that is not currently possible with existing metallic systems.

(ii) Focus on critical materials resources and driving programmes to ensure resilient supply chains.

(iii) Enhancing the UK skills base in applying digitalisation, machine learning and high throughput methods (applicable across many sectors and disciplines) with high-value jobs.

What we need to do in the UK to realise the opportunities in this area

METALLIC MATERIALS PRIORITY 1: High volume metallic materials with improved performance and increased application range	
Outcomes	Enabling competitive and innovative UK transport, energy, defence and civil infrastructure sectors: delivering enhanced and new metallic systems to power UK technology development in emerging high priority sectors such as electrification and transport.
	Robust, multi-scale predictive capabilities for material performance.
	Broader application of materials classes to improve agility of supply chain, including reduced proliferation of standards and grades with focus on performance and cross sector applications.
Enabled by	**Key interventions**
	A cross-industry-academia working group with the mandate to bring together existing expertise, determine priorities (on an ongoing basis), assess and address gaps, drive the necessary national programmes and identify and develop UK industrialisation partnerships supported by Catapults/RTOs.
	National programmes linked with UKRI and industry focussed on highest priority innovation for industry. For example: • Harnessing "impurities" to expand applications/properties and increase scrap utilisation. • Asset lifetime extension through novel repair technologies. • Predictive understanding of degradation in service. • Novel material design for prolonged life and end-of-life circularity. • Exploitation of UK existing manufacturing, optimising casting, processing (e.g. rolling extrusion and forging), joining and forming processes to improve performance characteristics and sustainability targets. Projects to be enabled and accelerated through integration of digital, data driven approaches and development of digital passports.
	Certification process applicable across all classes of metallic materials for multiple sectors, based on common ISO standards – reduction in unnecessary duplication of standards.
	An accessible national verification capability (standardised, rapid, non-destructive, testing, characterisation and validation) accelerating certification and qualification. Enabled through a collaborative national verification forum to address access and delivery gaps.
	Alignment with HEIs and industry to provide pipeline of skills applicable to: • Data modelling related to processing and performance of metallic systems. • Maintaining/re-skilling the UK skills base in fundamental physical metallurgy.
Underpinned by	**An enabling ecosystem**
	UK's investment in midscale manufacturing capability across the UK's HEI and RTO network enabling scale up of innovation.

Delivering solutions to	**Solve industry challenges**
	Access to certified fit-for-purpose materials, with better defined LCA.
	Verified and trusted materials data delivered through extensive existing national infrastructure.
	Meeting sustainability goals.
	Accessing a relevant talent pool.
	National resilience for critical high volume metallics.

METALLIC MATERIALS PRIORITY 2: Securing the supply chain for high-volume metals through circularity and performance improvement. Innovation in manufacture, repair, processing, and end-of-life solutions for sustainable metallic materials through technologies that reduce energy consumption, minimise emissions and optimise resource utilisation.	
Outcomes	Complete transformation to a circular economy based industrial sector across metals industry and wider supply chains.
	A coordinated and collaborative national forum to identify and drive solutions for metallics performance and recycling.
	New community of practice for design and modelling of metallic materials.
	Onshoring metals circular economies, improving economic and sustainability outcomes.
	A coordinated national infrastructure for receiving and sorting high volume metallics.
Enabled by	**Key interventions**
	Standardised alloy cleanliness measurement and control for recycling, particularly for critical application (for example, alloys in aerospace).
	Development of technologies for reusing and processing 'scrap' as a direct component in manufacturing.
	Designing and manufacturing certified systems for disassembly, closed loop recycling and reducing downcycling in key sectors (for example construction and transport).
	Identification of national single source capabilities and producing a robust redundancy/continuity plan.
	Digital material design tools incorporating life cycle assessment (LCA) and full digital passporting from mine to end of product use to improve resource efficiency.
Underpinned by	**An enabling ecosystem**
	Existing manufacturing and supply chain capabilities.
Delivering solutions to	**Solve industry challenges**
	Achieving sustainability goals.
	Reducing costs.
	Improved supply chain security.

METALLIC MATERIALS PRIORITY 3: Development of speciality, high-performance metallic materials to enable capability in key UK priority technologies such as clean energy and health, including critical supply chain and end-of-life considerations	
Outcomes	Innovative high performance metallic systems, enabling delivery and exploitation of UK priority technologies such as clean energy and health.
	Greater security in critical supply chains.
	Robust end-of-life solutions that re-capture value through circular economies.
	Coordination across sectors to find common solutions, defragmenting research and translation, and maximising return on existing investment.
Enabled by	**Key interventions**
	National collaborative forum (with requisite skills) established across industry and academia identifying cross-sector gaps, priorities and critical technology requirements.
	Cross-sector research programmes delivering material systems requirements and building on synergies to ensure optimisation of research resources. For example, for energy, construction and transportation.
	Coordination across early design to scale up capability across UK Higher Educational Institutions and RTOs to ensure a joined-up ecosystem for rapid evaluation of 'manufacturability' of new metallic systems and accelerate technology translation.
	Development of technologies for recovering high value critical elements.
Underpinned by	**An enabling ecosystem**
	High throughput capabilities to enhance materials discovery.
	Application of Materials 4.0 methods to enhance processing method optimisation for new materials systems.
	High value infrastructure investment across the UK in make, test, characterise capabilities from HEIs to the Catapult and RTO networks.
Delivering solutions to	**Solve industry challenges**
	Innovative metallic systems required to enable the UK to design, manufacture, exploit and benefit from emerging technology.
	Resilient supply chain security for high value and high-volume metals.

A2 – 3.4 Ceramic Materials

Overall opportunity

The global availability of raw materials, together with the unique properties of ceramic materials, such as chemical inertness, high melting temperatures, hardness, and low electrical and thermal conductivity, along with functional applications useful within electronics, have increased the commercial adoption of ceramics in diverse applications in recent decades. They are used to manufacture products ranging from decorative pots to dielectric resonators in telecommunications to nuclear fuel pellets.[55]

The UK has a long history in traditional ceramics (tiles, bricks and pipes, sanitaryware, abrasives, and pottery), with over 150 ceramic factories nationwide. These products are prominently used by the building and construction industry, and the market is predicted to grow in line with this sector. Ceramics manufacturing in these markets is crucial to the broader industrial infrastructure landscape. It plays a foundational role in various vital sectors, such as steel and glass manufacturing, and its contributions are integral to underpinning the overall strength of our national economy.

Adjacent to these more traditional applications, the UK has seen vigorous activity in advanced ceramics supporting our emerging and significant growth sectors, with products based on materials such as alumina, zirconia, tungsten carbide, silicon nitride and silicon carbide. These materials have enhanced properties, such as durability and high-temperature strength, alongside a plethora of functionalities: ion conducting, piezoelectric, biocompatible, electrical insulation and tuneable dielectric capabilities. This diverse high-value subsector is driven by increasing demand for their use in high-performance electronics, clean technologies (energy), transport (automotive, rail and aerospace), defence, and health (implants, other medical devices, and high-precision equipment).

High-volume ceramics are highly sustainable in many applications and have the potential to be reused repeatedly without losing their inherent properties or quality. However, finding synergistic uses for waste or ways to return to virgin conditions represents a key challenge and opportunity.

The global ceramics market, which includes traditional and advanced ceramics, is estimated to be around £200 billion in 2024, rising to £358 billion by 2035, with a CAGR

[55] There is a significant cross-over with the core themes on materials for advanced telecommunications and power electronics, which will require close collaboration between the steering groups to avoid duplication and maximise the ROI

of around 6%. Traditional ceramics account for 56% of the global market, dominated by the Asia-Pacific region. Advanced ceramics account for the remainder, of which the UK's market share is around 6%, worth £4.5 billion in 2024.[56] This sub-sector is expected to exhibit a significant CAGR, driven by increased demand from energy, communications, consumer electronics, transport, space, defence and health sectors, and the UK has the opportunity to substantially expand its share in this growth.

Market growth in Europe will be attributable to the application of ceramics to add functionality to systems and substrates and the rapid rise in demand for technical products in the region to support sectors ranging from health to energy and defence. For example:

- The booming electronics industry is expected to increase demand for electroceramics that can handle higher fields and temperatures.
- Biocompatible ceramics are being used for bone replacements, dental implants, and spinal correction segments. These ceramics are combined with new additive manufacturing techniques, which enable patient-specific devices.
- Innovation in ceramic materials is required to realise nuclear and other energy applications, such as:
    - Ceramics for heat recovery systems.
    - Next-generation nuclear fuels.
    - Solid–ion conductors in batteries, fuel cells and electrolysers.
    - Advanced fuel cell and high-temperature electrolyser solid electrolytes.
- Ballistic-resistant armour and irradiation-resistant ceramic composites.
- Communications and electromagnetic activity resistant ceramics.

Combining the UK's ceramics expertise with Materials 4.0 is seen as critical to rapidly unlocking the vast potential of ceramics discovery, ensuring rapid translation and deployment across these and emerging technology application areas.

Ceramics derive their capabilities from a combination of chemistry and processing. Innovation in this latter aspect is also essential. Advanced processing will ensure the UK's traditional ceramics sector can decarbonise while supporting high-quality, high-volume ceramics markets, for example, by lowering emissions by developing hydrogen and electric furnace technologies to mitigate carbon in manufacturing. Adopting new

[56]Fortune Business Insights Advanced Ceramics Market Report 2024

technologies to automate and streamline processes, reducing energy footprints and product development cycles, providing materials systems with enhanced or innovative properties, introducing in-line data analysis and collection, and improving the connection between the physical and digital world will significantly benefit the sector.

Investing in innovative manufacturing capabilities and harnessing data and machine learning approaches and technologies will enable the UK to realise the maximum ROI of its ceramic materials innovations and consequent value-add, reversing the increasing offshoring of higher-value aspects of the supply chains.

Opportunity Priorities

Two key priority areas in ceramics innovation have been identified as game-changing for the UK:

Priority 1: Developing the UK capability in advanced ceramics.

Benefits to the UK:

- (i) Critical to net zero targets by enabling a mixed energy vector net zero economy.
- (ii) Enhanced UK manufacturing competitiveness.
- (iii) Increased confidence and productivity for SMEs (supporting start-ups to develop innovative processes that large companies can adopt).
- (iv) Secure and resilient critical supply chains (for example, sovereign ceramic matrix composites for defence applications).
- (v) Developing ceramics manufacturing for high-value goods (biomedical/energy).
- (vi) A highly skilled workforce across the advanced ceramics sector and supporting nuclear, electronics, transport, renewable energy, defence and health sectors.

Priority 2: Manufacture and process innovations for the ceramics sector.

Benefits to the UK:

- (i) Reduced energy usage and decarbonisation of the sector, supporting net zero targets.
- (ii) Reduced embedded carbon across all industries.
- (iii) Enhanced manufacturing competitiveness.
- (iv) Lower-cost manufacturing will allow the UK to secure a larger market share.
- (v) UK manufacturing capability for high-value products (for example, communications, health, energy and defence) for domestic and export markets.
- (vi) Protect our ability to make larger systems by reducing reliance on imported critical materials.

What we need to do in the UK to realise the opportunities in this area

CERAMICS PRIORITY 1: Developing a portfolio of manufacturable advanced ceramics for a diverse range of applications	
Outcomes	Portfolio of high-value ceramic materials, designed, manufactured and tested with end-use focus.
	UK taking a global lead (and maintaining sovereign capability) in high-value ceramic market segments such as electronics, healthcare and structural (for example, ceramic matrix composites).
	Talent pipeline for the industry.
Enabled by	**Key interventions**
	Cross-industry-academia working group to map demand, identify priorities across markets, and coordinate collaboration partnerships to advance the sector.
	Programme of advanced ceramic materials development to meet the diverse industry demands across the manufacturing sector based on priority-setting by industry. Priorities may include: • New thermoelectrics and conductors and advanced thermal barrier and environmental barrier coatings. • High-permittivity ceramics for defence and telecoms applications. • High-temperature ceramics to enable hydrogen technologies. • Radiation-hard ceramics for nuclear and space applications. • Fatigue-, wear-, corrosion- and electromagnetic activity-resistant ceramics and Calcium-Magnesium-Aluminosilicate (CMAS)-resistant ceramics for aerospace applications. • Additive manufactured ceramics for complex geometry products such as personalised health. • Large free-form ceramics, ceramic fibres, ceramic cores for metal castings. • Low CO_2 formulations to eliminate process emissions.
	Application of Materials 4.0 – AI-assisted and physics-based modelling and digital twins to support materials development.
	Access to test and verification capabilities to support rapid design, development and translation of new materials to proof of concept, based on agreed standards.
	Review of national regulations and standards related to application of advanced ceramics to support export and adoption in critical technologies such as health, nuclear and electronics.
	Identification and delivery of skills to create a talent pipeline for the industry.
Underpinned by	**An enabling ecosystem**
	High-quality raw materials.
	Existing expertise and formulations across UK industry.
	Existing strategies to which ceramics contribute. For example, the fusion materials roadmap.
	Existing degree apprenticeship programmes.

Providing solutions to	**Solve industry challenges**
	Reducing energy costs.
	Decarbonisation of the industry.
	Access to new markets.
	Secure supply chains.

CERAMICS PRIORITY 2: Improved manufacturing and processing innovation for ceramics	
Outcomes	Scale up the low TRL processes developed in academia and bridge the TRL4–6 gap.
	Competitive UK ceramics sector by decarbonising manufacturing processes.
	Secure supply chains sovereignty and security for critical materials and components.
	Supply of products (for example, nuclear fuels) into international markets.
Enabled by	**Key interventions**
	Industry-led programme for the rapid development of substitution of natural gas for the sector (for example, application of hydrogen) and low-carbon firing processes such as electric furnace technology.
	Challenge led programmes and infrastructure driving collaboration between industry, academia and the Catapults delivering priority ceramic manufacturing capabilities (at scale). Including: • Ceramic fibre and pre-ceramic polymer production. • Additive manufacturing of ceramics. • Large-scale manufacturing of ceramic components for fuel cells electrolysers, batteries, and membranes. • High-temperature, co-firing of ceramics. • Repeatable coating processes. • Advanced sintering technologies.
Underpinned by	**An enabling ecosystem**
	Existing infrastructure that can be adapted or repurposed or used as demonstrators (for example, the Lucideon gas fired kiln capable of using gas mixtures from 0–100% H_2).
	Industry bodies to coordinate activities (Ceramics UK, Foundation Industry Sustainability Consortium, Midlands Industrial Ceramics Group).
	Some large-scale companies and a vibrant SME sector.
	Decarbonising UK Ceramic Manufacturing Industry Roadmap.
Providing solutions to	**Solve industry challenges**
	Deep decarbonisation.
	Competitiveness through value-add.
	Accelerated scale-up and path to markets.

