HENRY ROYCE INSTITUTE

NATIONAL MATERIALS INNOVATION STRATEGY

INTERIM REPORT

ROYCE

April 2024

Driven by Royce
Led by ScotChem Ltd

Foreword

Allan Cook, Chair of the Materials Innovation Leadership Group and David Knowles, CEO, Henry Royce Institute

This Interim Report, charting progress with the National Materials Innovation Strategy, is the result of a real collective endeavour. Under the stewardship of the Materials Innovation Leadership Group (MILG), we have consulted over 1200 materials innovators and worked closely with 350 across a wide range of strategic industries to understand their materials-related challenges/needs and to simultaneously surface the exciting cross-sector opportunities that if exploited, will ensure the UK maintains a world-leading position in the rapidly expanding materials markets. Materials innovation companies operating in the UK currently generate a turnover of £1 trillion and employ 1.9 million skilled workers globally.

This phase of work is laying the foundations for the success of the UK's Materials Sector, and at the next stage we will go deeper to provide the required detail to deliver a comprehensive strategy. We've categorised Core Themes where materials applications span multiple industries and populated these with identified Opportunity Workstreams, which we'll use to conduct deep dives and determine priority materials innovations for the UK.

This report represents a "Call to Arms," and we are now looking for individuals to form Expert Working Groups to provide the necessary clarity to the opportunities and put in place recommendations that help us realise their potential. Importantly, by decoupling the strategy from individual sectors, we aim for these groups to propose materials developments that are viable and sustainable across the whole economy.

It's clear from this work that the demand for both new and improved materials must continue to increase at a staggering rate in the coming decades. The opportunities identified so far are only a first sift. The next stage will be to test, refine, and consolidate these and identify any gaps. The expert working groups will also consider aspects such as scale-up facilities, skills and education, regulation, and standards to varying degrees.

Importantly, this report also provides us with comprehensive data on materials innovation and its importance to the UK. This will support the business case for implementing the strategy's key recommendations; econometric reporting, included in this report, is a fundamental and underpinning part of our work.

Materials have a critical role to play in the UK's prosperity. The sector is not only profitable but also invests in its future - £2 billion raised in research funding per annum to support its ability to produce new materials which help to provide us with a better quality of life. Now, more than ever, our drive for a more sustainable society is dependent on having the right materials at our disposal which requires a step change in our investment.

Materials are also a real bedrock of the UK economy—but we can't deliver impact at pace for the UK without the support of a clear and concise National Strategy so that we are working towards aligned goals. We will deliver this by the end of 2024 and will, for the first time, set out a consensus on the key interventions required that represent the needs of the wide materials innovation community.

This will provide momentum for an Action Plan that sees Government, industry, and academia working together to shape the future of materials and establish a thriving Materials Sector that is strongly rooted in the UK and delivers long-term benefits to society as a whole.

Finally, thanks must go to the members of the Materials Innovation Leadership Group for their insights and for steering the process – which given the depth and breadth of materials, is no mean feat! We also appreciate the huge effort from our delivery partner ScotChem, who is driving and co-ordinating this important work, undertaking substantial and unprecedented engagement across multiple sectors, from Perspective Economics for their expert use of machine-driven analytics to provide us with the updated data so urgently required in this space and from Urban Foresight for their expertise in participatory stakeholder engagement.

PREFACE

Background

Materials innovation is a key driver of economic growth and competitiveness in a national and global marketplace and pervades almost every technological challenge facing society. From ensuring a healthy population to delivering ambitious net zero targets, materials lie at the heart of the solution to national societal challenges.

We have now reached the point where the UK will not be able to 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, there is a need for a strategy that is sustained over the five to ten years needed to deliver this change.

The development of such a strategy presents considerable challenges because it touches on almost every manufacturing sector in the UK, as well as nascent and emerging topics. It also spans a diverse set of stakeholders whose requirements, ambitions and desired outcomes may not necessarily directly align, and it must anticipate requirements for the development of an appropriately skilled UK workforce.

UK context: contribution of materials innovation to the UK economy

Each year in the UK, £430 bn in revenue is generated from producing and exporting materials-reliant products and services[1].

Materials underpin the UK's manufacturing sector which ranks 8th globally by value of output[2]. It accounts for over 9% of total UK GVA[3], over 8% of employment (2.6 million people in 2023), 49% of all UK exports (2023) and 41% of all business R&D[2,4] (2023).

Materials innovation and the associated manufacturing processes are fundamental to addressing national priorities and play a vital role in strengthening and growing the UK economy.

[1] https://www.ons.gov.uk/businessindustryandtrade/manufacturingandproductionindustry/bulletins/ukmanufacturerssales byproductprodcom/2022results
[2] https://www.makeuk.org/insights/publications/uk-manufacturing-the-facts-2023#/
[3] https://commonslibrary.parliament.uk/research-briefings/sn05206/
[4] Office of national statistics: R&D Expenditure

The vision

The vision is to establish a national strategy for materials innovation which delivers coherency through the government, industry, academia and the materials community, giving the UK a world-leading position in the rapidly expanding multi-billion-pound materials markets, substantially enhancing the value of UK-based industries.

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

The strategy will seek to grow and further develop our materials industry (both developers and users), ensure that this capability remains strongly rooted in the UK and deliver long-term benefits to the regional and national economy.

Interim deliverable

Royce initiated the strategy development emphasising a demand-led approach, accelerating technology translation and adding value to the UK economy.

Following extensive engagement across all sectors, industry has identified its key challenges and opportunities, to which materials innovation will provide solutions or be a key enabler. This report summarises the more than 1,200 industry responses, which have been grouped into priority materials innovation areas for deeper exploration by the UK materials community.

The assistance of the UK materials community is now needed to identify the specific materials innovations that will deliver maximum benefits to UK industry. To register interest in contributing to the next stage of the Strategy development, please submit an expression of interest:

https://forms.office.com/e/5LXSqANknQ

EXECUTIVE SUMMARY

As UK Research and Innovation's (UKRI) national institute for materials research and innovation, the Henry Royce Institute for Advanced Materials (Royce) is seeking to establish a National Materials Innovation Strategy (the strategy) to be developed in partnership with the entire materials community. This topic has considerable inherent breadth and complexity. The challenge is to establish the priority impact areas and establish how the UK should take a leading role in the discovery, development, production, commercialisation and deployment of materials innovations at scale, recognising the constraints of sustainable use of our finite resources.

In 2023, Royce commissioned a Materials Innovation Strategy Framework (the Framework) which provides a rigorous and robust way to:

- Identify priorities for materials innovation aligned with national priorities and industrial demands.
- Identify the required enablers to deliver results for industry and the nation more broadly, including the commissioning of research, skills training, regulatory frameworks, investment and infrastructure barriers to innovation.
- Develop a set of preliminary investment cases for materials innovation so that industry, academia, financiers and Government can act in concert to deliver on the strategy in a progressive manner.

The approach is necessarily challenge-led, meaning that it draws on the input from industry and end users to identify the key national and global trends and drivers, which in turn inform the right opportunities for further exploration and development. 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.

The methodology for gathering and assessing data falls under three broad themes:

- Identifying trends and drivers which require notable innovation.
- Clarifying and grouping the applications (products, services, solutions) and process development which provide the opportunities for value creation and impact.
- Grouping materials innovation that will contribute to realising these opportunities and identifying the enablers required to support the materials innovation.