A2 – 4 ADVANCED SURFACE TECHNOLOGIES

A2 – 4.1 Materials and modelling for surface engineering & tribology

Overall opportunity

Corrosion is the world's best-known example of the in-service degradation of material systems, which has massive implications and impacts almost all industrial sectors. The global cost of corrosion in 2016 was estimated to be £2 trillion, equivalent to 3.4% of the global GDP,[57] not including individual safety or environmental consequences. In the UK, the cost of corrosion is now estimated to be more than 5% of GDP. Addressing corrosion or degradation in materials based on existing technologies could result in savings of between 15% and 35%. For example, the MoD notes that 30% of the through-life cost of a new boat is due to corrosion. Corrosion is an example of a surface-related phenomenon most generally tackled through surface coatings/treatment. Innovation in surface engineering, only considering this one degradation process, will generate economic benefits estimated at over 1.4% of the UK's GDP.

The impact of surface engineering and the integration between surfaces is much greater than that of corrosion. Surface engineering treatments of manufactured surfaces can transform durability and are essential to the overall performance of surfaces in many demanding applications. Such treatments are crucial for safeguarding and enhancing assets in the energy, automotive, industrial, agricultural, marine, construction and health sectors and play a key role in boosting productivity by adding considerable value to manufactured products. Beyond protecting the underlying materials' surface-surface interactions, materials' modifications are crucial in developing more efficient processes and devices, especially in combatting friction and wear[58] and developing self-lubricating technologies that can operate in various environments. Processes for surface treatment range from painting to ion implantation and metal deposition. Across the UK, these represent a community of manufacturers with over £11 billion in business and play a key role in producing over £140 billion of products.[59]

Enhancing our understanding and prediction of degradation and surface interactions remains a major challenge. Harnessing Materials 4.0 approaches, AI, and new modelling

[57]International measures of prevention, application, and economics of corrosion technologies study; NACE International; http://impact.nace.org/economic-impact.aspx
[58]Tribology opportunities for enhancing America's Energy Efficiency. US Department of Energy ARPA-E Report. 2017
[59]Surface Engineering and Advanced Coatings SIG Report 2016

techniques represent a significant opportunity to transform our understanding and control of material degradation, particularly surface corrosion, surface-surface interactions, and the behaviour of surfaces and coatings across all environments.

Furthermore, several in-use coatings are restricted (for example, under Registration, Evaluation, Authorisation, and Restriction of Chemicals (REACH) regulations) and require replacement solutions. The Expert Working Group on “Materials for Extreme Environments” also recognised the importance of developing innovative materials systems and advanced coatings to mitigate environmental degradation.

The UK has one of the most innovative surface engineering industries globally. The combination of enhanced tools to understand degradation with novel manufacturing capabilities and chemistries, fuelled by the opportunities from Materials 4.0 and ecological drivers, will underpin the following:

- A transition away from restricted use materials.
- Enhanced protection coatings, barriers and surface treatments.
- Development of new materials/processes that improve or extend the overall performance of surfaces.

Opportunity priorities

Two key priority areas in surface protection, engineering and tribology have been identified as game-changing for the UK:

Priority 1: Sustainable high-performance surface protection and tribology solutions to extend life.

Benefits to the UK:

(i) Significant cost reductions – around 1.4% of GDP.
(ii) Growing the UK’s market share in surface engineering technologies and capabilities.
(iii) High-skill, high-value, productive jobs.
(iv) Meeting energy infrastructure needs.
(v) Meeting net zero targets (both directly and indirectly).
(vi) Critical supply chain security.
(vii) UK leadership in this area with significant global implications.
(viii) Improving materials design and deployment through enhanced modelling, characterisation, testing and certification.

Priority 2: Modelling and designing for optimisation of tribology and surface protection solutions.

Benefits to the UK:

(i) Industry 4.0 modelling and data capability to underpin materials innovation across all sectors.

(ii) Increasing inward investment.

(iii) Delivering high-skill, high-value jobs.

(iv) Efficiency-driven cost-reduction.

(v) Improved ROI.

What we need to do in the UK to realise the opportunities in this area

ADVANCED SURFACE TECHNOLOGIES PRIORITY 1: Improved performance surface protection materials and tribology solutions to extend technology/infrastructure lifetime	
Outcomes	Low-wear, low-friction, and low-corrosion/degradation surfaces to reduce fuel consumption and extend machine life.
	Suite of high-performance coatings and processes for use across different substrates and environments and dual-capability solutions.
Enabled by	**Key interventions**
	Cross-sector working group to clarify and rationalise national priorities, gaps in innovation infrastructure and drive implementation of a national programme.
	Programme to develop coatings for multiple application areas which are: • Environmentally sustainable • Multi-functional • Damage-tolerant • Self-healing Example applications: turbine blades, fuel cells, nuclear reactors, aviation fuel storage and use, electrolysers, ceramics) for surface protection and enhancement.
	Programme for tribology optimisation of surface interactions to: • Minimize wear • Reduce friction and improve efficiency
Underpinned by	**An enabling ecosystem**
	World leading capability in modelling of surface degradation and corrosion.
	Testing and imaging capabilities investment across UK universities and RTOs.
	Strong, innovative SME sector.
Providing solutions to	**Solve industry challenges**
	Extended life leading to global cost reductions.
	Environment-appropriate coatings for energy technology protection. (including those urgently needed for renewable energy infrastructure).

ADVANCED SURFACE TECHNOLOGIES PRIORITY 2: **Improved materials design and deployment through enhanced modelling, scale up, characterisation, testing and certification**	
Outcomes	Rapid materials development and deployment.
	Accurate prediction of material durability for design.
	Improved testing and characterisation (including, environmental test capability & capacity, high throughput screening, imaging, live monitoring capabilities.
	Strengthened UK materials 4.0 capabilities.
Enabled by	**Key interventions**
	Cross-sector working group to undertake a comprehensive review of scale-up and validation capability in manufacturing (surface engineering): • Creation of a community of practice. • Gap analysis of existing capability – for scale-up/pilot/testing. • Proposals to repurpose/fill gaps in scale-up existing capability and review of certification processes.
	Nationally coordinated materials modelling, design, testing and validation capability for surface engineering.
	National programme for integrated computational materials engineering and application of Materials 4.0 approaches including: • Processing tools development. • Rapid chemistry discovery methods and application of AI. • Materials integrity assessment (applied to design/in service performance). • Skills/training alignment.
Underpinned by	**An enabling ecosystem**
	Existing training & skills programmes.
	Nascent wider Materials 4.0 centre for doctoral training.
Delivering solutions to	**Solve industry challenges**
	Rapid materials design and deployment.
	Faster ROI.
	Access to skilled workforce.
	Access to shared tools and models whilst maintaining data security.
	Increased competitiveness.

A2 – 4.2 Surface treatments and materials for demanding environments

Overall opportunity

Materials systems in demanding environments must operate in harsh and challenging conditions, including extremes in pressure, temperature, corrosion, radiation, and high impact rates. Many material systems must perform under a combination of these demanding conditions. These materials are vital to the structural and functional performance and integrity of complex industrial systems. Essentially, they are the bedrock and underpinning requirement for delivering innovations in energy, aerospace, space, defence, and transport to meet immediate and emerging industry and linked societal needs.

New approaches to design, testing (especially in environments representative of intended use), and validation for use in demanding environments are also urgently needed to accelerate their translation for these applications.

Materials suitable for extreme thermal environments have been identified as a priority area for innovation. These include high-temperature alloys, ceramic matrix composites, intermetallics, materials that can withstand a wide range of temperatures (for example, tropics to polar marine environments, cryogenic fuel to combustion flame temperatures, plasma strikes in fusion technology), and the application of next-generation coating systems, such as corrosion-resistant thermal barrier coatings. There is an immediate need for radiation-resistant and low-activation materials for energy, aerospace and defence applications. This includes the underlying material systems, advanced joining technology and coating/layering systems, which add essential protection and functionality and will be crucial enablers for these key sectors to achieve net zero.

Although extreme environments often pose unique challenges for deployed materials, approaching materials innovation to accelerate tackling these challenges must become cross-cutting rather than remaining entrenched in traditional discipline silos. For example, areas such as the design of metallics and coating/protection systems should be brought together to address opportunities in many sectors, from transport and space to biomedical applications, with innovations for specific extreme environments being the focus of sub-programmes, where applicable.

Extreme environments present a considerable challenge (and enabler) in materials design and through-life management due to multiple competing and cooperating mechanisms during service exposure. New materials systems and validated performance models must be developed based on a detailed understanding of operative degradation mechanisms. This must be coupled with technologies for in-service performance monitoring, life extension and repair. Design and modelling for materials in demanding environments traditionally rely on empirical approaches and expert knowledge and have not drawn on new methods to data mine the plethora of historical data and new machine learning processes to help optimise materials systems and processing. Further, current handling and testing processes for evaluating material behaviour under extreme conditions rely on intensive, time-consuming, human-in-the-loop interventions.

Adopting Materials 4.0 will harness advances in data sciences, modelling, AI, robotics, and high throughput testing to enable rapid, targeted development and translation of new materials for extreme environments. Building this national capability will give the UK a leading global position, secure national supply chain sovereignty, and fast-track materials translation. Success, however, depends on the availability of extensive, curated and reliable materials data, efficient data and physics-driven models, and a well-integrated data system. New data must be collected systematically through coordinated, national, life-capture testing and evaluation capabilities.

Research and development programmes must focus on the UK's essential needs for energy, transport, aerospace, cryogenics and more specific defence requirements.

Opportunity priorities

Two key priority areas in materials for extreme environments have been identified as game-changing for the UK:

Priority 1: Functional materials designed for thermal, radiation and chemical extremes.

Benefits to the UK:

(i) Ensure that UK national interests are protected.

(ii) Enable the energy transition and opportunities/needs in transport and defence.

(iii) Securing sovereignty in required sectors (for example, defence and space) while maximising what can be sourced from allies or offshore sources.

(iv) Supply chain resilience and more efficient resource use through technologies for reuse, reprocessing and/or recycling of speciality and high-value materials.

(v) Maximise commercial returns in critical and emerging aerospace, space and energy industries.

(vi) Generate maximum ROI from core materials innovation programmes.

Priority 1 is only sufficient with a step change in processes and application of infrastructure and methods to deliver the innovation at the necessary pace. Priority 2 focuses on deploying resources and methods to speed up the innovations captured in Priority 1.

Priority 2: Autonomous design and testing of materials for extreme environments, enabling rapid development and test capability fused with materials 4.0 methods to accelerate development and deployment across the supply chain.

Benefits to the UK:

(i) Rapid translation of new materials critical to the energy, transport, defence, and space industries. For example, fusion and hydrogen technologies.

(ii) Building a global reputation for data-based materials modelling and in-life data generation and curation (underpinning next-generation materials discovery and lifing predictions).

(iii) The materials sector can develop and deploy solutions at pace to high-value technology sectors across the UK.

(iv) Improving safety, in-service performance and life extension of major national critical infrastructure.

What we need to do in the UK to realise the opportunities in this area

DEMANDING ENVIRONMENTS PRIORITY 1: Developing and refining material systems and functional materials for specific conditions: a. thermal and radiation extremes and b. multi-extreme environments	
Outcomes	Suite of urgently needed materials systems (including coatings and functional graded materials for demanding environments) designed and validated with proven scale-up ability for rapid deployment in energy, transport and defence sectors.
	An agile and resilient supply chain for specialist materials systems to support ongoing requirements for energy, transport and defence sectors.
Enabled by	**Key interventions**
	A national industry-academia working group with a mandate to develop and coordinate national programmes against industry and UK priorities (aligning with cross-government initiatives).
	Development of a national programme for materials in demanding environments, drawing together cross-sector research and manufacturing capabilities to identify and deliver innovation against national priorities in a cohesive manner. For example, exploiting synergies across industries such as fusion and aerospace.
	Specific inclusion of materials for demanding environments (especially thermal and radiation extremes) in manufacturing innovation programmes. For example, in metallics, composites and surface coatings. (Avoiding duplication and promoting a truly cross-sector approach.)
	A suite of nationally curated databases including thermodynamic data, materials properties and in-life functionality data.
	Technology development for the efficient reuse, reprocessing and/or recycling of speciality and high value materials for sustainability and resource security.
Underpinned by	**An enabling ecosystem**
	An existing and agile research community supporting industries based on deployment in demanding environments.
	UK speciality materials supply chains including coating, specialist alloy production and state of the art processing capabilities (Catapults).
	Defence Materials Centre of Excellence (DMEx).
	Materials 4.0 capabilities being developed across the materials sector.
Delivering solutions to	**Solve industry challenges**
	Addressing the current and future demands of high value industry in the UK and delivering to the supply chain.
	Bringing materials innovations rapidly to market, aligned with need and proactively rather than responsively.
	Enabling commercially viable emerging sectors essential to the economy, including fusion, hydrogen, high temperature gas reactors and space.
	Eliminating the siloed nature of extreme environment materials development and improving ROI.
	Improving critical performance such as time-on-wing for aerospace components.

DEMANDING ENVIRONMENTS PRIORITY 2: Advancing the UK's capability in autonomous design, enabling rapid development and test capability (fused with materials 4.0 methods to accelerate development and deployment across the supply chain)	
Outcomes	Respond at pace to the UK's need for deploying unique materials solutions for emergent high demand environments through a world-leading capability in autonomous design and deployment of materials for extreme environments (and other applications).
	Coordinated test capabilities generating verified and trusted data based on agreed standards.
	Increasing ROI in current capabilities, filling gaps and creating a truly coordinated system to meet national priorities.
Enabled by	**Key interventions**
	Coordinated and streamlined access to UK research infrastructure across academia, RTOs and industry to enable joined up research workflow and accelerate materials innovation from design through to deployment. This will also identify the gaps and maximise ROI across existing capabilities in academia, RTO and industry (which are often highly specialised).
	Deployment of materials 4.0, including advanced data searching and processing methods (for example, data mining), modelling and application of new rapid throughput experimental processes to accelerate material development to include: • Skills development for rapid throughput methods and data methods applied to demanding environment applications. • Validated federated and accessible models for materials performance across demanding environments. • Handbook of materials properties (such as basic thermo-physical properties or thermodynamic data).
	Development of methods to support through-life inspection and repair of high value complex materials systems in critical applications.
Underpinned by	**An enabling ecosystem**
	Existing skills and capabilities (including NPL, Catapults, DMEx, Materials 4.0 CDT).
	Access to databases of existing materials in, for example, existing fleet of advanced gas-cooled reactors and engine experience.
	Well established frameworks of modelling and testing to develop materials as a foundation for Materials 4.0 techniques.
Providing solutions to	**Solve industry challenges**
	Rapid development of proven materials systems in response to need.
	Agile specialist research and manufacturing capability resilient to changing market needs with capability for rapid (re) deployment.
	Access to validated UK-manufactured materials to enable delivery of national priorities with secure supply chains.

A2 – 5 NEXT GENERATION ELECTRONICS, TELECOMMUNICATIONS AND SENSORS

A2 – 5.1 Materials for power electronics

Overall opportunity

From semiconductor switches to power control mechanisms, power electronics deliver system efficiency and improved performance in applications that require stable and reliable electric power with the desired specifications. These devices are critical to deploying transport electrification, integrating renewable energies into the grid, defence and aerospace applications such as high-performance passive components and sensors, and building more efficient consumer electronics. They are fundamental to reaching net zero targets and are increasingly recognised as essential to driving progress in emerging technologies such as AI.

The global power electronics market is worth £24 billion and is predicted to rise to over £40 billion by 2035. The auto-electrification market offers a £24 billion opportunity, with £10 billion coming directly from power electronics. Transport electrification and the expansion of renewables contribute to a rapidly increasing CAGR. [60]

State-of-the-art power electronic systems can handle power from a few watts to several megawatts. This enables efficient and reliable interfaces between raw and regulated power, delivering precise power control, increasing current carrying capacity, optimising thermal conductivity, increasing thermal shock resistance, and improving system reliability while reducing costs.

Silicon (Si) has been the principal material for power switching and control mechanisms for decades. However, as the performance of Si electronic devices reaches its theoretical limits (i.e. Si has a relatively low breakdown voltage), they cannot meet the high voltage or high current switching specifications demanded by energy transition technologies. Therefore, the focus is now being placed on improving wide bandgap (WBG) materials, such as silicon carbide (SiC), and gallium nitride (GaN) and developing new ultra-wide bandgap materials, such as gallium oxide (Ga_2O_3), aluminium nitride (AlN), aluminium gallium nitride (AlGaN), and diamond (especially for high-temperature, high-pressure applications). WBG technology requires radically different manufacturing techniques compared to Si, and manufacturing capacity is being deployed rapidly as the WBG

[60] Future Market Insights Power Electronics Market Report. 2024

technologies gain traction. For example, the SiC-Power opportunity is expected to reach £7.9 billion by 2029 with 24% CAGR, and the GaN-Power opportunity is expected to reach £1.6 billion by 2029 with 41% CAGR.[61] However, these materials are at different TRL levels, have unique challenges and end uses and, therefore, will require different interventions to bring to market.

An appropriately skilled workforce will be required to deliver potential benefits to the UK. A skills programme aligned with materials development must focus on diagnostics, troubleshooting, practical bench skills (especially in cleanroom conditions), printed circuit board (PCB) design, application of materials 4.0 approaches, and deeper knowledge about the properties and characteristics of power semiconductors, their materials, wafer and chip fabrication, operation, driving, and testing.[62]

While global recognition and exploitation of this opportunity exist (especially in Germany, France, and Italy), the UK is in a strong position to capture the benefits and take technology leadership in specific focus areas such as equipment, instrumentation, and process development. This builds on the UK's existing strengths, capabilities, and strategic planning in high-value manufacturing (especially semiconductors and power electronic assemblies).

It will provide critical supply chain sovereignty in crucial components and support new UK-based supply chains.[63] With a GVA of over £150,000 per annum per job, it is estimated to create over 5,000 high-skill, high-value jobs across the UK and a further 25,000 indirect jobs, feeding an export-intensive market and attracting new inward investment.

Opportunity priorities

Two key priority areas in materials for power electronics have been identified as game-changing for the UK, taking into account international perspectives and developing opportunities specific to UK strengths and gaps in global markets and supply chains:

Priority 1: Development and integration of Wide Bandgap (WBG) and Ultra-Wide Bandgap (UWBG) materials aligned to a national skills provision for power electronics.

[61] Yole Intelligence. 2024
[62] Roadmap of Power Electronics Knowledge and Skills. 2022
[63] Semiconductors in the UK. 2022

Benefits to the UK:

(i) Supporting the high-value semiconductor manufacturing sector in the UK by delivering a portfolio of materials for critical components in power electronics.

(ii) Enabling high-value sectors, such as EV manufacturing and aerospace, driving innovation in other high-value areas, such as AI, and supporting critical defence applications.

(iii) Maximising ROI of existing capabilities.

(iv) Enabling net zero initiatives.

(v) Growing a highly skilled workforce to deliver these innovations.

Priority 2: Strengthening the UK semiconductor supply chain.

Benefits to the UK:

(i) Securing critical infrastructure by growing a competitive UK semiconductor sector, strengthening national security (for example, in defence applications).

(ii) Ensuring supply chain autonomy (reducing reliance on China) in critical infrastructure.

(iii) High-skill, high-value job creation with the potential for 5000 new direct jobs and a further 25,000 indirect jobs.

(iv) Economic returns from a rapidly expanding global market.

What we need to do in the UK to realise the opportunities in this area

POWER ELECTRONICS PRIORITY 1: Developing and integrating wide- and ultra-wide bandgap materials aligned to a national skills provision for power electronics	
Outcomes	Portfolio of characterised and tested WBG and UWBG materials and packaging solutions for industry application.
	Accelerated path to market for WBG and UWBG materials.
	Harnessing existing strengths and maximising ROI on existing capabilities.
	Flourishing UK semiconductor industry supported by an industry-led skills academy approach, integrating new skills across schools, colleges, apprentice programmes and universities.
Enabled by	A highly skilled workforce with highly transferrable skills.
	Key interventions
	An integrated programme for the development and scale up (beyond low TRL levels) of: • SiC, Ga_2O_3 AlN and AlGaN, including on alternative substrates and heterogeneous integration (such as Si and SiC on one platform) and lower cost substrates (acknowledging that these materials are at different TRL levels, and have unique challenges and end uses). • Diamond materials and devices for high-temperature applications. • Device packaging compatible with new materials.
	A national approach/capability in metrology and characterisation of WBG and UWBG materials (maximising the ROI on existing facilities).
	Access to appropriate infrastructure for training at all levels such as cleanrooms alongside comprehensive HE/FE programmes including: • Diagnostics, troubleshooting and practical bench skills (especially in cleanroom environments). • Application of materials 4.0 to materials design, device fabrication and chip testing. • Deeper knowledge about the properties and characteristics of power semiconductors, their materials, device fabrication, operation, driving, and testing. • Converter topologies and their analysis. • PCB and high-frequency magnetic design and electromagnetic compatibility. Linking higher and further education programmes to enable focussed and relevant training of technicians
Underpinned by	Consolidation of existing short-term funding (e.g. via Innovate-UK) into three- to five-year funding programmes to allow for full market development.
	An enabling ecosystem
	UK expertise and capabilities.
	Active regional clusters of integrated capability spanning universities, RTOs and industry around the UK.

Providing solutions to	**Solve industry challenges**
	Create the next generation of semiconductors with wide applicability across critical applications (including electrification of transport, integration of renewables, communications, aerospace and defence.
	Provide access to existing translation and scale-up capabilities on a timeframe required by industry (balancing translation and scale-up with need for ROI).
	Strengthened decision-making to invest based on clear and consistent strategy, support and access to existing capabilities.
	Secure the talent pipeline.

POWER ELECTRONICS PRIORITY 2: Strengthening the UK power electronics supply chain	
Outcomes	Secure critical infrastructure.
	Coherent and aligned UK power electronics industry based on high-value opportunities underpinning a highly successful sector.
	UK manufacturing expertise in WBG and UWBG materials.
	Maximising ROI on existing capabilities.
	Unified oversight of a comprehensive roadmap and implementation plan for the sector.
	Taking advantage of economies of scale and maximising existing capabilities and investment.
Enabled by	**Key interventions**
	Develop a nationally accessible suite of new fabrication processes and facilities for WBG and UWBG materials and devices (for both scale-up of materials and device fabrication).
	An industry-led taskforce from across the supply chain, developing and driving a coherent and aligned implementation plan to deliver a UK power electronics supply chain. Where necessary feeding into national policy (for example, import/export challenges) issues.
Underpinned by	**An enabling ecosystem**
	Existing UK expertise.
	UK Semiconductor Strategy.
	Existing elements of relevant supply chains.
Delivering solutions to	**Solve industry challenges**
	Lack of scale-up and/or programmes not fit for purpose (for example, inadequate timescales).
	Provide import/export confidence in a sector beset by geopolitical insecurity.
	Improved attraction and retention of a highly skilled workforce.

A2 – 5.2 Materials for quantum technologies

Overall opportunity

Many governments worldwide recognise the importance of quantum technologies (QTs) in advancing applications, from computing to communications, sensing, and timing. Countries that develop and use quantum technologies will gain advantages in productivity, economic growth, health, sustainability, and national security. The UK's National Quantum Strategy envisions the UK as a leading quantum-enabled economy, acknowledging the significance of QTs for the nation's prosperity and security.

The global market value for QTs is anticipated to reach between £32 and £72 billion by 2035,[64] driven by the application of quantum computing in financial services and developments in quantum communications and sensing. Material development and innovation, specifically addressing the requirements for application within QTs, will play a vital role in implementing and commercialising these technologies.

The Materials for Quantum Network (M4QN) was established in 2022. It coordinates the world-leading UK materials research base, the existing National Quantum Technologies Programme (NQTP), and the country's developing quantum technologies industry. M4QN has two main objectives: forming new interdisciplinary research communities and identifying new interdisciplinary research topics within application areas.

The M4QN has undertaken a review, supported by Royce, to determine the future quantum materials-related needs to support the UK's National Quantum Technologies Programme (UK-NQTP). Future directions include connecting the capabilities and materials to science and applications, especially linking materials to the UK-NQTP National Quantum Strategy goals and missions. This would be supported by a national intervention to ensure materials development and characterisation capability are integrated with the UK-NQTP. It should be aligned with ensuring the ability to scale quantum technologies, partnering with key industry enablers, and addressing the need to provide a skilled workforce. In parallel, protecting intellectual property will be essential to ensure that the development of materials and novel devices from these developments adds value to the overall UK effort.

Examples of material innovation priorities relating to computing and communication and sensing and imaging include:

[64] McKinsey Quantum Technology Monitors 2024

- Materials development and efficient photonic integration of solid-state quantum emitters:
  - Multifaceted material integration, including heterojunctions, nanophotonic device fabrication, and precise interfacing techniques.
  - Development of materials towards on-chip photonic systems. For example, integration of source/transmitter and receiver/detector.
  - Ultra-low-loss optical materials for quantum photonic integrated circuits.
  - Developing new materials for non-linear optics in quantum photonics.

- Material quality and characterisation quality control, and defect engineering:
  - Quality control in defect materials, for example, SiC, diamond, rare earth doped crystals, etc.
  - Tailoring doping, isotopic composition, and purity with resilient UK supply.
  - Material quality and characterisation, including trap density management, defect control, nano-atomic characterisation, and understanding of polycrystalline structure.
  - Micro and nanofabrication challenges of control and positioning for technologies on solid-state.
- Material and quantum systems discovery and modelling:
  - Investigation and discovery of new qubit systems, including 2D, topological and spintronics systems.
  - Exploring alternative growth techniques like MBE and PEALD.
  - Research on materials with higher critical temperatures and pressures.
  - High-quality thin film materials.
  - Automated discovery and characterisation of spin systems in different materials with optimal measurements.
  - Material discovery and formulation innovation.

Opportunity priorities

The primary materials innovation opportunities in QTs sit across (i) quantum computing and communications, (ii) quantum sensing and imaging, and (iii) quantum positioning, navigation and timing (PNT). They have been reviewed and identified as:

Priority 1: Develop and maintain a world-leading capability in the characterisation of quantum platforms and metrology.

For example, for calibration in vivo, internal strain, environmental variables, nanoscale spectroscopic characterisation at low temperatures, in-situ materials characterisation interfaces and operation under vacuum.

Benefits to the UK:

(i) Unlocking the UK's ability to characterise and realise performance benefits from quantum technologies.

(ii) Underpinning the development of disruptive technologies vital to both the economy and security of the UK.

(iii) Building on existing capabilities and government investments in capital.

Priority 2: Developing and facilitating access to microfabrication, nanofabrication and integration capabilities.

Within this priority, two key focus areas have been identified:

- Delivering the spatial control of functionality and interfaces for solid-state QTs (for example, precise positioning of colour centres in diamond, control of host isotopic purity, defect/impurity control, surface quality management, and functionalisation for enhanced quantum sensing).
- Allowing efficient integration of solid-state quantum devices with photonic networks (for example, on-chip quantum dot (QD)-based photonic sources, control of the desired QD state, and high-brightness site control).

Benefits to the UK:

(i) An opportunity to develop and demonstrate the manufacture of cutting-edge quantum technologies.

(ii) A highly skilled and productive workforce to support a growing national industry.

(iii) Sovereign manufacturing capability.