Under the leadership of Royce and the Materials Innovation Leadership Group[5], industry stakeholders were invited to identify priority industrial applications enabled by materials innovation. Over 1,200 individual responses were correlated against cross-sector impact and categorised into priority innovations:

- ***core themes*** - requiring deeper exploration of materials innovation primacies
- ***cross-over themes*** - common across all priority areas

The core and cross-over themes are outlined below.

[5] The Materials Innovation Leadership Group (MILG) has been established to oversee and champion the development of the National Materials Innovation Strategy. The MILG is made up of senior representatives from a range of industry and key research organisations.

CORE THEMES

1. Energy materials
2. Soft materials
3. Biocompatible materials (health, life sciences & agriculture)
4. Structural materials
5. Materials for surface enhancement & protection
6. Materials for electronics, telecoms, sensing & computing technologies

CROSS-OVER THEMES

1. Sustainability & circular economy: designing and producing materials for sustainability and circularity
2. Materials 4.0, digital thread, AI, intelligent discovery, design and manufacturing: using digital thread/AI and big data to accelerate materials discovery and application; digital twinning; digital material passports.
3. Skills, including re-skilling, up-skilling and developing new skills capabilities.
4. Critical minerals & materials for supply chain resilience and sovereignty.
5. Manufacturing & scale-up: capabilities for testing, verification and scale-up relevant to specific requirements.
6. Policy, regulations & standards: enabling materials innovation.

Thirty Opportunity Workstreams have been identified under each of the core theme headings. The workstreams identify and facilitate the gathering of the necessary experts to undertake a deeper exploration of materials innovation in each priority area.

Sub-strategies will be developed against these opportunities (either individually or as groups). They will be combined as the overarching National Materials Innovation Strategy, along with enabling cross-over themes—namely, sustainability, digital, policy and regulatory enablers, supply chain resilience and sovereignty and future skills needs.

We are now looking for individuals to form the expert working groups for each opportunity workstream. If you are interested in contributing to the groups, To register interest in contributing to the next stage of the Strategy development, please submit an expression of interest:

https://forms.office.com/e/5LXSqANknQ

CONTENTS

1. BACKGROUND, AIMS AND OBJECTIVES

1.1 BACKGROUND

Materials form the physical basis for almost everything we can observe around us and materials technology is fundamental for sustainable, responsible societal development.

Materials innovation includes optimising/adapting properties and expanding applications of existing materials, developing new materials to meet application challenges, and enhancing and developing processes that produce, process, integrate, or use materials. It lies at the heart of economic growth, societal prosperity, and well-being.

"Conventional" commodity materials (metals, concrete and plastics) have undergone substantial developments in recent decades complemented by the evolution of a diverse range of composites, protective coatings, and new alloys. Functional materials, ranging from semiconductors and photovoltaics to biomaterials, have opened major new opportunities for green energy production, a digital environment and the next generation of healthcare.

However, many of these developments are now also challenged by the requirements for sustainability, circularity, resilience, and reduced carbon footprints.

A cohesive approach to materials innovation, including suitable policies and an agile regulatory framework, is required.

1.2 AIMS AND OBJECTIVES

The overall aim is to identify the compelling opportunities that materials innovation offers to solve our societal challenges and, at the same time, to realise new economic activity for the UK.

The strategy is industry-led, identifying industrial and societal challenges that are enabled by materials innovations and opportunities[6].

This materials innovation initiative will build on and expand multidisciplinary, cross-sector and international research collaborations.

The objectives of the Strategy will be to:

- Stimulate innovation, applications and market opportunity in the UK and overseas aligned to societal, environmental and economic goals.
- Ensure optimum involvement of industry and other important stakeholders in establishing UK materials research, development and translation priorities.
- Allow synergies across traditional sectors to be harnessed.
- Enable a strong foundation of capability in the UK, supporting a leading global position and competitiveness for UK technology in the materials domain.
- Create a collaborative materials innovation ecosystem in the UK.
- Better coordinate and (re)allocate the portfolio of investments in materials innovation and identify opportunities for gearing of international and national investment.
- Grow and diversify a skilled UK workforce in materials innovation.
- Create the right social and regulatory context across diverse market sectors to maximise the benefit to the UK from international engagement.
- Address global challenges such as climate change, resource depletion and security through the development of sustainable materials and processes.

[6] https://www.royce.ac.uk/collaborate/innovationstrategy/

- Identify key barriers in the required national infrastructure and opportunities to benefit from agile regulatory frameworks.

The UK needs to focus resources and effort and make decisions about priorities and the strategy will systematically prioritise the needs and opportunities in a consultative and traceable way and provide clear and transparent evidence for policy interventions. To this end, it is essential that:

- Key government departments are engaged with the strategy's development to ensure that it drives government priorities and guides investment.

- The project connects to other national and regional activities which draw on materials innovations to ensure alignment and inclusion of work being done elsewhere.

1.3 NATIONAL MATERIALS INNOVATION STRATEGY PROCESS

The Henry Royce Institute for Advanced Materials (Royce) is leading the materials innovation agenda. Under the guidance of the Materials Innovation Leadership Group (MILG), it is developing a National Materials Innovation Strategy (the strategy).

Following the demand-led, systematic approach outlined in the Framework for a National Materials Innovation Strategy[7], industry stakeholders were invited to identify priority industrial applications which will be enabled by materials innovation. Over 1,200 individual responses were received, primarily through a set of workshops and information requests. The information was correlated against cross-sector impact through the development of several opportunity workstreams broadly categorised into:

- **Cross-over Themes:** national and industrial sector priorities including trends and drivers, market needs and industrial sectors.
- **Core Themes:** key application and process developments to which materials innovation can contribute via value-creation opportunities.

This document outlines the opportunity workstream areas for consideration and exploration, including examples of innovation focus areas which fall into individual workstreams. Ultimately this consists of scoping, definition and appropriate grouping/identification of:

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

Mapping the main elements of supply and value chains for key markets will reinforce, during the strategy process, the identification of value-creation opportunities and key material innovations that generate the most economic, societal and environmental value. Promoting those will offer the greatest future value potential and impact on national priorities.

The key associated gaps, barriers, enablers and interfaces in technology translation and commercialisation will also be considered.

Ultimately, the strategy should provide recommendations for:

[7] https://www.royce.ac.uk/content/uploads/2023/04/Materials-Innovation-Strategy-Framework-Report-April-2023.pdf

1. Funding and other support for the commercialisation and translation of materials capabilities, technologies, and know-how to accelerate the materials commercialisation cycle. New areas of materials research could also be signalled to existing funding bodies.
2. Encouraging the development of investment vehicles – including public-private partnerships – that bridge the gap between basic research and commercialisation and can lead to the development of new materials.
3. Providing incentives for companies to invest in new materials innovation and adoption. This can include tax credits, grants, and other forms of financial support to help offset the costs of research and development. In addition, the Government can provide regulatory incentives to encourage the adoption of new materials in key industries.
4. Supporting education and training programmes in materials science and engineering.
5. Highlighting any substantial gaps in national infrastructure or capability which are a barrier to technology translation due to their absence, particularly concerning proof-of-concept, pilot trials and scale-up infrastructure.
6. Reviewing the impact which any relevant regulatory environment may be having on innovation opportunities.

In the next project phase, experts will identify the current state of R&D and research gaps associated with each opportunity workstream, explore mechanisms for deeper collaboration, and highlight investment opportunities. The common goal is to accelerate specific materials innovations to solve industry-identified challenges. These efforts will also promote capacity building, information sharing, and high-impact R&D and technology development.