What we need to do in the UK to realise the opportunities in this area

QUANTUM TECHNOLOGIES PRIORITY 1: World leading capability in characterisation of materials for quantum materials	
Outcomes	A world leading capability for the characterisation of materials for quantum platforms and metrology.
Enabled by	**Key interventions**
	A cross-industry-academia group to establish and drive a national material for quantum programme, linked to the national strategy and M4QN future quantum materials review.
	Clear policy to stimulate activities at a national level for: • Skills development, and focus areas. • International partnerships. • Attracting international talent.
	Critical review of the current and future characterisation infrastructure to include: • Imaging • Spectroscopy • Analysis techniques necessary for the discovery, characterisation and performance evaluation of different concepts and systems
	The development and standardisation of common Figures of Merit across the technology areas explored including: • Qubit coherence time. • Emission and collection efficiency of emitters; time/transfer, time/number of gates, latency/delay.
Underpinned by	**An enabling ecosystem**
	Existing UK expertise and capabilities in quantum space and a motivated materials community working in the discipline.
	World leading capabilities in imaging in characterisation and major investments in Institutes such as Royce and NPL to support a national programme.
	Leadership in the development of metrology and standards to underpin quantum technologies and support innovation.
Providing solutions to	**Solve industry challenges**
	Access to a joined up national laboratory for characterising and testing materials for quantum.
	Development of appropriate standards and figures of merit to allow international comparison and to unlock commercial and investment opportunities.

QUANTUM TECHNOLOGIES PRIORITY 2: Development and access to micro, nanofabrication and integration capabilities	
Outcomes	World leading, nationally accessible capability for fabrication of materials for quantum and their integration into devices.
	A highly trained workforce responding to the national need for quantum.
Enabled by	**Key interventions**
	Review the development of, and access to, critical fabrication facilities/capabilities across the UK including: • Access to small-scale laboratories for 2D material synthesis, nanofabrication facilities. • Large-scale infrastructures for manufacturing quantum devices. • Wafer testing pilot production facilities and open foundries to enable industrial-scale manufacturing and integration in the UK.
	Consider the case for a UK capability dedicated to diamond material innovation, to foster transition from high-precision development to practical, large-scale production.
	Comprehensive skills and training programme across all technology areas: • Simulation and modelling including 'materials 4.0'. • Attracting new researchers into the field. • Upskilling and/or continuing to develop existing researchers. • Creating new educational and community programs to train the next generation of researchers and engineers in QTs.
Underpinned by	**An enabling ecosystem**
	Existing UK-wide critical infrastructure across academia, industry and RTOs across the UK.
Delivering solutions to	**Solve industry challenges**
	Access to a pipeline of development and scale-up facilities and funding across all TRL levels.
	A growing skilled workforce.

A2 – 5.3 Materials for connectivity and telecommunications

Overall opportunity

The UK telecom industry is valued at £32.4 billion and is estimated to rise to £50 billion by 2035, with a CAGR of 4.6%.[65] Technology advances across telecom applications, including 5G, the Internet of Things (IoT), and edge computing, require materials innovation beyond and across traditional boundaries. These materials harness the power embedded in advanced networks and computing platforms and combine materials' functional and structural performance in products. They will also be fundamental in delivering system efficiencies, growth and other outcomes demanded by the sector.

Telecom operators account for 2–3% of global energy demand. In 2018, energy costs for telecom operators accounted for 5–7% of operating costs. This has now increased to between 15 and 40% and is expected to continue rising.[66] Addressing the dramatic increase in power consumption of, for example, the web, data centres and servers, power radio frequency electronics, IR communications (especially for defence applications), and optical communication is a global priority. Energy efficiencies of between 10% and 20% are estimated to rely on materials innovation,[67] which needs vastly accelerated delivery.

Through high-volume production and integration of application-based innovations in areas such as metamaterials, there is also the opportunity to secure new economic returns and enhanced national security. For example, Radio Frequency (RF) metasurfaces can enhance low-energy coverage for 5G. In addition, for satellite and high-altitude pseudo-satellite (HAPS), novel RF materials create the availability of energy-efficient, miniaturised and lightweight sub-systems, including niche applications that are rarely driven by commercial justification but are critical to defence. Relative to commercial/civil sector trends, the RF domain remains vital within the electromagnetic spectrum for defence and national security.

Significant growth opportunities exist in applying disruptive materials innovation at the convergence of semiconductors, photonics, and metamaterials (alongside structural materials) to improve existing technology and drive the adoption of new technology for connectivity, telecommunications, and future computing. This materials innovation underpins energy challenges and economic growth (via enhanced capabilities) and

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[65]Mordor Intelligence UK Telecom Market Size Report 2024
[66]Global System for Mobile Communications Association
[67]McKinsey & Co; The case for committing to greener telecom networks

strengthens national security/resilience, infrastructure, and supply chains. The opportunities to build leading applications-based translational programmes and those to attract a skilled workforce to the growing telecom sector are particularly strong.

Implementing new technology in commercial networks (for example, through mobile network operators) can be arduous. However, as new use cases and developments emerge, there will be more opportunities to implement technology, particularly for smaller innovators who need support to enter commercial networks. Focusing on particular use cases and deployments would help spark innovation and a faster commercial pull-through.

Building on its expertise (across RF, mm-wave, THz, and photonic materials and devices), the UK can become a world leader in translational research by providing the materials needed for telecoms infrastructure, especially satellite, space, and defence systems. This must be coupled with a national capability to scale up and manufacture more efficient devices and systems in an environment that accelerates adoption. This requires purposeful leadership and signalling from the government in partnership with industry and the wider innovation ecosystem. The benefits will be long-term and multi-generational.

Opportunity priorities

With overarching leadership and drive, two key priority areas in materials for telecommunications have been identified as game-changing for the UK:

Priority 1: Developing a portfolio of materials for higher efficiency communication systems (5G, optical, RF, IR, RADAR, etc).

This priority is designed to:

- Embrace materials 4.0 capabilities to accelerate the UK market edge for materials.
- Deliver components with improved performance to increase network capacity, allowing network growth, enable faster network changes and manage varying traffic demands while making communication cheaper, more accessible and energy efficient.

Benefits to the UK:

(i) The UK is a world leader in advanced telecommunication systems.

(ii) Increased ROI via UK 5G mobile network operators.

(iii) Meeting UK and industry sustainability goals in the energy-intensive telecoms and computing sectors.

(iv) Supply chain sovereignty in critical components for national security.

(v) Future-proof freedom of action and operational advantage for defence.

(vi) Growing the UK photonics industry (from the current £17 billion per annum output to £50 billion by 2035).

(vii) Supporting growth in the UK compound semiconductor industry (from the current £23 billion to £39 billion by 2035).

(viii) Establishing UK industries in mm-wave, THz and metamaterial technologies.

(ix) Underpin innovation and growth in emerging quantum, AI, and future computing sectors.

(x) Inward investment and new employment opportunities by re-entering the value chain of the few large international Telecoms OEMs and attracting new mid-stream companies to the UK.

Priority 2: Coordinating and integrating capabilities for application-based translation and manufacturing of materials and components for telecommunications to facilitate faster translation.

This will be underpinned by standardised testing, and validation and scale-up

Benefits to the UK:

(i) Rapid translation of urgently needed technologies to strengthen national security and resilience.

(ii) The UK as a destination for rapid translation of technologies.

(iii) Economic returns through enabling new mainstream and niche applications.

(iv) New domestic supply chain opportunities.

(v) Increased ROI of existing capabilities through integration.

(vi) Better support across multiple sectors beyond telecoms.

(vii) High-skill, high-value jobs.

What we need to do in the UK to realise the opportunities in this area

CONNECTIVITY & TELECOMS PRIORITY 1: Materials for higher efficiency communication systems (5G, optical, RF, IR, RADAR, etc)	
Outcomes	Greater energy efficiency across connectivity systems.
	Increased network capacity, faster network changes and improved traffic demand management.
	Enabled 5G capacity and coverage.
	World-leading expertise in modelling, design and manufacture of applications-based materials for telecoms.
	Reshoring photonics manufacturing.
Enabled by	**Key interventions**
	Cross-industry-government-academia working group to identify applications-based materials needs and drive the programme to deliver coherent outputs across the activities of both Priority 1 and Priority 2 (with equal weight).
	Coordinated materials development programme aligned to semiconductor and photonics needs for high efficiency connectivity - accelerating the application-readiness of materials designed to improve energy consumption, and capacity and coverage in telecoms systems and produced at scale.
	Materials 4.0 capability to support analysis of large data, automation processes and materials discovery.
	International collaboration to increase attractiveness of the materials and application sector to diverse cross-disciplinary talent.
	Supply chain development programme to support translation and adoption and strengthen supply chain resilience.
Underpinned by	**An enabling ecosystem**
	Existing UK capabilities, including the 5G-6G Innovation Centre, Catapults (Satellite Applications, Compound Semiconductor, Connected Autonomous Vehicles and Digital) Defence and National Security (including NCSC), National Telecoms Lab (NPL), TechUK, Photonics UK, the UK Metamaterials Network Plus), OFCOM and DCMS.
Delivering solutions to	**Solve industry challenges**
	Technology translation and scale-up on timescales required by industry.
	Meeting key sustainability goals (especially increasing operational/functional energy efficiency of devices and systems).
	Access to a domestic talent pool, with improved retention opportunities across the ecosystem.

CONNECTIVITY & TELECOMS PRIORITY 2: Coordinated and integrated capabilities for application-based translation and manufacturing of materials and components for telecommunications	
Outcomes	Connected whole-system approach to innovation for the telecoms sector.
	World-leading, integrated translation-prototyping-manufacturing capability in key materials and components for advanced telecommunications, with a demand-led mandate.
	Fast-tracking telecom technology discovery-translations and adoption.
	Commercial and non-commercial (Defence) technology needs addressed.
	Agile talent pipeline mobile across the sector.
Enabled by	**Key interventions**
	Application-focussed national connectivity innovation hub enabling access to a whole-system approach for demonstration, evaluation, pilot-lines, scale-up, manufacturing, metrology and standards (integrating existing research capabilities and new capabilities where needed, such as a photonic foundry).
	National access to a capability for standardised testing and validation of materials, based on user demand and national standards and rules for materials and components and their integration into systems.
	Development of skills and capacity, with end-to-end industry participation, enhancing attractiveness of the materials and application sector to diverse cross-disciplinary talent from apprenticeships through to post-graduate researchers (provided through the innovation hub).
Underpinned by	**An enabling ecosystem**
	Existing UK capabilities, including the 5G-6G Innovation Centre, Catapults (Satellite Applications, Compound Semiconductor, Connected Autonomous Vehicles and Digital) Defence and National Security (including NCSC), National Telecoms Lab (NPL), TechUK, Photonics UK, the UK Metamaterials Network Plus), OFCOM and DCMS.
Delivering solutions to	**Solve industry challenges**
	Technology translation and scale-up on timescales required by industry.
	Meeting key sustainability goals (especially increasing operational/functional energy efficiency of devices and systems).
	Access to a domestic talent pool, with improved retention opportunities across the ecosystem.

A2 – 6 CONSUMER PRODUCTS, PACKAGING & SPECIALIST POLYMERS

A2 – 6.1 Materials for sustainable packaging

Overall opportunity

Plastics are energy efficient, inexpensive to make, and have a wide range of applications. They are the material of choice for packaging due to their ability to be tailored to multiple requirements and ease of processing. However, the current production and deployment of plastic far outpaces our ability to manage it once it has fulfilled its initial purpose (and is often considered as 'waste'). Furthermore, most plastics are used for single-use items, meaning their usefulness is short during their lifespan. UK households generate 90 billion pieces of plastic packaging waste each year, of which only 17% is recycled domestically. Current amounts of plastic packaging waste are expected to triple by 2050.[68]

As countries impose bans on single-use plastics and with upcoming legislation, such as the Extended Producer Responsibility (EPR) legislation and EU plastic packaging policy initiatives, companies are actively adopting recyclable solutions, facilitating the integration of circular packaging methods. Furthermore, the industry is moving away from complex multi-layer packaging systems, preferring mono-material packaging that is more easily recyclable. Although unlikely to be a major focus for the UK, biodegradable packaging is being explored for specific applications such as food-contaminated products. The global recyclable packaging market is expected to reach £48 billion by 2035, at a CAGR of 4–6%, and the global biodegradable packaging market is expected to reach £157 billion by 2035 at a CAGR of 5–6%, both offering economic opportunities for the UK.[69]

Food and drink is the UK's largest manufacturing sector and requires UK-based packaging solutions to reduce reliance on imports and the overall carbon footprint of products. Other key sectors include consumer goods, pharmaceuticals, health, retail, and industrial packaging. A priority is mass-production products (including active packaging) that can be easily recycled using existing technologies. Considerations of compositional variability and quality control, as well as the use of additives and reducing contaminants, will be critical in developing new materials systems. The industry also requires improved

[68]The Big Plastic Count 2024; Greenpeace, Everyday Plastic and the University of Portsmouth
[69]Source: Market Research Future – Market Insights

recyclable barrier materials and more specialist applications, such as those in the pharmaceutical market, which presents considerable opportunity.

Bio-based materials, such as bio-polyethylene and bio-polypropylene, offer potential alternatives to traditional plastics in packaging applications, such as food packaging films, paper coatings, and food service items. More generally, demand for solutions to the circularisation of packaging materials is rapidly growing due to their environmental benefits; for example, integrating waste streams into their production can reduce waste, minimise environmental impact and align with circular economy principles. Additionally, bio-based materials can be used in various sectors beyond packaging applications, including automotive and transportation, textiles, agriculture and horticulture, and in environmental applications (for example, pheromone traps and fertiliser rods). However, while feedstock diversification will lower the carbon intensity of products, assessing the availability of bio-based feedstocks and the net environmental balance of such innovations must also be considered in developing a portfolio of materials and products that will meet agreed sustainability goals.

Sustainable packaging solutions will also require a standard approach to infrastructure (such as waste sorting and recycling) to enable circular economy opportunities. Their adoption will also be supported by collaborations across the materials community, social sciences and the humanities to better understand behaviour concerning the sustainability of plastic packaging, provide insights into how diverse communities use technologies and novel materials, inform new and improved designs, technologies and processes, and address knowledge gaps and misconceptions that will impact future business models. Social and cross-cultural dimensions are vital here, particularly if we want to transition to an inclusive circular economy.

Policy and regulatory drivers are critically important in this field and must be based on adopting an agreed-upon definition of, for example, bioplastic and percentage recycled. This will clarify and streamline the industry's EPR and tax obligations, improving the cost of these materials compared to fossil fuel-based plastics. A global opportunity exists to develop genuinely sustainable packaging materials that retain or enhance existing properties and combine them with systems for reuse or recycling.

Building on existing expertise and programmes, a systems approach will be critical to consistently and accurately assessing products' carbon values. This approach will also direct the prioritisation of materials innovations, capture full lifecycle challenges, and offer potential solutions through materials innovation.

Opportunity priorities

Three key priority areas in materials for sustainable packaging have been identified as game-changing for the UK:

Priority 1: Developing and translating bulk sustainable plastic packaging processing, manufacturing and circularity.

Benefits to the UK:

(i) Meeting net zero targets.
(ii) Less market volatility due to reliance on imported materials.
(iii) Reduction in landfill.
(iv) Reduce overall resource use.
(v) Maintaining a UK chemical sector.

Priority 2: Developing bio-based, biodegradable, sustainable packaging materials based on agreed environmental parameters.

Benefits to the UK:

(i) Growth of UK world-scale production of bio-plastics industry.
(ii) Use of renewable bio-based feedstocks.
(iii) High-skill, high-value jobs in bio-based plastics-related roles across multiple sectors.
(iv) Access to new, high-value markets and improved regional economic opportunities.

Priority 3: Ensuring an enabling policy/regulatory environment to facilitate priorities 1 and 2.

(Whilst this is not materials innovation *per se*, it will be critical as an enabler to deploying the materials innovations from priorities 1 and 2)

Benefits to the UK:

(i) Enabling priorities 1 and 2 in delivering sustainable solutions for plastic consumer goods and packaging development, processing, and EoL solutions (re-use, recycling, circularity).

(ii) Connected sustainable packaging manufacturing ecosystem underpinned by enabling policy and regulation and standardised approach to recycling.

(iii) Supporting the UK-based sustainable packaging industry, which further supports an extensive range of sectors (including food and drink, consumer goods, agriculture and horticulture and retail).

(iv) Enabling technology export opportunities for UK businesses and global adoption of UK Standards).

(v) Transitioning to inclusive circular economies.

What we need to do in the UK to realise the opportunities in this area

<table>
<tr><th colspan="2">SUSTAINABLE PACKAGING PRIORITY 1:
Bulk plastic packaging processing, manufacturing and end of life solutions</th></tr>
<tr><td rowspan="3">Outcomes</td><td>A portfolio of less complex composite packaging with maintained or improved functionality including options for cost-conscious markets, developed with application/end-use and recyclability as a focus.</td></tr>
<tr><td>UK circular economy in bulk plastic packaging.</td></tr>
<tr><td>Maximising ROI from existing infrastructure.</td></tr>
<tr><td rowspan="4">Enabled by</td><td>Key interventions</td></tr>
<tr><td>Cross-industry-academia-regions (local government) working group to assess current capabilities and needs, identify gaps and drive solutions towards circularity or other modes of sustainability.</td></tr>
<tr><td>Programme for delivering large-scale commodity solutions, including:
• New technologies (such as, mono-material polymer packaging, reducing layers and capturing functionality in fewer layers for flexible packaging, standard combinations for multi-application use to facilitate simpler recycling, and additive innovation for longevity in polymers that are mechanically recycled).
• Maximising materials compatibility with existing manufacturing infrastructure.
• Producing renewable chemical feedstocks by adopting fermentation and new catalytic processes, and developing circular economy infrastructure.</td></tr>
<tr><td>Nationally accessible processing hub to drive innovation in processing techniques and end-of-life (EoL)solutions:
• Polymer and paper test & development capability for packaging materials based on fit-for-purpose next-generation measurements, standards and application of digital/data driven methods (Materials 4.0).
• Circular economy solutions to include re-use, depolymerisation (recycle to monomer, recycle to base chemical) and polymer production.
• Accredited biodegradation, composability and recyclability testing facilities.
• Rental pilot facilities to scale up innovations/technologies.
• Further integration of AI into materials discovery, testing and recycling.</td></tr>
</table>

Underpinned by	An enabling ecosystem
	World-leading industrial and academic expertise in sustainable polymers/plastics and packaging production and utilisation.
	UK capabilities including the UKRI Smart sustainable packaging initiative and the Oxford SCHEMA Hub, British Plastics Federation.
	Readily available UK waste streams to convert into raw materials.
	Adaptable established waste management sector capable of implementing new methods for collection of waste streams.
	Innovative sorting technologies to automate waste selection.
Providing solutions to	**Solve industry challenges**
	Enabling circular supply chains.
	Greater choice of recyclable-grade packaging across the supply chain.
	Recycling of waste packaging reduces scope 3 emissions of industry.
	Access to new international market opportunities.
	Access to further raw materials supply from international waste streams.
	Clarity and consistency in circularity assessment (LCAs and beyond).

SUSTAINABLE PACKAGING PRIORITY 2: **Bio-based biodegradable, sustainable packaging based on agreed environmental parameters**	
Outcomes	A portfolio of bio-based biodegradable, high-value packaging solutions for multiple sector application/end-uses.
	UK-based world-scale production of bio-based biodegradable plastics (>250,000 Tonnes).
	Smart packaging innovations to facilitate the recovery and reuse of high-value products (for example, medicines).
	National manufacturing capability: • Infrastructure providing sustainable feedstock (raw materials, CO_2 capture). • Production plants for chemicals, resins and plastics based on existing infrastructure.
Enabled by	Microplastic reduction.
	Key interventions
	Cross industry-academia working group to: • Assess current capabilities and needs, identify gaps, define what "Bioplastics UK" should make at a global scale (opportunity identification), and drive solutions. • Map UK secondary biomaterials and where they create the most impact in environmental net gain, so winners can be prioritised.
	National programme to translate bio-based and/or biodegradable packaging materials into mainstream use, including: • Key biobased and/or biodegradable polymers (PLA, PHA, PBAT, PCL). • Biobased polyolefins, PET, PA. • Algal/seaweed polymers. • Biobased packaging from natural agricultural wastes and marine sources. • Use of biorenewable waste streams: o Development of polymers from waste material feedstocks. o Approaches to feeding in waste streams. o Exploring waste streams to chemical opportunities. • Agricultural mulch films containing built-in nutrients. • Feasibility study of large-scale bio-based packaging from natural agricultural wastes, marine sources, municipal solid waste and other waste streams.
	National programme to improve bio-based packaging processing and maximise secondary impacts, including: • UK capability in biomass to monomer to polymer processing, including quantifying agricultural capability/capacity to meet feedstock demand. • Development of new and novel processing for the manufacture of biomaterial packaging. • Biogas production from the composability of plastics. • Anaerobic digestion of food waste and valorisation.

Underpinned by	**An enabling ecosystem**
	World-leading industrial and academic expertise in biodegradable and compostable materials and in renewable chemicals (for example, catalyst design).
	Readily available UK sources of biomass to convert into raw materials.
	Oxford SCHEMA Hub, Preventing Plastic Pollution with Engineering Biology (P3EB) Mission Hub, Centre for Enzyme Innovation.
Providing solutions to	**Solve industry challenges**
	Access to tested and certified products based on industry application and scale.
	Access to new international market opportunities.

SUSTAINABLE PACKAGING PRIORITY 3: An enabling policy/regulatory environment	
Outcomes	Industry-enabling ecosystem to adopt new packaging solutions and technologies.
	Improved access to international markets and expanded export opportunities.
	Regulatory standards supporting a uniform national approach for recycling packaging.
Enabled by	Global adoption of UK standards.
	Key interventions
	Development of policy and regulation drivers for sustainable packaging, aligned with global trends, including: • Internationally aligned standards and regulations to facilitate technology export (for example, FDA requirements, European Packaging and Packaging waste Regulations, Extended Producer Responsibility compliance, Carbon Border Adjustment Mechanism (CBAM). • Alignment with other jurisdictions and clarity on use of mass balance as incentive for recycled content. • Compliance with UK Emissions Trading Scheme and alignment with the UN Plastics Treaty. • Policy and standards clarity for biodegradable polyolefins (UK are leaders in the field). • Standardised national approach to life cycle assessments (to end-of-life). • Mandated recycled content of packaging. • Incentivisation of circular supply chains. • Clarity on UK REACH.
	National infrastructure approach for end of life (EoL) solutions: • Standardisation of household & industrial waste collection across the UK. • Embracing new EoL strategies.
Underpinned by	Interdisciplinary programme working across materials and social sciences/ humanities leading to improved design, insights into how diverse communities use technologies and novel materials and the communications which are required to address knowledge gaps and misconceptions.
	An enabling ecosystem
	Existing world-leading standards.
	Extant but fragmented innovation supply chain from materials producers to packaging designers and fast-moving consumer goods clients for innovation projects.
	Expertise within regulatory bodies.
Providing solutions to	Existing regional recycling infrastructure and expertise.
	Solve industry challenges
	Operating under unified standards.
	New export opportunities.
	Challenges in circularity assessment (LCA and beyond).

A2 – 6.2 Sustainable elastomers

Overall opportunity

Elastomers are used in a vast range of finished products, from tyres on vehicles and conveyor belts to disposable surgical gloves, medical implants and seals. Properties such as heat, abrasion, chemical and weather resistance, electrical insulation, and flexibility make elastomers highly adaptable and valuable in applications across many industry sectors.

The industry encompasses over 180,000 organisations globally and is projected to reach a value of £165 billion by 2030, exhibiting a CAGR of over 5%.[70] The UK elastomers industry is a significant sector driven by various end-use industries such as automotive, medical, packaging, consumer goods, and aerospace. The country is home to several prominent elastomer manufacturers and suppliers, including Weir Group PLC, DLR Elastomer Engineering, and Elastomer Engineering Ltd. A conservative estimate for the UK elastomer market size is between £1.6 and £2.4 billion,[71] around 2–3% of the global market.

Elastomers have two key market demographics:

- High-value, specialist application elastomers.
- High-volume elastomers for sectors such as transport and manufacturing.

Seals cover either demographic depending on use.

Elastomeric materials have high-value applications, ranging from heart valves to acoustic tiles. Due to their wide range of properties, they are critical to high-growth sectors such as health, robotics, haptics, aerospace, and defence. High-performance elastomers are also essential to developing our renewable energy sector. Components in wind turbines, hydrogen production, storage, and transport, and coatings for undersea electrical cabling and electric vehicle charging cables rely entirely on elastomeric materials.

The high-volume elastomer market faces a distinct challenge in managing more than 17 million tonnes per annum of waste (globally), especially in tyres and conveyor belts. In the UK alone, it is estimated that around 50,000 tonnes of waste tyres are generated each year. [72] For example, manufacturing conveyor belts consumes enormous natural

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[70]Precedence Research Global Elastomer Market Report 2022
[71]Based on the size of the European Elastomers market and the UK's position in it, from Fortune Business Insights Market Analysis
[72]European Tyre and Rubber Manufacturing Association

resources whilst producing significant greenhouse gases (GHGs) throughout all stages of production and use. Extended use, repair and reuse are essential to reduce the consumption of virgin materials. Recycling elastomers can lead to their repurposing into new materials with desirable properties that virgin rubbers lack. Increasingly, both manufacturers and legislators realise that recycling is essential for environmental sustainability and can improve the cost of manufacturing.

Employing new technologies to extend in-use life and finding sustainable end-of-life solutions is a significant challenge for the industry. Solving this challenge will position the UK as a world leader.

Opportunity priorities

Two key priority areas in elastomeric materials have been identified as game-changing for the UK:

Priority 1: Delivering high-value specialist elastomeric materials for specialist applications in growth sectors.

Benefits to the UK:

(i) Driving new, high-value economic growth and job opportunities.

(ii) Supporting renewable energy sectors with sustainable elastomer-based components, delivering net zero targets.

(iii) Improving economic outcomes through new circular economy opportunities.

(iv) Securing supply chains for critical components.

Priority 2: Improved sustainability through extended in-life service, end-of-life processing and recyclability of high-volume elastomeric materials.

Benefits to the UK:

(i) New circular economy in elastomer recycling.

(ii) Improved environmental outcomes, reducing the UK's manufacturing carbon footprint and landfill.

(iii) Supporting manufacturing sectors with sustainable elastomer-based components, delivering net zero targets and contributing to sustainability goals.

What we need to do in the UK to realise the opportunities in this area

SUSTAINABLE ELASTOMERS PRIORITY 1: High-value, specialist application of elastomeric materials to support high-growth sectors	
Outcomes	Building UK capabilities in global growth markets including health, robotics, haptics materials for extreme environments, electric vehicles and their infrastructure.
	Supporting required developments in more established sectors critical to the UK such as renewable energy, aerospace and defence.
	Accelerated materials innovation and deployment for emerging technologies.
Enabled by	**Key interventions**
	Focussed industry-academia working group (including material manufacturers and end-users) to agree priority target applications, existing capabilities, gaps and solutions.
	Programme for the accelerated development and translation of high-value elastomeric materials: • For high-value applications such as biomedical implants and tissue engineering, and robotic and haptic components. • With increased performance (such as higher thermal and electric stress insulation applications, improved erosion-resistance, high stability formulations for aerospace and defence. • With improved erosion resistance for elastomeric coatings, tapes, or shells in renewable energy applications especially wind turbines. • Advancement in polymer material science such as new vitrimer technology, acoustic sealants, synthetic latex, liquid silicone rubber (LSR) and nanocomposites. • Application of additive manufacturing and other technologies to expand elastomer applications.
	Access to national verification capability: material testing capability clusters both at micromechanical level and large-scale system level and for extreme environmental conditions.
	AI-generated formulation methods (Materials 4.0) to accelerate development and high throughput screening methodologies.
Underpinned by	**An enabling ecosystem**
	Existing industry expertise from SMEs to large-scale companies.
Delivering solutions to	**Solve industry challenges**
	Expanding growth opportunities in health, transport and manufacturing sectors through diversification of products.
	Meeting demand in health, transport and defence sectors.
	Producing required components to enable renewable energy sectors.
	Increased resilience to critical and high CBAM attracting materials.
	Resolving issues of potential PFAS bans.

SUSTAINABLE ELASTOMERS PRIORITY 2:

Improved sustainability through extended in-life service, new formulation, end-of-life processing and recyclability of high-volume elastomeric materials

Outcomes

- UK supply chain of sustainable elastomers based on industry application needs.
- UK reverse supply chain capability based on elastomeric materials.
- Cross-industrial sector strategy to harness economies of scale.
- Redefining the industry's environmental footprint.