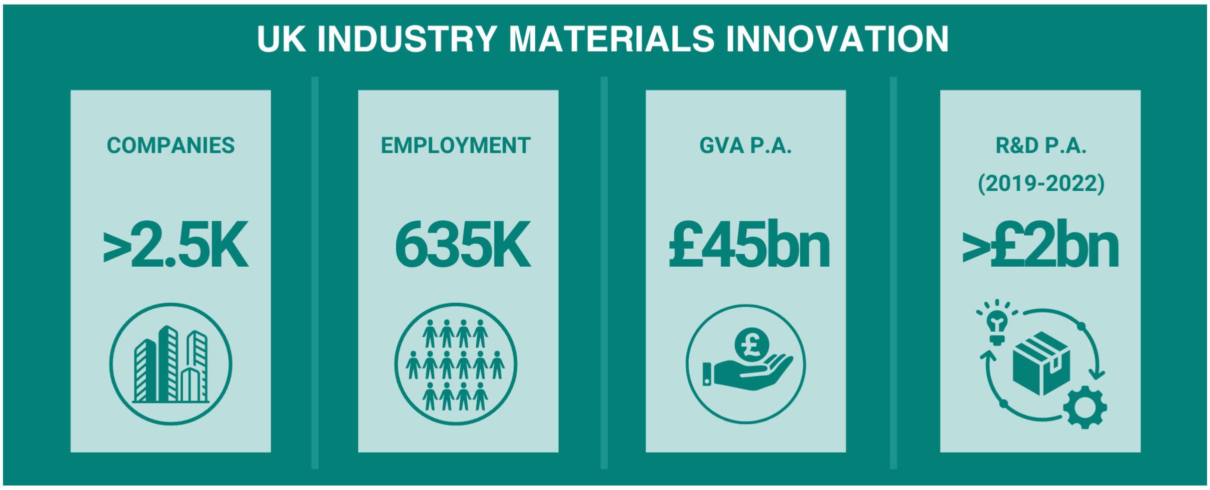
2. ECONOMETRICS STUDY

The strategy will also consider the economic context of materials innovation[8]. The initial focus has been on analysing companies identified as active in materials innovation in the UK using a multi-source identification process. Additionally, the study identified the sectors in which the companies operate (based on Standard Industrial Classification (SIC) codes) and this has provided sectoral analysis.

2.1 MATERIALS INNOVATION SECTOR PROFILE

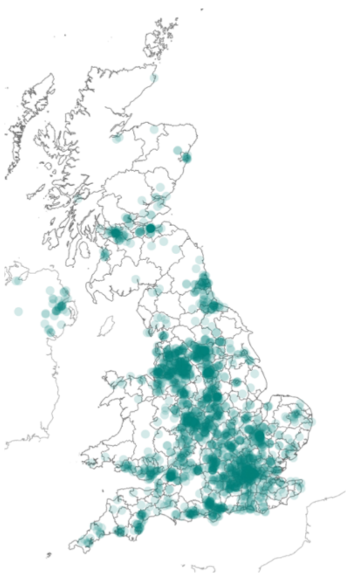
Using over 700 key terms associated with materials and materials innovation and a multi-source identification process, the analysis has identified 2,574 companies in the UK, active in materials innovation.

[8] Carried out by *Perspective Economics*



Combined, they employ more than 635,000 people[9], contribute just under £45 billion p.a. to the UK economy[10] (with a turnover of just under £1 trillion p.a. globally), and have secured more than £2 billion p.a. in external grants and funding for innovation activity within the UK in the last three years[11].

Figure 2.1 – Location of UK companies active in materials innovation



Registered Office postcodes were available for a total of 2,551 companies (98.7%).

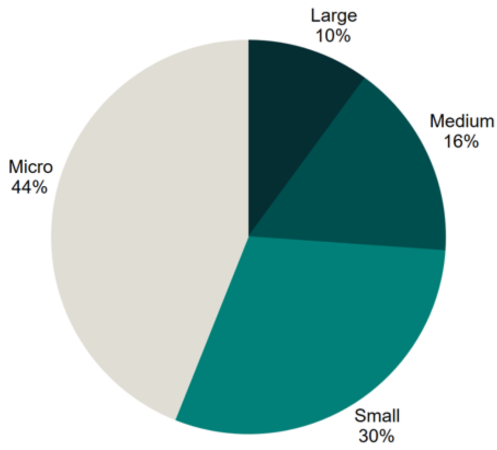
Seventy percent of the companies identified have Registered Offices outside of London and the Southeast[11].

[9] 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.

[10] GVA per employee based on ONS GVA reference tables (Regional Gross Value Added by Industry) and Employment by Industry, calculated at the level of SIC Sections.

[11] Source: Glass.ai, Bureau van Dijk, Tussell, Beauhurst, Sector Experts

Figure 2.2 – Size of UK companies active in materials innovation



Approximately three-quarters of the companies identified are micro or small-sized companies (between 1 and 49 employees). Sixteen percent are medium-sized companies (between 50 and 249 employees) and ten percent are large companies (250 employees or more)[12].

The companies are registered under 217 unique SIC codes[13]. Of the top SIC codes identified, 50% of companies are in manufacturing, and 40% are in R&D.

2.2 SECTOR CLASSIFICATION

The analysis used machine learning techniques to categorise companies into the following sectors:

SECTORS

1. Construction
2. Consumer goods
3. Defence
4. Energy (electricity, oil and gas)
5. Foundation Industries (metals, ceramics, glass, chemicals, paper, cement/concrete)
6. Health & Life Sciences (including biosciences and agriculture)
7. Manufacturing Engineering
8. Professional services
9. Technology
10. Transport (including aerospace, space, automotive, rail, maritime)
11. Other

Sector definitions are given in Appendix 1.

[12] Based on UK employment figures
[13] Just over 1/3 of all UK Standard Industrial Classification (SIC) codes

Most companies identified are categorised as manufacturing engineering companies (Figure 2.3). This definition is broad and includes mechanical, chemical, electrical, and industrial engineering and equipment manufacturers.

While manufacturing engineering firms account for one-third of the materials innovation companies identified, other sectors also contribute substantively to employment and GVA.

Figure 2.3 – Sectoral breakdown of UK companies active in materials innovation[14]

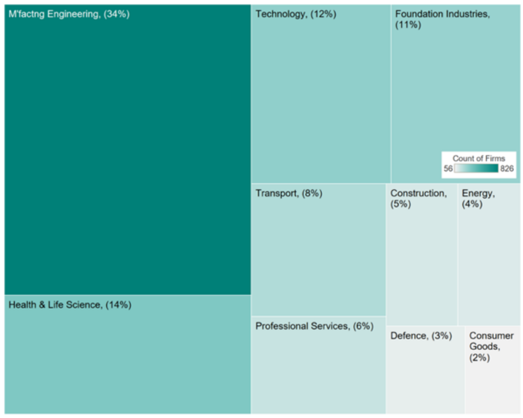


Table 2.1 – Economic metrics by sector[11]

	% Firms	% Estimated Employment	% Estimated GVA	Median Turnover
Construction	5%	6%	5%	£4.3M
Consumer Goods	2%	3%	3%	£4.3M
Defence	3%	19%	18%	£11.0M
Energy	4%	6%	8%	£1.2M
Foundation Industries	11%	7%	8%	£10.4M
Health & Life Science	14%	9%	10%	£2.2M
M'factng Engineering	34%	13%	13%	£4.1M
Professional Services	6%	8%	7%	£1.7M
Technology	12%	15%	17%	£2.2M
Transport	8%	14%	13%	£8.0M

Table 2.1 provides a breakdown of key economic metrics by sector. Defence, technology and transport companies each account for between 13% and 20% of estimated employment and GVA.