Enabled by

Key interventions

- Cross-industry-academia expert working group (including material manufacturers and end-users) to prioritise existing capabilities, gaps and solutions.
- Programme to accelerate the development and translation of sustainable elastomeric materials, including:
  - Biodegradable/compostable elastomers.
  - Identifying and deploying bio-based feedstocks.
  - Recyclable thermoplastic elastomers to replace cross-linked (thermoset) materials.
  - Accelerated catalyst and process engineering design for renewable monomers.
  - High-temperature thermoplastic polyurethane to replace polyvinyl chloride for EV charging cables.
  - High profile and impact end products for tyre and conveyor belt and belt in-use life-extension and recycling.
- Development of in-performance, automated monitoring solutions such as non-destructive examination to identify performance degradation and mechanical failure methods, extending in-life use (only replace when necessary).
- Nationally implemented improved waste sorting including processes to recover thermoplastic elastomers and separation of complex multi-component systems.
- Materials passports and systems to track materials and components through their lifetime – Materials 4.0 digital fingerprints.
- Legislation and regulations to drive sustainability across all sectors. For example, directing elastomers to recycling, adoption of technology to extend life, clear national targets for recycling, definition of who is responsible at what stage of life cycle and disincentivise sending plastics to landfill.

Underpinned by

An enabling ecosystem

- Existing life-extension and recycling expertise.
- Alignment with existing international regulations and directives (for example, EU Landfill directive).

Providing solutions to

Solve industry challenges

- Solutions to support circularity around high volume areas such as tyres and belts.
- Cross-sector engagement underpinning economies of scale and supporting a UK sustainable elastomer supply chain.

APPENDIX 3

Cross-cutting Theme Sub-strategies

Positioning the UK as a great place with which to do business, built on a foundation of materials innovation

A3 – 1 MATERIALS 4.0

Overall opportunity

Materials 4.0 will radically change the rate and responsiveness of materials innovation, increasing its impact on society and the economy through a data-centric, digital, interoperable approach to innovation, characterisation and manufacture in the materials sector. Significant value is in the data associated with the materials and acquired from experimentation and monitoring their in-life applications. However, much of this value is not realised through a combination of factors. These include:

- Incompatibility between data systems and data providence
    - Curation of the UK's extensive research output
    - Verification of trusted data
- Lack of awareness of the value of existing data
- Reluctance to share data

To accelerate the development and translation of materials innovation and maximise its ROI, we must find a way to effectively validate, use, and share data, including sensitive data, across the innovation supply chain. This is a complex and challenging area, but it has the potential to unlock massive economic and social benefits across all sectors, from energy, transport, and space to construction, health, and consumer products.

Increased digitisation in materials innovation and manufacturing creates new opportunities and demands in design, testing, processing, procurement, service, recovery, and reuse. However, to eliminate incompatibility and obsolescence in data systems, we must manage the digital representation of relevant materials data for industrial applications using agreed-upon standards. This approach must also include new technologies for digital security and trust. The benefits of this approach include significant cost/time reductions for industry and new application opportunities identified with an accelerated path to market.

Based on this data acquisition and management approach, improved, physics-based modelling combined with machine learning and AI (and other digital tools) will accelerate materials discovery and translation by providing accurate and scalable predictions of material responses to various stimuli. This is particularly important for understanding and optimising material properties and designing new materials with specific characteristics.

It will reduce the time to market and risks in deploying new materials technologies for industry applications.

Materials data also underpins material passports, which store information on materials, carbon and environmental impact, material health and safety and warranty and certifications. They can be constructed with different levels of data, creating other types of passports, from material and product to system-level passports. Material passports are vital to unlocking circularity[73] across various sectors, from construction to transport. They will also become critical in responding to international trade requirements. The UK will unlock new economic opportunities and improve sustainability outcomes by designing and adopting material passports. It will also future proof its industries for increased international trade when requirements such as CBAM and broader resource accounting measures come into force.

Opportunity priorities

Three key priority areas in Materials 4.0 have been identified as necessary in accelerating materials innovation across all sectors:

Priority 1: Access to trusted materials data based on national standards and protocols for materials-related data acquisition, curation and access.

Benefits to the UK:

(i) The UK becomes a global leader in interoperable manufacturing data acquisition, through-life management and access.
(ii) Improved competitiveness of all manufacturing sectors.
(iii) High-skill training and employment in data sharing and management.

Priority 2: Next-generation materials modelling, application of machine learning techniques, and its combination with high-fidelity experimental and process data.

Benefits to the UK:

(i) Increasing industry investment in and use of materials innovations.
(ii) Improved competitiveness of all manufacturing sectors by extending the life of products and infrastructure.
(iii) High-skill training and employment in modelling (transferrable skills across multiple sectors).

[73]Hoosain et al., 2021. Material passports and circular economy.

Priority 3: Development of materials passports.

Benefits to the UK:

(i) Driving a circular economy across multiple sectors.

(ii) Achieving sustainability goals (both nationally and at an industry level).

(iii) Complying with international trade regulations.

What we need to do in the UK to realise the opportunities in this area

MATERIALS 4.0 PRIORITY 1: Access to trusted materials data underpinned by national standards and protocols for data acquisition, curation and access	
Outcomes	Reducing the time from discovery to translation to deployment, improving economic returns for industry and improving research return on investment.
	Developing the UK's materials 4.0 capability as a world leader to provide competitive advantage to the materials, manufacturing, energy, transport and defence sectors.
	Realising the true value of materials-related data through accelerated translation of materials innovations and expansion of applications.
	All sectors supported by a national Materials 4.0 approach with agreed data sharing standards and protocols (designed for interoperability and rigorous through-life management).
	Interoperable, curated and trusted materials databases, accessible to researchers and industry.
Enabled by	**Key interventions**
	Cross-industry-academia-government working group to drive Materials 4.0 development structure and priorities, oversee materials data curation and protocols and managed legacy materials data.
	Agreed protocols for describing and managing materials data.
	Developing robust methods for data trust and exchange across industrial suppliers to ensure a 'pathway' for digital information.
	Consideration of a national curation centre for strategic materials data.
Underpinned by	**An enabling ecosystem**
	Fledgling and highly skilled UK materials 4.0 community – seeking a common purpose to harness develop of coherent methods.
	Existing capabilities which could be brought together, with gap-filling, to provide a comprehensive and aligned approach.
	UK digital capabilities and AI platforms (including capabilities such as Alan Turing Institute) for expedited materials development.
Providing solutions to	**Solve industry challenges**
	Cross sectors development of Materials 4.0 methodologies and methods to align with Industry 4.0 opportunities.
	Common methods across complete materials supply chain to enable true cross-sector agility in materials manufacturing and applications.
	Cost reductions and increased competitiveness.
	Realising the value of materials data.
	Accelerated translation of materials innovations and improved through-life monitoring and adaptation; current development timescales (15 years plus) are too long to allow industry to respond to market opportunities.

MATERIALS 4.0 PRIORITY 2:
Materials modelling and application of machine learning/large data methods

Outcomes

- Accelerated discovery and translation of materials designed for industry applications, improving economic returns for industry and improving research return on investment.
- Reducing the costs of material and component validation (currently very high), substituting with in-silico simulation – "right first time".
- Improved in-life durability (extending life), monitoring and repair.
- Improved sustainability outcomes ("sustainable by design").
- Developing the UK's materials 4.0 capability as a world leader to provide competitive advantage to the whole materials, manufacturing, energy, transport and defence sectors.

Enabled by

Key interventions

- Cross-industry-academia-government coordination network to set Materials 4.0 priorities, oversee materials data protocols and curate legacy materials data.
- Prioritise skills in physics-based modelling for materials and material systems to complement ML capabilities and bridge the gap to high fidelity experimentation.
- Development and deployment of robust materials and process informatics challenges; embedding the power of ML capabilities into materials discovery, processing and application – using major challenge programmes as exemplars to develop common frameworks/interfaces for application into workflow of materials supply chains.
- Improved predictive modelling to facilitate probabilistic life cycle/functional assessments which address material variability in safety critical and high reliability applications.
- Focus on a comprehensive national skills programme for development and application of Materials 4.0 methods across all technical and research grades.

Underpinned by

An enabling ecosystem

- Fledgling and highly skilled UK materials 4.0 community – seeking a common purpose to harness develop of coherent methods.
- Existing capabilities (such as the Thomas Young Centre, Manchester Materials Modelling Centre) brought together with gap-filling to provide a comprehensive and aligned approach.

Providing solutions to

Solve industry challenges

- Accelerating deployment of materials innovations.
- Reducing costs by extending life of components and systems.
- De-risking investment in translating materials innovations.
- Supporting data-based decision-making for sustainability initiatives.

MATERIALS 4.0 PRIORITY 3: Development of material passports and digital fingerprinting				
Outcomes	A UK system for material passports.			
	CBAM-ready products and services.			
	Supporting circularity and quality assurance through digital fingerprinting methods.			
	Supporting new circular economies.			
	Accelerating decarbonisation of sectors such as construction and transport.			
Enabled by	Developing the UK's materials 4.0 capability as a world leader to provide competitive advantage to the whole materials, manufacturing, energy, transport and defence sectors.			
		Key interventions		
		Cross-industry-government-academia working group to identify material passport needs and drive the technology to implementation.		
		Develop a national materials passport framework and system that is scalable and cross-sectoral.		
Underpinned by		Accessing integrated, curated data (see Priority 1).		
			An enabling ecosystem	
Providing solutions to			Multiple pilot and concept programmes (for example, Building as Material Banks Horizon 2020 programme, and the Global Economic Forum Battery Passport proof-of-concept pilot).	
				Solve industry challenges
				Supports routes to circularity for high-value materials.
				Access to product information, data and providence.
				CBAM compliance.
				Greater transparency for stakeholders.
				Expanded export options.

A3 – 2 SUSTAINABILITY AND CIRCULAR ECONOMIES

Overall opportunity

Materials innovations are central to delivering against our national priorities, economic growth, and sustainability outcomes across multiple manufacturing sectors, including manufacturing, transport, construction, and health. Many of these innovations will be specific to application opportunities. However, the EWGs across all materials innovation areas identified two cross-cutting opportunities that will be critical in realising the true value of the innovations themselves: Materials 4.0 and sustainability.

Sustainability demands that the needs of the present be met without compromising the future. It includes environmental, economic, and social considerations. Over the last thirty years, various processes, such as life cycle assessment (LCA), have been developed to quantify and control the impacts of materials transparently, systematically, and consistently.

One of the biggest challenges for most companies is the transparent, systematic, and substantial application of sustainability. Understanding and quantifying products' total system-wide cradle-to-grave impacts is essential for evaluating and improving their environmental sustainability, enabling informed decision-making, and driving innovation and policy development.

Accurate sustainability assessment underpins informed decisions about product design, material selection, and process optimisation, identifying innovation and improvement areas and driving new technologies' development. By undertaking such through-life analyses, companies should be able to identify hotspots in manufacturing processes and products, enabling directed innovation that reduces environmental impacts. It helps evaluate product sustainability, allowing the organisations to prioritise more environmentally sustainable options and reduce their ecological footprint. They can also provide a clear and transparent framework for communicating environmental impacts to consumers, investors, and regulators. As governments and international organisations seek to develop more sustainable and environmentally conscious policies, such analysis is increasingly used for policymaking and regulation. Many industries, including automotive, aerospace, and consumer goods, have adopted standard environmental assessment and improvement tools. However, more work is needed to ensure a consistent approach and transparency.

A full LCA aims to address all aspects of sustainability, including some specific items, most notably Carbon Footprinting, which can be used in isolation from other aspects. Some industries have developed standard reporting formats voluntarily, such as the Environmental Product Declaration (EPD), which contains many but not all aspects of a full LCA. The LCA, Carbon Footprint or EPD of a product can inform companies and consumers of the sustainability characteristics of that product. In addition, policymakers and regulators are increasingly utilising LCA or one of its components to agree standards and incentivise decarbonisation. For instance, the forthcoming CBAM regulations in the EU and UK will require importing companies to provide carbon footprint data. The EU Ecodesign for Sustainable Products Regulation (ESPR) will require many products to have a Digital Product Passport containing the environmental credentials of component materials. Increasingly, companies aim to integrate sustainability into the design stage of new products and materials using Safe and Sustainable by Design (SSbD) principles.

International standards have been developed to ensure consistency and comparability across regions and industries. For example, the LCA standards (such as ISO 14040 and ISO 14044) describe the principles and framework for LCA and life cycle inventory (LCI) studies. They do not, however, describe the LCA technique in detail nor specify methodologies for the individual phases of the LCA. Furthermore, the intended application of LCA or LCI results is considered in defining the goal and scope, but the application itself is outside the scope of the International Standards. This leaves a lot of scope for interpretation and consequent difficulties in comparing results across products or between practitioners adopting differing practices. In addition, it means a high level of skill and experience is needed to perform LCA.

In addition to difficulties with different methodological approaches, LCA relies on data to quantify impacts. These are often derived from standard data sets, which can be offered as a commercial product. Using alternative data sources can also result in different results and conclusions.

Companies need urgent assistance in adopting appropriate systems because of the complexities of undertaking LCA and the range of available tools and data sets. This is especially true for SMEs, who may not have the resources or in-house expertise to develop bespoke solutions. Such impact assessments can be costly (for example, LCA can cost anywhere between £4,000 for simple products or processes (and £150,000 or more for products with multiple components or complex systems), becoming out of reach for smaller companies and a very costly activity for those more highly resourced. It is crucial to have a unified approach to delivering impact analyses that are robust, comprehensive, comparable, transparent, and cost-effective. A national approach could provide competitive benefit.

Opportunity priorities

Two key priority areas in sustainability and circular economies have been identified as fundamentally necessary in delivering materials innovation across all sectors and game-changing for the UK:

Priority 1: Develop a robust, comprehensive and standardised sustainability framework, including LCA tools and an available skilled workforce to implement them.

The EWGs identified an urgent need to develop standardised, workable and reliable tools for a systematic sustainability assessment that can be either integrated with or used to source other sustainability parameters (for example, carbon footprinting, social responsibility assessments, and circular economy strategies) to provide the sustainability perspectives needed for regulatory compliance and product development.

They could include:

- Expert-level modelling and reporting.
- Functional unit definitions (or guidance) for different materials and products.
- User-friendly interfaces and automated data collection for businesses and organisations.
- Guidance on methodological choices for specific sectors, such as biogenic carbon accounting and recycling rates.
- Scalability and flexibility for large and small organisations alike.
- Integration with design software and databases for construction and product design.

The value of a standardised sustainability assessment lies in its ability to provide a comprehensive and standardised framework for assessing environmental impacts, driving sustainability decision-making, informing innovation and R&D efforts, and supporting product export. Establishing common methodologies and databases will create the approaches necessary to underpin new circular economies, which have been identified as another key opportunity for industry growth enabled by materials innovation.

Benefits to the UK:

(i) Enabling a common framework, informed decisions, and normalised processes across our manufacturing sector will ease the burden of regulatory compliance, reduce 'greenwashing' and allow organisations to drive demonstrable environmental impact.

(ii) Increasing the UK industry's competitive advantage by enabling our companies to compete in markets increasingly demanding sustainability performance, and facilitating exports.

(iii) Reducing public costs by maximising the efficiency of industrial processes and minimising industrial waste, as well as costs associated with environmental regulations and liabilities.

(iv) Ensuring regulatory compliance (such as with CBAM or ESPR).

(v) Driving innovation in industry and research by better-informed product design and development, creating more sustainable products and services through SSbD principles.

Priority 2: Develop a framework to grow new circular economies with UK industry (underpinned by sustainability approaches to materials innovation, and Materials 4.0).

Benefits to the UK:

(i) Achieving the national net zero goals

(ii) Increasing the UK industry's competitiveness and expanding market and export opportunities.

(iii) Reducing public costs by maximising the efficiency of industrial processes and minimising industrial waste, as well as costs associated with environmental regulations and liabilities.

(iv) Driving innovation in industry and research through circular supply chain opportunities.

What we need to do in the UK to realise the opportunities in this area

SUSTAINABILITY PRIORITY 1: Developing and implementing a comprehensive and standardised sustainability framework and tools	
Outcomes	A scalable, comprehensive, versatile, common sustainability assessment process that can be applied to various industries and diverse product portfolios.
	Streamlined data collection with user-friendly interfaces and automated data collection processes, reducing the time and effort required for data gathering.
	Improved sustainability decision-making for organisations.
	Improved sustainability assessment expertise in companies.
Enabled by	**Key interventions**
	Steering group to coordinate a cross-industry-government approach to LCA for materials in the UK (and connecting to the Materials 4.0 steering group initiatives to ensure data standards and collection are LCA-appropriate).
	Development of a standard, scalable LCA framework that is ISO compliant but also workable for industry application.
	Training and skills programme to support researchers and companies in understanding and completing sustainability assessments.
Underpinned by	**An enabling ecosystem**
	International LCA standards and sector-specific guidelines.
	Existing LCA expertise in government, academia and companies contributing to the LCA Regulatory Science and Innovation Network.
Providing solutions to	**Solve industry challenges**
	LCA Data-driven insights enabling companies to track progress, identify areas for improvement, and make data-driven decisions on sustainability, including climate change.
	Cost savings by optimising processes, and thus minimising costs associated with environmental regulatory compliance, and reducing greenwashing by providing normalised measures across a diverse manufacturing sector.
	Improved regulatory compliance including CBAM and ESPR.
	Increased competitive advantage by showcasing their commitment to sustainability and environmental responsibility.
	Continuous improvement by monitoring and evaluating the effectiveness of sustainability initiatives, identifying areas for further improvement and driving ongoing sustainability efforts.

SUSTAINABILITY PRIORITY 2:
Growing new circular economies

Outcomes

Growing new circular economies for the UK generating economic and social benefits.

Placing circularity as a key material design (and application) parameter:

- Strengthens the UK's industrial base by development of new business models and opportunities for both new and established companies.
- Improves UK supply chain security with increasing proportions of raw material production onshored to the UK using circular routes of "waste to raw materials".
- Provides opportunities for decentralised production models, delivering regional economic benefits.

Contributing to net zero targets through reuse and recycling.

Increasing sustainability outcomes and reducing public costs (for example, in major infrastructure and defence) by optimising and extending lifecycle of major assets.

Enabled by

Key interventions

Scale emerging materials, process technologies and recycling concepts across the maturity scale to enable the exploitation of underpinning technology developments and de-risk industry investment.

Networks, supply chains and growth partnerships to support the wider conditions for exploitation and maturation of new materials and to create sustainable and/or circular economies.

Connecting adjacent material research, processes and supply chains (e.g. pharma with mixed mode/complex waste streams):

- Mapping waste and recyclable components/materials.
- Develop new pathways for waste including infrastructure for recycling and reuse and common standards for reusable material.
- Incentivise circularity and life extension through policy to include development re-use/repair/renew strategies.

Develop best practice and training (e.g. handbook for green design, data collection, repair and reuse). (This also links to the life extension priority below.)

Prioritise development of repair/rejuvenate approaches and standards across all sectors that will allow longer in-use lifecycles.

Incentivise methods to ensure life extension of major infrastructure through enhanced life assessment tools and degradation abatement technologies and damage monitoring/prediction repair and damage abatement innovations from coatings to structural repair methods (which will also be a focus area for the Opportunity Workstream on surfaces).

Underpinned by	**An enabling ecosystem**
	A flexible national infrastructure well linked to academia and industry with the capability to rise to clear national challenges and system thinking around sustainable innovation in materials.
	Existing adjacent supply chains with similar issues.
	World leading community spanning industry and academia in the development and application of life assessment methods for high integrity infrastructure assessment (structural integrity) and monitoring (including nuclear, offshore structures and aerospace).
	World leading research capability in materials degradation and prevention, including corrosion and coating.
Delivering solutions to	**Solve industry challenges**
	Industry demand for more sustainable components to deliver market growth.
	Reduce costs (especially public costs) by extending lifecycles.
	Early product withdrawal due to lack of understanding/standards for repair.
	Optimising and extending useful life of infrastructure to maximise the value of assets and ensure national resilience.
	Enable operational compliance with environmental standards by using industrial waste.

A3 – 3 SKILLS

Overall opportunity

Ensuring the UK has the people with the right skills to deliver, apply and use materials innovations is vital to securing the broadest possible benefits. This includes direct and indirect benefits, from designing and manufacturing materials for industry applications to delivering large numbers of high-skill, high-value jobs across all industrial sectors, and the resultant economic and social benefits these bring.

Up to 52,000 materials innovation-specific jobs exist in the UK industry, representing almost 8% of the total UK materials-related employment figure. Each job supports up to 18 other jobs in more than 2,700 companies directly engaged in materials innovation. The GVA associated with the materials-innovation-specific jobs is estimated at between £3.1 billion and $4.4 billion.

Dependence on materials-related employment is more acute within smaller companies. On average, 40% of all roles within micro-sized materials companies are materials-related, and 22% within small companies are materials-related. The average proportion of materials-related roles within medium and large-sized companies is 10% and 6%, respectively.

Significant vacancy rates are running across the materials sector. Compared to a UK average of 24%, up to 75% of vacancies in materials or materials-related roles are hard to fill due to a shortage of applicants with the required skills.[74] This skills shortage costs employers £1.5 billion a year (across the STEM landscape) in additional training costs, recruitment, temporary staffing and inflated salaries.[75]

Despite the increase in STEM undergraduates in recent years and the higher average salaries of STEM roles, the relatively low number of graduates entering STEM occupations is a serious cause for concern among employers. Forty per cent of employers cite a shortage of STEM graduates as a critical barrier to recruiting appropriate staff, 50% of employers warn that a lack of talent could deter foreign investment and over half (56%) expect the shortage to worsen over the next decade, particularly in the light of a forecast 7% increase in UK STEM jobs by 2035.[76] This

[74] UK Commission for Employment and Skills (UKCES)
[75] STEM Learning report. 2018
[76] Lightcast UK Labour market analytics 2024

challenge is exacerbated by the increase in people retiring from STEM roles leading to even more vacancies.

Added to the broader STEM skills challenge, the materials sector suffers from a low awareness of materials applications and materials-related jobs.

Theme steering groups should identify immediate and future-specific skills gaps and opportunities and coordinate responses to these needs. A national approach would bring together the myriad training and engagement initiatives, learning from and disseminating successes and increasing their overall impact and return on investment. The materials community must also unite to articulate the importance and excitement of working in materials and materials-related sectors.

Whilst some challenges must be met at a national level (for example, curriculum reform, prioritising STEM education and joining up the education-skills-jobs pipeline), there is a clear opportunity for the materials sector to play a significant, coordinating role in identifying current and future skills needs and innovative solutions for re-skilling/upskilling and raising awareness of the sector's training, job and career opportunities. The community can also advocate for curriculum reform, emphasising STEM education and support. Solutions include addressing regional and industry-specific needs (rather than a one-size-fits-all approach). As such, it could become an exemplar from which other STEM sectors and areas learn and benefit.

Opportunity priorities

Two priority areas in skills to support materials innovation have been identified as game-changing for the UK:

Priority 1: Coordinated action to identify current and future skills needs and attract and retain appropriately skilled talent in materials-related employment.

To address critical skills shortages across industry and supporting ecosystems, holistic action is urgently required to attract and retain appropriately skilled talent in materials-related employment. A detailed analysis of immediate and future skills needs must underpin this. It must be supported by an opportunity outreach (awareness-raising) campaign delivered at national and local levels to encourage the uptake of STEM education and progression into materials-related roles.

Benefits to the UK:

(i) Creating a future pipeline for a skilled workforce based on industry needs.

(ii) Addressing the current and future critical shortage of suitably skilled materials-related employees, enabling materials innovation.

(iii) Supporting talent pipelines, especially for micro-companies and SMEs.

(iv) Delivering economic and social benefits by increasing the overall number of STEM-skilled people entering and remaining in the materials-related workforce.

Priority 2: A joined-up, STEM-focussed education-skills-employment pipeline for the materials sector, facilitating entry and re-entry into the materials ecosystem.

Benefits to the UK:

(i) Retaining expertise and experience in the materials sector, with more opportunities for employee movement between academia and industry, fertilising cross-industry-academia collaboration.

(ii) The UK will become a leader in STEM-focussed curriculum design and delivery, in collaboration with industry and with national and local solutions.

What we need to do in the UK to realise the opportunities in this area

SKILLS PRIORITY 1: Coordinated action to identify current and future skills needs and attract and retain appropriately skilled talent in materials-related employment	
Outcomes	Government, policymakers, industry, education and academic institutions delivering a holistic plan addressing current and future materials-related skills needs.
	More people attracted to and retained in high-value, high-skill employment in materials-related jobs.
	Increased inclusion and diversity in the workforce with equity of opportunity.
Enabled by	**Key interventions**
	Theme steering groups will identify their core skills and educational needs (including optimisation of existing capabilities in materials discovery, translation and deployment). This will require collaboration between educational institutions, government bodies, and industry stakeholders to map current and future skill gaps/needs and identify necessary training programs. They will report generic requirements to the materials strategy coordination group to consolidate cross-cutting priorities.
	A coordinated outreach programme for the materials community: • *Materials Matter and Discover Materials:* articulating what materials are, the fundamental global, real-world importance of materials, career opportunities and pathways, and encouraging diversity. • The Young Materials council/skills taskforce to feed into the above intervention outreach programme. • Education and support plan for parents, teachers and careers professionals enabling them to understand and promote materials-related opportunities.
Underpinned by	**An enabling ecosystem**
	Multiple existing roadmaps ranging across all education key stages, colleges, universities, apprentice programmes, life-long learning, retirement planning and STEM engagement.
	Multiple providers and existing programmes – ranging from STEM engagement activities to apprenticeship programmes.
Providing solutions to	**Solve industry challenges**
	Access to an appropriately skilled workforce and at the numbers required.
	Improved workforce planning.
	Reduced costs.
	Increasing diversity in the workforce.

SKILLS PRIORITY 2:
A joined-up, STEM-focussed education-skills-employment pipeline for the materials sector

Outcomes

- More people encouraged to enter materials-related employment or return to materials-related careers after a break.
- A model for a joined-up education–employment pipeline for other use across other STEM sectors.
- A focus on promoting STEM education from an early age, integrating practical learning experiences, and adapting the curriculum to align with industry needs.

Enabled by

Key interventions

The Theme Steering Groups will engage with relevant industry and education/training providers and government to:

- Map cradle to retirement education/career/employment pathways (including all players weaknesses that lead to the leaky pipeline (at all ages) and areas of re-entry into the ecosystem) allowing organisations and individuals to explore how and when to enter the materials education-employment pipeline (in a "no-wrong-path" approach).
- Input into a review of current apprenticeship and T-learning provision with a focus on materials-related training programmes.
- Stimulate and support new initiatives to facilitate smooth transitions into and across materials careers (across industry and academia).

A cross-industry-education pilot for a joined-up education-employment pipeline for the materials sector, using Materials 4.0 and Sustainability Assessments as exemplars.

Materials Leadership group to advocate for and support broad curriculum design that delivers for the materials community.

Underpinned by

An enabling ecosystem

- Existing education–employment pipeline.
- Existing STEM-focussed initiatives.

Providing solutions to

Solve industry challenges

- Delivering long-term skills needs.
- Retaining expertise and experience.
- A collaborative model for re-skilling/up-skilling.

A3 – 4 TRANSLATION AND MANUFACTURING

Overall opportunity

The UK has an exceptional history in materials discovery and development. Several major multinational companies have globally significant UK-based research, development, and manufacturing centres. The country has a strong track record of creating spin-out companies and one of the world's most robust private investment communities.

To create economic and social value, materials need to be translated from the laboratory to manufacturing at scale and proven to meet relevant standards and regulations in service. This is true whether the material is for construction, aerospace, medicine, electronics, or any other application. When the need to demonstrate manufacturing at scale arises, major hurdles are often experienced – generally concerning producing material with the required consistency or quality against its projected performance/function and access to appropriate machinery, equipment and instrumentation to characterise, test and manufacture the material and the products made from it.

The expert working groups (across SMEs, large companies, investors, universities, and the public sector) have all identified the need for the UK to improve its performance in scaling up, characterising and testing, manufacturing, and applying all types of materials. Key priorities that will strengthen our success in bringing research discoveries and inventions to market more quickly have been identified.