Median turnovers are reflective of the composition of each sector. For example, the Defence sector includes a relatively small number of companies, many of which are comparatively large.

Figure 2.4 – Size of companies by sector[11]

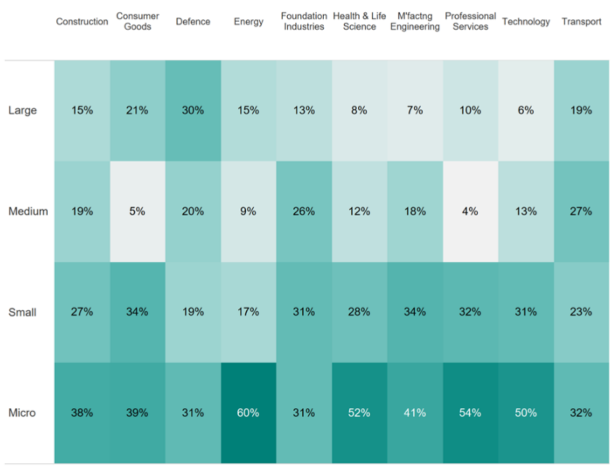


Figure 2.4 provides a breakdown of the size of companies across all sectors. Most sectors are dominated by micro and small companies, following the global trend in company size in many manufacturing sectors.

Future econometrics analysis will focus on the economic scale and opportunity of the priorities emerging from the strategy's development.

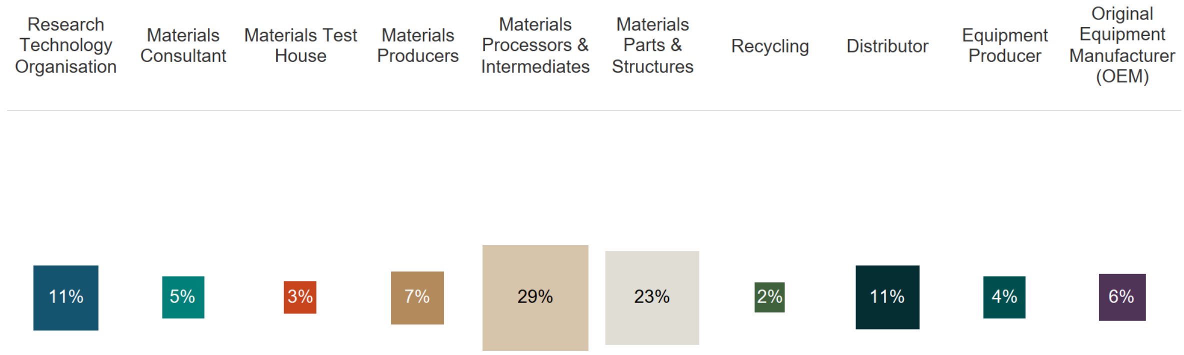
[14] Source: Glass.ai, Perspective Economics

2.3 VALUE CHAIN ANALYSIS

Analysing descriptive information suggests that UK companies active in materials innovation span the entire value chain. However, over half of the companies identified are involved in materials processing, the production of intermediaries, or the production of materials parts and structures (Figure 2.5). 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.

Value Chain definitions are provided in Appendix 1.

Figure 2.5 – Value chain analysis of companies active in materials innovation[15]



OEMs account for 41% of UK employment, and materials processors and parts producers account for 35%. OEMs' value added is estimated to be 43% of total GVA (~£20bn), while the value added of materials processors and intermediaries and materials parts and structures producers is 18% of total GVA.

Figure 2.6 – Company size by value chain segment

	RTO	Materials Consultant	Materials Test House	Materials Producers	Processors & Intermediate.	Materials Parts & Structures	Recycling	Distributor	Equipment Producer	OEM
Large	4%	11%	6%	17%	7%	12%		5%	5%	41%
Medium	6%	6%	9%	18%	18%	22%	16%	11%	16%	20%
Small	26%	19%	32%	23%	34%	28%	28%	36%	39%	22%
Micro	64%	64%	54%	42%	41%	37%	57%	48%	40%	17%

An analysis of company size by value chain segment (Figure 2.6) 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, the materials innovation industrial landscape is dominated by small and micro companies across most of the value chain.

[15] Source: Perspective Economics

Analysis of company numbers by both sector and value chain segment (Figure 2.7) suggests that, for example, 68% of defence companies are either OEMs or producers of parts and structures, 59% of foundation industries companies are either materials producers or processors / intermediates, more than one third of health and life sciences companies are RTOs and just under two thirds of professional services companies are either RTOs, consultants or test houses.

Figure 2.7 – Company size by sector and value chain classification

	RTO	Materials Consultant	Materials Test House	Materials Producers	Materials Processors & Intermediat.	Materials Parts & Structures	Distributor	Recycling	Equipment Producer	OEM
Construction	3%	2%	1%	3%	33%	43%	11%	3%		1%
Consumer Goods	4%			5%	48%	13%	25%	5%		
Defence	3%	4%	3%	1%	15%	38%	5%		1%	30%
Energy	16%	4%	3%	5%	26%	27%	3%	8%		9%
Foundation Industries	5%	0%		28%	31%	8%	22%	5%	1%	1%
Health & Life Science	35%	3%	2%	12%	20%	14%	7%		4%	4%
Manufacturing Engineering	4%	1%	3%	4%	39%	24%	11%	0%	8%	5%
Other Sector	13%	1%	5%	6%	28%	13%	14%	14%	5%	1%
Professional Services	11%	47%	7%	3%	12%	10%	6%	3%		1%
Technology	18%	4%	2%	5%	25%	17%	11%	1%	10%	7%
Transport	5%	1%	2%	1%	16%	57%	3%	0%	1%	13%

3. INDUSTRY ENGAGEMENT

The strategy is being developed using a demand-led approach. Therefore, this project stage has been designed to assess industry-identified high-impact applications to which materials innovation can be applied (i.e., market pull). It has identified the high-level key innovations required (which have a materials dimension) and cross-mapped these against national priorities, enabling technologies, and sectors. The output identifies opportunity workstreams that will underpin the strategy going forward.

To facilitate this, industry clusters were brought together in a series of online workshops, one-to-one interviews and feedback opportunities under the following groupings:

INDUSTRY CLUSTER WORKSHOPS

1. Built Environment/Building & Construction
2. Chemicals
3. Electronics, Solar & PV
4. Energy
5. Equipment & Machinery
6. Foundation Industries
7. Health, Food and Agriculture
8. Packaging, Fashion & Consumables
9. Transport

Representatives from over 350 companies/organisations across multiple sectors participated. They contributed over 1,200 individual insights regarding industry priority topics where materials innovation is/could be an enabler. The workshops also identified key enabling technology areas in which the UK has existing expertise and/or that have the potential for substantial economic growth.

The outputs from the industry cluster consultations are summarised in the following sections.