Scale-up

Several key challenges are evident:

- Universities rarely operate scale-up capabilities which allow material to be produced at scale.
- SMEs developing new technologies often lack easy access to relatively high-capital-cost facilities or plants to demonstrate their manufacture; still, the investment community will only engage once this step has been proven.
- Larger organisations cannot risk running new batch products through high capital value production facilities and often require proof of concept on the pilot plant, which has the necessary flexibility and technical staff support.

Despite these challenges, the scale-up infrastructure to address these barriers is often present across the materials ecosystem (around the UK), and it is acknowledged that the country has most of the building blocks to support scale-up. The underlying challenge is that scale-up infrastructure must be better integrated into an easily accessed and agile delivery system that leverages public and private investment and can rapidly adapt to industry needs across multiple sectors.

Therefore, the UK can integrate and link its investments with private-sector organisations into a collaborative system that converts ideas into viable scaled-up products. Creating this scale-up and manufacturing ecosystem will allow the partners to define a route forward that minimises investment and risk while allowing materials to be brought to market more quickly. Less good ideas can also be stopped before too much time and money are wasted.

This will involve defining the process(es) required to take research ideas through scale-up and on to commercial delivery. The focus should be on the activities necessary to make scale-up happen, including how relevance is proven and how the partnerships required to ensure successful delivery are brought together. This intervention is as much about the system of scale-up as the physical. This system needs to capture, prioritise, and select the ideas with the best chance of success. It must include company needs as well as Government policy and strategy drivers.

A complementary task would be understanding the extent of the existing capability for scale-up in the UK. This would include:

- University assets
- Catapult centres
- Independent research organisations
- Public and private product testing, certification, standards and regulatory bodies
- Public and private investors in materials and materials-using companies

This will underpin the development of a UK taskforce for scaling up capability based on a gap analysis of current capability and future needs. Many physical scale-up assets are believed to exist already, and this task will focus on making the existing facilities and capabilities more accessible and integrated.

Manufacturing

The advanced M&E sector is also vital in distributing materials innovations by manufacturing, characterising, and testing new or refined materials used in all industrial applications. For example, focussed ion beam (FIB) microscopes are essential tools for high-precision analysis of materials and their properties. Microchips and artificial intelligence advancements heavily rely on developing advanced semiconductor production machines, among the world's most sophisticated machines.

As outlined in this strategy, new, innovative, functional materials are essential for industrial applications. However, without the machinery, equipment and instrumentation needed to characterise, test and make these materials and transform them into products, they will not be translated into industry applications, and the potential value added will be lost. This highlights the need to develop machinery, equipment and instrumentation that characterises, tests and makes innovative materials, turns them into products, and maximises the ROI from the new technologies.

There is already a trend for manufacturers to invest in new technologies to deliver innovative products. Seventy-one per cent of UK manufacturers have planned or are investing in technology this year, and 59% expect technology to positively impact their business performance and ability to adopt innovative technology solutions.[77]

However, the UK's advanced M&E sector has been impacted by a general trend of offshoring manufacturing activities, resulting in fragmented value chains and UK companies offshoring their manufacturing activities. This has resulted in rising imports and reducing the UK's share of the global M&E market.[77] Economic benefits for innovation in materials and manufacturing will be partially negated if machines, equipment and instrumentation are imported to address new manufacturing processes and to test and characterise new materials and material-related technologies. Reinvigorating the UK's advanced M&E and instrumentation capabilities will help these sectors grow and protect the projections regarding innovative materials and manufacturing across all other sectors.

Sustainability must also be embedded in designing, developing, and deploying new advanced machinery, equipment, and instrumentation. For instance, with the global shift towards cleaner manufacturing, the implementation of circular economy principles, and the development of low-carbon products and processes, the industry is anticipated to see the widespread adoption of electrical machinery. In addition, manufacturers are becoming more transparent when reporting their environmental performance, including accounting for the environmental impact of the machinery and equipment used in their product development and manufacturing processes.

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[77] MakeUK

Advanced machinery and equipment will also be pivotal in delivering "made smarter" processes. These will use real-time analysis and the application of large data methods to optimise quality and enable fully automated processes.

New machinery is needed to manufacture and develop new, innovative materials and the high-value products made from them. This directly supports capturing global opportunities in high-value sectors such as defence and energy markets. It will also generate greater value in the UK's manufacturing sectors, where value creation is coupled with manufacturability to enable materials and products from the outset. For example, the development of plant to process novel or reusable materials is becoming increasingly important.

This will require close collaboration between the UK's advanced machinery and equipment (M&E) and instrumentation sectors and the materials innovation community. Together, they must plan for the M&E and instrumentation requirements for characterising, testing and making materials innovation technologies (both the innovative materials themselves and the products from which they are made) and drive machinery and equipment design closely aligned to product manufacture selection. This must be supported by a connected manufacturing, scale-up and materials ecosystem to accelerate the deployment of application-specific materials innovation based on user needs and supported by a skilled workforce.

Implementing these cross-cutting priorities should accelerate materials development and translation into industrial applications. This will occur within a connected scale-up and manufacturing ecosystem, with new, sustainable-by-design machinery, equipment, and instrumentation to characterise, test, and manufacture innovative materials and technologies at industrial scales, and supported by an appropriately skilled workforce.

Opportunity priorities

Two priority areas have been identified as fundamentally critical to enabling industry adoption of materials innovation in the UK:

Priority 1: Developing and implementing a world-leading connected materials scale-up and commercialisation ecosystem for the UK, accelerating the translation and adoption of materials innovations.

Benefits to the UK:

(i) Increased return from investment in capital and equipment.

(ii) Establishment of a UK-distributed scale-up capability.

(iii) Creation of more secure, agile and integrated materials supply chains.
(iv) Increased margin and profit on sales of materials and products that use those materials.
(v) More new profitable products and companies driving up productivity.
(vi) The development of people with the skills to scale up processes and businesses and the ability to repeat the process.
(vii) The creation of high-skill, high-value jobs in manufacturing processes and associated activities.
(viii) Realising the value in intellectual property, including know-how.
(ix) Social and financial benefits from the use of the product.

Priority 2: Designing, producing and accelerating the deployment of next-generation machinery, equipment and instrumentation to manufacture, characterise and test innovative materials and make products from them.

Benefits to the UK:

(i) Adding value to innovative materials developed, designed and produced in the UK (and elsewhere).
(ii) Enabling application-led machinery and equipment design and manufacture to support the production and use of innovative materials across all manufacturing areas.
(iii) Supplying core infrastructure for all UK manufacturing sectors, supporting growth in manufacturing sectors such as aerospace and automotive, and protecting the economic projections regarding materials and manufacturing across all sectors.
(iv) Increasing ROI from across the existing research and innovation network in the UK.
(v) First-mover global advantage for the UK in developing and manufacturing next-generation machinery and equipment to make products from innovative materials.
(vi) Improving the competitiveness of UK businesses (across all sectors).
(vii) Increasing the UK's global M&E market share and its retention of value-add in the UK economy.

What we need to do in the UK to realise the opportunities in this area

TRANSLATION & MANUFACTURING PRIORITY 1: Connected and accessible capabilities for scale-up

Outcomes

- Integrated end-to-end innovation ecosystem for materials innovation to take it from lab to industry production.
- Access to more agile scale-up facilities relevant to material classes (improving the connections between existing scale-up facilities and filling gaps for specific materials).
- Making the UK a fully integrated and attractive place in which to do innovation and scale up development to increase growing internal and external investment.

Enabled by

Key interventions

Each theme steering group will undertake:

- Scale-up mapping and gap analysis .
- Drive the process(es) to allow integrated access and use of existing capabilities.
- Identify where gaps need to be filled (including IP, patent and licencing expertise).
- Develop UK Policy for scale-up capability based on current capability and future needs and a sustainable funding model (including options for investment or international collaboration) to deliver a world-leading scale-up capability.

Establishment of a national verification network for materials to de-risk investment and accelerate translation opportunities (UK characterisation, testing, validation & certification facility across TRL levels).

A targeted programme to streamline and harmonise access to existing funding and scale-up capabilities across the UK aligned with key national challenges.

Underpinned by

An enabling ecosystem

- An industrial strategy that defines long-term (15 to 20-year) policy and strategy.
- Existing funding to support translational research (although it is currently fragmented and poorly connected).
- Existing national scale-up infrastructure and institutionally based infrastructure across world leading institutes and universities (Innovate UK, Catapult network, RTOs, etc).

Delivering solutions to

Solve industry challenges

- Lack of clarity on access to funding and facilities for scale-up delays innovations reaching markets – huge effort required by SMEs to navigate schemes and capabilities.
- Lack of access to robust materials verification capabilities (and analysis) to accelerate innovation out of very early-stage development to secure pre seed funding.
- Ongoing trend of offshoring of industry-based R&D to jurisdictions where the innovation ecosystem is better connected and more agile.

SCALE-UP & MANUFACTURING PRIORITY 2:

Designing, producing and accelerating the deployment of next-generation machinery, equipment and instrumentation to manufacture, characterise and test innovative materials and make products from them

Outcomes

- Ensuring value leverage to innovations across all manufacturing sectors.
- Manufacturing and rapid translation of materials innovation for specific engineering challenges to allow production at scale with the required levels of quality control.
- Strengthening the UK's machinery capability through next-generation design, production and rapid deployment of manufacturing infrastructure that is sustainable by design.

Enabled by

Key interventions

- A cross-industry-academia process to signal to machinery developers the types of machinery, equipment and instrumentation required to make, characterise and test innovative materials and new products made from them, overseen by the Advanced Machinery and Productivity Institute.
- M&E Innovation programme supported by the application of made smarter principles and sustainable by design methods and technologies to align M&E development requirements with end-product manufacture.
- Improve technical education, especially for the younger workforce, ensuring enough people are trained in the mechanical, electrical, and increasingly digital skills required by the sector.
- A mechanism to connect the research, translation and scale-up ecosystem with market opportunities (involving industry (at all levels), government (national and local) and academia.

Underpinned by

An enabling ecosystem

- Strong advanced M&E and instrumentation sectors.
- Materials innovation community.
- Research and development network.
- Existing strategies and capabilities such as: securing technology-critical metals for Britain; UK critical minerals strategy, Advanced Machinery and productivity Institute (AMPI).

Providing solutions to

Solve industry challenges

- Identification of current and future manufacturing capabilities required by the materials innovation community and end users.
- Improved business competitiveness by accessing high-value markets and driving new business opportunities.
- Reinvigorating the UK M&E sector to translate materials innovation development into products, improving the overall value add to the economy.

A3 – 5 POLICY, REGULATIONS & STANDARDS

Overall opportunity

It is well established that effective policy and regulation can create a supportive environment for innovation by providing clarity, consistency, and incentives while addressing potential risks and challenges. It is an area where direct government intervention can create a highly enabling innovation ecosystem.[78,79]

Policy and regulatory clarity, consistency, and certainty are of primary importance to industry and were common priorities across all EWGs. The Regulatory Innovation Office will support evolving and embedding innovation systems in sectors while allowing agility and responsiveness and balancing regulations' positive incentive functions and the negative compliance burden.

A highly functioning policy and regulatory environment will:

- Establish industry-wide standards for quality, safety, and interoperability, promoting collaboration and reducing technical barriers to entry.
- Encourage investment by offering incentives, such as tax breaks, subsidies, or low-interest loans, to attract investment in innovative industries or projects.
- Simplify and reduce bureaucratic hurdles to facilitate developing and deploying new technologies and products.
- Provide clear and predictable regulatory frameworks, reducing uncertainty and allowing innovators to plan and invest with confidence.
- Encourage competition by promoting open markets, reducing barriers to entry, and protecting intellectual property rights.
- Support research and development by allocating resources and funding for research and translation and incentivise companies to invest in R&D.
- Facilitate collaborations between government agencies, industry, and academia to accelerate innovation and deployment of new technologies.
- To support innovative projects and startups, offer financing options such as grants, loans, or equity investments.

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[78] Patanakul, P. & Pinto, J. K. 2014. Examining the roles of government policy on innovation

[79] Closing the gap: Getting from principles to practices for innovation friendly regulation. 2022. Independent report for DBEIS and DSIT

- Encourage regulatory agencies to adopt innovative approaches, such as regulatory sandboxes or pilots, to test new policies and regulations.
- Assess the impact of regulations on innovation regularly and adapt policies as needed to ensure they remain supportive of innovation and growth.

Opportunity priorities

The current picture regarding regulations, sectors, companies, and the time horizon of regulatory impacts is heterogeneous. Close collaboration between material developers and users and those who set policies and regulations will facilitate the development, translation, and adoption of materials innovations in UK companies.

Benefits to the UK:

(i) An agile system that enables innovation development and adoption whilst balancing safety and security.

(ii) Making the UK a great place in which to do business.

(iii) Facilitating export of materials innovations.

(iv) Derisking private investment by providing policy stability and clarity.

What we need to do in the UK to realise the opportunities in this area

POLICY, REGULATIONS & STANDARDS PRIORITY: Enabling materials innovation	
Outcomes	Establishing a more agile and competitive innovation ecosystem across the National Strategy's materials themes enabled and supported through flexible standards and regulations tailored to different materials applications/sectors.
	Make doing business with the UK easier through an innovative regulatory framework – attracting investment and an environment for materials innovation for regulated sectors.
Enabled by	**Key interventions**
	The Theme Steering Groups to liaise with the RIO to inform the development of an appropriate regulatory framework which supports materials innovation aligned with key national materials challenges, act as spear heads for change, and address critical issues related to international regulations and initiatives. For example, providing clarity on regulations for: • CBAMS/PFAS bans. • Halogenated solvents reduction or elimination.
	Policy agility and certainty to encourage regulators to develop clear frameworks and eliminate unnecessary barriers to materials innovation entering their sector.
Underpinned by	**An enabling ecosystem**
	A UK regulatory environment which is open to innovation.
	An innovation industry seeking more flexible environment to test and trial new materials innovations.
	Existing close interaction between regulators and regulated companies.
Delivering solutions to	**Solve industry challenges**
	Lack of clarity on qualification and regulatory standards for manufacture, use and recycling currently discourages agility and cross working in the supply chain and creates a barrier to industrial growth.
	Current under-exploitation of export opportunities due to lack of a UK standardised approach to export/import under CBAM.
	Highly regulated sectors acting as a barrier to new materials innovation through bureaucracy and high-cost barriers which discourage investment.

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