4. CORE THEMES (CT) & OPPORTUNITY WORKSTREAMS (OW)

To allow efficient grouping, the workshop outputs have been reviewed and sorted into core themes that capture the key priorities to emerge from the consultations. Core themes are those where materials applications/properties have been highlighted across multiple industries/sectors and where synergistic opportunities exist. For example, structural materials where there is a large grouping of cross-sector opportunities. Further segmentation of core themes has identified opportunity workstreams that will take deeper dives into materials innovations that will deliver solutions for the industry.

The opportunity workstreams will have a crucial role in exploring key areas for innovation and progress more focussed, individual sub-strategies that will form the basis of the overarching National Materials Innovation Strategy. The core themes are:

CORE THEMES

1. Energy materials
2. Soft materials
3. Biocompatible materials (health, life sciences & agriculture)
4. Structural Materials
5. Materials for surface enhancement & protection
6. Materials for electronics, telecommunications, sensing & computing technologies

Under each core theme, the overarching challenge, opportunities and priorities have been outlined. Each section table identifies the opportunity workstreams (based on industry identified challenges) and example focus areas for consideration by each workstream.

The core theme tables are followed by commentary to provide context for each opportunity workstream.

4.1 CORE THEME 1: ENERGY MATERIALS (Table 4.1)

THE CHALLENGE

The efficient and sustainable generation, storage, transmission, and use of energy is arguably society's key challenge today. Materials design and discovery are cross-cutting needs for the entire energy technology portfolio. Accelerating the exploration, discovery, and integration of "clean energy" materials will expand the opportunities to speed up our transition to a low-carbon economy. Energy materials innovation will be key to achieving the United Nations' Sustainable Development Goal 7 (ensuring access to affordable, reliable, sustainable, and modern energy for all) and supporting industry to become more sustainable. Industry feedback indicates that their priorities for energy materials focus on energy conversion, storage and efficiency.

THE OPPORTUNITY

The UK has clear strengths in this broad area and could not only lead in the global energy sector but also underscore the national commitment to environmental sustainability while generating widespread economic benefits for the UK. Innovation in this domain will benefit a wide range of energy sectors and applications and can also transform other industries such as transport, construction and manufacturing.

New energy materials have specific application areas, including advanced batteries and solar cells, low-energy semiconductors, thermal storage, energy-harvesting coatings for various applications, electrolyser materials for hydrogen production, fuel cell materials for power generation (for example, for shipping) and catalysts for converting and capturing carbon dioxide (CO_2) and hydrogen production.

THE PRIORITIES

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

Table 4.1 - CORE THEME 1: ENERGY MATERIALS

OPPORTUNITY WORKSTREAM	Example Innovation Focus Areas
OW1 Materials for electrochemical energy storage - batteries for grid-scale to domestic applications	• H_2O-based electrochemistry • Optimised electrolytes (including gel electrolytes) • Non-toxic/chemically safer electrolytes (such as organosilicon liquids) • High conductivity-low porosity bipolar plates • Materials to create solid-state batteries for high-capacity applications with fast charging times • Printable solid-state batteries using existing infrastructure • Thermal management: interfaces, cooling fillers • Hybrid systems for transport (batteries/hydrogen)

OW2 Materials for electrochemical energy generation – fuel cells, electrolysers, super-capacitors	• High-efficiency fuel cell and electrolyser anion and proton exchange membranes (for example, high proton conductivity at high temperatures and improved chemical stability) • Improved electrode and electrolyte materials for high-efficiency solid oxide electrolysers for long life and low-cost • New materials for high-efficiency fuel cells with new fuels like ammonia • Next-generation materials robust to environmental poisons for lowering overall systems cost • Durable membrane electrode assemblies • H_2O-free proton-conducting membranes (for better performance in low humidity conditions) • Nano-engineered materials for water management within fuel cells • Nano-engineered high-conductivity and high-capacitance materials • Low-temperature, higher ionic conductivity electrolytes • Stable (thermally and mechanically robust) solid oxide and polymer electrolytes • Improved cooling mechanisms (for example cooling loop nanofluids) • Lower costs and controllable microstructures for supercapacitor thermal management (for example, cellulose nanofibril materials) • Low-cost, more sustainable fuel cell and electrolyser catalysts, including platinum alternatives and/or catalyst optimisation (for example, nano-engineering techniques that reduce iridium usage without compromising performance). • Higher-efficiency MEC electrodes • Application of big data methods to predict system degradation
OW3 Materials for innovative heat exchange, storage applications and waste heat recovery	• Phase transition materials for heat (energy) storage • High thermal capacity storage materials • Thermoelectric conversion devices • Higher-efficiency caloric energy conversion devices • Bi-polymer systems for waste heat recovery
OW4 Materials for energy-harvesting including photovoltaic and piezoelectric	• Lightweighting Solar PV for aerospace/space applications • Structural solar PV for construction • PV integrated glazing • Continuously produced PV systems on steel/metal substrates • PV device interconnects, substrates, thermal management • Solar cell transparency • Improved grid inverter efficiency • Organic photovoltaic materials • Piezoelectric synthetic materials for integration into building components
OW5 Materials for high-voltage electrical transmission	• Low-resistance conductors for energy networks (for example, high-temperature ceramic superconductors • High electrical conduction coils & wiring • Thermal management: interfaces, cooling fillers • High-voltage switching gear • High-performance dielectrics • Non-greenhouse gas circuit breakers (SF6 alternatives)
OW6 Recyclable, low-Rare Earth Elements (REE) magnetic materials	• Recyclable permanent magnets • Reducing REE content in magnetic materials

(also relates to core theme 5.6 – electronics)	
OW7 Advanced Nuclear fuels (Structural materials for Nuclear – see OW16)	• Advanced fuels (for example, coated particle fuel development and manufacture (such as TRISO) and HALEU fuel enrichment

OW1 Materials for electrochemical energy storage - batteries for grid-scale to domestic applications

High-performance materials for use in batteries are a clear focus for continued innovation as global demand for energy storage continues to grow. The overarching priorities include increasing energy density, improving safety, and reducing reliance on toxic or scarce raw materials without increasing cost.

Redox-flow batteries

Advantages of redox-flow battery technology include single-cell voltage, power density, long cycle life, and low capital costs. A priority is low-cost redox flow batteries combining optimized cell architecture with low-cost chemistry based on non-toxic, chemically safer and abundant materials. Specific applications also include grid storage (where weight is not a consideration).

Solid-State Batteries (SSBs)

Conventional batteries, such as lithium-ion batteries usually have liquid electrolytes. However, they provide limited energy densities, pose safety risks and have relatively long charging times. SSBs are more energy-dense, safer and can support more rapid charging. Using solid metals, polymers, or glass as electrodes provides higher mechanical and thermal stability and cyclability. Materials such as graphene offer higher electrical conductivity and act like supercapacitors. Solid-state electrolytes (SSEs) include those based on sulphides, garnet-structure oxides and nasicon-type phosphates.

Solid-state batteries are also amenable to printing techniques, which opens up applications ranging from miniature sensors to wearable electronics. A priority is SSB materials that enable the printing of SSBs using roll-to-roll printing techniques common in paper and textile industries, thereby using existing technology and infrastructure.

Carbon Batteries

Batteries that use carbon as one or both electrodes last longer. They also enable integrated batteries, embedded or laminated into the device or chassis, further reducing weight. Moreover, using carbon makes battery manufacturing more sustainable (compared to lithium or cobalt). This technology could also enable high energy density applications for micro-mobility, drones, portable energy, and energy management.

OW2 Materials for electrochemical energy generation: fuel Cells, electrolysers and super-capacitors

Fuel Cells

Fuel Cells are a strategic net-zero technology. They offer several benefits over internal combustion engines (ICEs), such as no toxic combustion products (for example, carbon monoxide or nitrogen oxides), good efficiencies and lower greenhouse gas (GHG) emissions. Further, due to having no moving parts, they operate almost silently, and they have the potential for integration with other energy technologies, leading to improved efficiencies. As an energy conversion technology, fuel cells feature certain advantages compared to wind and photovoltaic technologies (their capacity factor is about 95%, while those of wind and solar systems are 17.5% and 25.8%, respectively). In addition, they have relatively short payback periods.

Proton Exchange Membrane Fuel Cell (PEMFC), Solid Oxide Fuel Cell (SOFC), Direct Methanol Fuel Cell (DMFC), Molten-Carbonate Fuel Cell (MCFC), Phosphoric Acid Fuel Cell (PAFC) and Alkaline Fuel Cell (AFC) are the common types of fuel cells. The efficiency of the fuel cells is directly related to different factors such as the type of fuel and electrode, and the operating conditions (for example, working temperature can massively influence fuel cell efficiency).

Applications include vehicles (including heavy-duty), stationary power generation systems, aerospace systems, remote off-grid supply, military operations, drones, Internet of Things (IoT) systems, portable devices, space equipment, and maritime/shipping (which is a huge UK opportunity).

PEMFCs and SOFCs dominate the fuel cell market. They are widely usable in stationary and mobile applications and range from small devices (micro-cogeneration modules) to large power and propulsion units.

While PEMFCs have had the greatest share of the total fuel cell capacity installed, there has been a major increase in the practical use of SOFC units, which operate at high temperatures and are used with various fuels (including natural gas and biogas, reducing the dependency on pure hydrogen).

However, problems such as the degradation of membrane electrode assemblies (MEAs), a critical component in fuel cells, hinder their wide-scale adoption and integration. A priority is the development of durable MEAs that withstand higher temperatures and chemical degradation combined with thermal stability and proton conductivity, enhancing their overall lifespan and efficiency. This could include metal separators and composite membranes.

Additionally, water and thermal management within fuel cell stacks requires improvement. A considerable part of the fuel energy is transformed into heat, and removing this heat is essential for their smooth operation. The development of durable ceramic materials and electrode designs resilient to thermal (and mechanical stresses) underpins progress in SOFC technology. Uneven distribution of water produced during fuel cell operation, causes flooding and dry spots reducing efficient operation. Nanomaterials could provide water management solutions within fuel cells, actively channelling and distributing water. Moreover, nano-engineered materials with higher thermal conductivities can enhance heat dissipation, maintaining a stable operating temperature. Nanotechnology-based electrode design further improves the distribution of reactant gases, increasing the surface area available for reactions.

A focus should also be on improving the efficiency and durability of fuel cells, making them more suitable for various environments. These innovations would expand the applications of alternative fuel cells such as portable power sources, stationary power generation, and auxiliary power units in transportation (especially heavy-duty vehicles and maritime transport).
Another significant problem related to sustainability and sustainable resource use is the dependence on expensive and scarce precious metal catalysts such as platinum or palladium.

Microbial fuel cells (MFCs) break down organic waste to generate electricity. They convert a wide range of organic materials, including those found in wastewater, into electrical energy, thereby enhancing the efficiency of waste-to-energy (WTE) conversion.

Priorities are innovations in electrode materials and designs within MFCs to improve the interaction between the microorganisms and the electrodes, leading to higher electricity generation.
Applications include waste treatment and bioremediation. The technology also promotes a circular economy by functionalizing wastewater as a feedstock for fuel production.

Electrolysers

Electrolysers employ electrical energy to electrochemically decompose a substance, for example, water into oxygen and hydrogen. Where the energy is supplied from renewable sources, "green hydrogen" can be produced. In this context, electrolysers are effectively energy conversion devices that store electricity in the form of an energetic molecule (hydrogen). It follows that the performance of electrolysers directly affects the efficiency of energy storage and is, therefore, of high significance.

Electrolysers' operating parameters, including temperature and pressure, vary from one type to another. Proton exchange membrane (PEM) and Alkaline Water (AW) electrolysers operate at moderate temperatures, while solid oxide electrolysis cells (SOECs) operate at high temperatures.

Feeds and catalysts also vary across the different electrolyser types. PEM systems use expensive and rare platinum group catalysts (platinum, iridium and ruthenium) while electrodes in anion exchange membrane (AEM) electrolysis operate in a neutral or slightly alkaline environment, which allows non-noble, low-cost catalysts to be used. Their operating pH is also safer and easier to manage compared to AWEs.

SOECs are maturing fast, with huge customer interest. They have the inherent advantage of high efficiency and synergies for combining with industrial heat for ammonia, e-chemicals or steel production. The key materials challenges for this technology are durability (long life) and being inherently robust to environmental poisons. Sustainability and supply chain management of rare earth materials that are often used in this technology is also important.

In contrast, AEM electrolysers are at a relatively early stage of development. The major technical challenge facing a consumer-level AEM electrolyser is the low durability of the membrane, resulting in a short device lifetime. To overcome the obstacles to large-scale usage of AEM electrolysers, increasing ionic conductivity and durability of the membranes is essential. The systems must also tolerate the presence of oxygen, high pH, and temperatures exceeding 60°C. This will require the development of catalysts, new membranes and Membrane Electrode Assemblies (MEAs) to deliver optimised electrolysis cell performance that matches that of PEM systems.

Microbial electrolysis cell (MEC) technology can produce hydrogen using organic matter, including renewable biomass and wastewater. It is closely related to microbial fuel cells (MFCs), but the operational principle is the reverse of MFCs.

Given the importance of hydrogen in a net zero scenario, priority in developing new hydrogen-related materials is high. This especially relates to finding alternative or improved performance catalysts, membranes and electrodes and optimised MEAs.

Supercapacitors

Supercapacitors are some of the most versatile energy devices, widely used for delivering electrical energy quickly and in applications that demand a long shelf life. They utilize electrode materials with high surface area and thin dielectric materials to achieve greater capacitance. Supercapacitors can be employed independently or in a combined system with batteries to enhance the overall performance. Importantly, supercapacitors are usable over a wide range of temperatures. In contrast with batteries, the electrode materials employed in a supercapacitor do not undergo phase change or chemical reactions during charging/discharging cycles. Consequently, supercapacitors exhibit a very high cyclability and life span because of their inherent reversible mode of operation. As with fuel cells and electrolysers, thermal management in supercapacitors is a major challenge.

The main technical challenge is increasing the energy density of supercapacitors (to at least match that of batteries). This will require the development of new electrolyte and electrode-active materials with higher corresponding electrochemical performance, such as high surface area materials combined with organic electrolytes which can endure a larger voltage window.

Applications include systems that require bridging power interruptions (such as uninterruptable power supplies), smoothing electrical flow, pulse applications (such as pulsed lasers), telemetry, and peak power assistance. They are also used as energy harvesters for solar cells, wind turbines and wave power.

OW3 Materials for Innovative heat exchange, storage applications and waste heat recovery

Thermoelectric materials convert thermal energy and electrical energy into each other. They are safe, energy-saving, lightweight, accurate, reliable and environmentally sustainable. Opportunities include the development of inorganic thermoelectric materials such as thermoelectric glass-ceramics, organic thermoelectric nanocomposites (particularly displaying mechanical flexibility and low or no chemical toxicity) and hybrid organic-inorganic thermoelectric materials.

This is a significant emerging area with the potential for significant materials innovation.

Thermoelectric devices generate power in a range of applications, including solar-thermal systems, implantable and/or wearable devices, transport, and the Internet of Things.

Caloric materials are solid-state refrigerant alternatives that show reversible significant thermal changes when an external driving field is applied. Electrocarolics, magnetocalorics, barocalorics and elastocalorics are driven by electric fields, magnetic fields, pressure and stress respectively.

There are challenges across each caloric material category, including energy recovery, efficient delivery of the driving field, and durability (including lifecycles), whilst others are specific to each category. For example, developing 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.

There is great potential for new environmentally friendly cooling applications in a wide range of markets, from microelectronics to macro cooling devices.

Heat transfer and storage technologies are critical to the manufacturing and process industries. In a context where increased energy generation efficiency has become a priority, high-efficiency heat exchangers and phase change materials for thermal energy storage represent a significant opportunity across several thermal energy storage applications. Solutions may include inorganic systems (salt, salt hydrates, and metal alloys), organic compounds (paraffins and fatty acids, for example), and polymeric materials (polyethylene glycol, for example).

Industrial waste heat recovery is also a significant opportunity to improve efficiency and reduce energy bills. Lower maintenance costs and improved equipment productivity can also result, as energy-using equipment can be operated less intensely. As much as 80% of the energy lost as heat in manufacturing processes can be cost-effectively recovered. A key innovation in this area is bi-polymer systems for waste heat recovery.

OW4 Materials for energy-harvesting, including photovoltaic and piezoelectric

Solar Photovoltaic (PV) technology is the most widely adopted method that converts energy from sunlight into electricity and is crucial to the delivery of net zero. The energy generated depends on the size and number of panels and their efficiency. Light is directly converted to electricity with this method. Photons from sunlight strike and ionize the semiconductor material of solar panels, which in turn break atomic bonds of electrons, and they vibrate freely. Semiconductor structure forces electrons to move in one direction, thus creating an electric current. However, only a certain percentage of light is absorbed, and the rest is reflected.

Monocrystalline or polycrystalline structures of panels are commonly used along with inverters and battery banks to provide energy flow after sunset. Other types of photovoltaic technology include integrated photovoltaic systems (concentrating photovoltaic arrays) and thin film photovoltaic.

Recent advances in solar PV cells have largely focused on efficiency, cost reduction, and improved reliability. But at the multi-TW production scale, new challenges, such as materials availability, supply chain, and embedded energy and CO_2, have had consequences for the industry.

Some of the most exciting areas for innovation, in addition to increasing efficiency, include reducing the use of scarce materials, developing circular technologies, and obtaining lower-cost dual-junction devices.

Another key direction for future research is the coupling of solar cells, where two or more materials create low-cost tandem devices. New, efficient materials are crucial to support the rapid expansion of solar PV needed to meet demand.

Organic photovoltaic (OPV) is a rapidly emerging technology that uses flexible, lightweight, and inexpensive polymer-based solar cells. A key focus is on improving cell efficiency, expanding performance lifetime, and developing the potential for roll-to-roll manufacturing.

OPV's great strength lies in the diversity of organic materials that can be designed and synthesized for the absorber, acceptor, and interfaces, but further innovations are needed in scaling efficiency for large-area modules based on materials with improved energy-level alignment, spectral response, and transport properties.

The building-integrated PV market is a potentially significant market for OPV because absorbers are available in any colour, and efficient, transparent devices can be made.

Piezoelectric synthetic materials transform mechanical strain and vibration energy into electrical energy. This property allows renewable and sustainable energy to be implemented through power harvesting and self-sustained smart sensing in buildings.

The successful application of piezoelectric materials for sustainable building development will rely on a better understanding of the mechanism of the piezoelectric properties of various building components and how they can be integrated into sustainable buildings.

OW5 Materials for high-voltage electrical transmission

High-voltage transmission (HVT) lines are part of the critical national energy infrastructure, moving the bulk of electrical energy from a generating site, such as a power plant, to an electrical substation.

A priority is improving the transmission network's efficiency by increasing the load and building systems that are easier to install, manage, and maintain. This involves innovations in almost every component of transmission systems (from coils, wiring, and insulation to switching gear and circuit breakers). A particular materials challenge is developing efficient insulating materials suitable for HVT.

OW6 Recyclable, lower Rare Earth Elements (REE) magnetic materials

Modern permanent magnets have revolutionized many industries due to their high magnetic strength and stability. They are directly linked and critical to the energy transition due to their applications in electric motors and wind power and are indispensable for today’s technology, including transportation, medical equipment, consumer electronics and defence applications. However, with less than 1% of magnets being recycled[16], the production and disposal of modern permanent magnets have significant environmental impacts that must be addressed.

When modern permanent magnets reach the end of their useful life, they are often disposed of in landfills or incinerated. This can lead to the leaching of toxic metals into the environment or the release of harmful gases into the atmosphere. To minimize these impacts, it is important to reduce our reliance on Rare Earth Elements (REE) by developing alternative materials or improving materials design and recycling technologies to enable the harvesting of REE. Moreover, Life Cycle Assessment studies (LCAs) exist for neodymium magnets produced from virgin raw materials and for magnets produced using a magnet-to-magnet recycling process. The results show that the recycling process has significantly less environmental impact than production from raw materials[17].

In addition, REE across multiple applications have a substantial supply chain risk and a high commercial value. Thus, with permanent magnets containing over 30 wt% REE, the recycling of end-of-life products is a promising route to improve supply chain resilience and create value through a circular economy.

The need for recyclable, easier to dismantle magnets with lower use of REE and/or the ability to harvest REE, has been highlighted across multiple sectors, from energy and electronics to wastewater treatment. The materials challenge is creating magnets that are easily dismantled and a more efficient process of recycling these materials on a large scale, while focusing on the retention of the magnets' original strength.

OW7 Advanced Nuclear fuels

Nuclear power provides 10% of the world's total electricity and one quarter of its low-carbon supply[18]. With its low carbon footprint and reliable energy generation, nuclear power will be a key player in the clean energy transition, and innovations in the nuclear industry will be critical for harnessing its full potential toward net zero goals.

Priorities relate to small modular reactors, advanced microreactors, and defence applications. Materials innovation opportunities here include developing and manufacturing accident-tolerant fuel (for example, Tristructural isotropic fuel - TRISO), enriching high-assay low-enriched uranium (HALEU) fuel, and developing advanced moderator materials.

4.2 CORE THEME 2: SOFT MATERIALS (Table 4.2)

THE CHALLENGE

Soft materials are generically classed here as materials that can be easily deformed by stresses at ambient temperature. Soft materials include liquids, polymers, foams, gels, colloids, and granular materials. Soft materials are widely used across most sectors. Applications range from drug delivery and the development of new insulation and textiles to displays, formulations, and packaging.

In particular, plastics are easy and inexpensive to make with a vast range of applications. But plastic waste has become a global challenge. Plastic can take hundreds of thousands of years to decompose. Over the last 60 years, 8.3 billion tons of plastic have been produced around the world, but only 9.5% of it has been recycled. The remaining 7.5 billion tons is waste. Furthermore, most plastic is for single-use items - meaning its usefulness is very short while its lifespan is very long.

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[16] Fastmarkets Insights 04 April 2024: Rare earth magnet recycling technology.
[17] EU Innovation Hub
[18] World Energy Outlook 2022 published by the International Energy Agency (IEA)

Per- and polyfluoroalkyl substances (PFAS) are also widely used, long-lasting chemicals whose components break down very slowly over time. Thousands of PFAS chemicals are found in many different consumer, commercial, and industrial products (from mobile phones, waterproof fabrics, cosmetics and medical devices to wind turbines and solar panels). Moreover, many products that do not contain PFAS are produced using machines or industrial processes that rely on these substances. The US has developed a PFAS Strategic Roadmap (including restrictions on certain PFAS chemicals)[19] whilst the EU is proposing widespread restrictions, aiming to significantly limit the manufacturing, use, and import of PFAS across a wide range of sectors[20].

THE OPPORTUNITY

Today, the production of plastic far outpaces our ability to manage it when it becomes waste, and the current amounts are expected to triple by 2050. A global opportunity exists to develop truly sustainable soft materials that retain or enhance existing properties and systems whereby they can be reused or recycled. This sits alongside lower volume, more niche opportunities, including application to high-performance machinery such as haptics in robotics.

With imminent bans on some widely used PFAS, an opportunity exists to find alternatives with similar properties that can be used across a wide range of applications.

Policy drivers and sustainability infrastructure will be important in applying innovations to the high-volume market of these opportunity areas.

THE PRIORITIES

A major priority for industry (and society) is developing and manufacturing sustainable soft materials and plastics, ranging from packaging and elastomers to textiles. The UK has a global opportunity to lead in soft materials circularity.

Finding alternatives to PFAS has been highlighted across all industry sectors as a major and urgent priority.

TABLE 4.2 - CORE THEME 2: SOFT MATERIALS (Sustainable polymers, elastomers and textiles across multiple sectors)	
OPPORTUNITY WORKSTREAM	**Example Innovation Focus Areas**
OW8 Materials for sustainable packaging	• Designing circularity in polymers/elastomers • Circularity in paper and hybrid products (including ability to recycle paper/hybrid products more effectively) • Biodegradable packaging for high-value products • Enzymes for producing and recycling soft materials • Active packaging to increase perishable product shelf life
OW9 Materials for sustainable elastomers for high-performance applications	• Bio-inspired elastomers • Liquid-silicone rubber • Heavy-duty, recyclable tyres • Recyclable conveyor belts • Elastomers for extreme environments (for example, cryogenic) • Expanding elastomer applications (for example, suitable for 3D printing)
OW10 Materials for sustainable textiles	• Vegan products • Stain-resistant textiles • Biodegradable

[19] EPA PFAS Strategic Roadmap
[20] European Chemicals Agency

	• Phase changing textiles • High-performance – vapour control, high-strength • New fibres with embedded performance (reducing use of coatings)
OW11 Soft materials for robotics & haptics	• Advancing dielectric elastomers for commercial applications • Ferrofluid and electrorheological fluid-based actuators • Stimuli-responsive organic materials
OW12 Materials to replace per- and polyfluoroalkyl substances (PFASs)	• Material substitutes to PFAS that offer equivalent performance without the associated risks • Policy framework to mandate the transparency of product composition (for example, providing PFAS-free labels on all relevant goods)

OW8 Materials for sustainable packaging

Sustainable packaging addresses the environmental impact of traditional packaging materials, reducing plastic pollution and promoting a circular economy.

As countries impose bans on single-use plastics, companies are actively adopting recyclable materials, facilitating the integration of circular packaging methods. An example is the utilization of post-consumer resins (PCR), which are packaging materials derived from recycled consumer waste and can themselves be recycled.

Furthermore, the industry is moving away from complex multi-layer packaging systems and creating mono-material packaging that is easily recyclable. The global recyclable packaging market is expected to reach USD 31.81 bn in 2024, at a CAGR of 5.8%[21].

Innovations in sustainable packaging continue to include streams related to biodegradable materials such as plant-based plastics, recycled materials, and compostable packaging. The global biodegradable packaging market is expected to reach USD 166.2 bn by 2032 at a CAGR of 5.45% from 2024 to 2032[13]. Opportunities include developing mass-production products that can be easily recycled using existing technologies to niche biodegradable packaging for specific, high-value markets. The industry also requires improved barrier recycling, particularly in the recycling of glass drink bottles where current barriers on the inside of glass bottles can render them unrecyclable, creating a significant issue in packaging circularity.

Active packaging is also an influential trend, extending the shelf life of products in the food, beverage, and pharmaceutical sectors. For example, modified atmospheric packaging employs oxygen or ethylene absorbers and moisture regulators to maintain food freshness. Other innovative forms of active packaging introduce natural antimicrobial agents, thwarting bacterial growth and ensuring product safety or integrated nanotechnology to assess and record food freshness.

OW9 Materials for sustainable elastomers for high-performance applications

Elastomer is used in a vast number of products, from tyres on vehicles and conveyor belts to disposable surgical gloves and medical devices. The industry encompasses approximately 181K+ organizations globally and is projected to reach a value of USD51.21 bn by 2027, exhibiting a CAGR of 5.3%[13].

Properties such as heat, abrasion and weather resistance, insulation, and flexibility make elastomers highly useful and valuable in various end-use products with applications across many industry sectors, including construction, manufacturing, transport and engineering. Products include tyres, adhesives,

[21] Source: Market Research Future – Market Insights

hoses, gaskets, seals, transmission belts, non-flat belts, elevator cables, surgical supplies, medical devices, textiles and consumer goods.

The volume of waste produced globally (exceeding 17 million tonnes per annum[22]) makes it difficult to manage as accumulated waste, especially in the form of tyres and conveyor belts, which do not easily break down and can pose a significant fire risk. Recycling elastomers prevents this problem and can produce new materials with desirable properties that virgin rubbers lack. Increasingly, both manufacturers and legislators are realising that recycling is essential for environmental sustainability and can improve the cost of manufacturing. A major challenge for the industry is finding sustainable end-of-life solutions and new market opportunities.

Innovation opportunities include harnessing bio-based materials, developing liquid silicone rubber (LSR) and nanocomposites, advancing tyre and conveyor belt recycling, using 3D printing and other technologies to expand elastomer applications and increasing elastomer properties for use in more diverse environmental conditions. Elastomers that perform at extreme temperatures are also a priority, especially for cryogenic seal applications. Innovation must also enhance product performance and sustainability while redefining the industry's environmental footprint.

OW10 Materials for sustainable textiles

The textile industry increasingly focuses on eco-friendly practices, with sectors from fashion to transport demanding sustainable, high-performance products, reflecting pressure from governments and consumers alike.

Technological innovations such as smart textiles and phase change materials (PCM) are revolutionizing the industry, and AI is playing a significant role in streamlining textile design and manufacturing processes. There is also a growing emphasis on transparency and traceability across the textile supply chain.

From automotive to fashion, sectors are demanding vegan, biodegradable, high-performance textiles that are compatible with new surface coatings to promote longevity and performance characteristics and, crucially, are sustainable. Opportunities include the development of new fibres that reduce the need for post-manufacture processing (such as dying or waterproofing) and nano-technology integrated textiles to promote self-cleaning and other performance characteristics.

OW11 Soft materials for robotics & haptics

The goal of haptics is to create technologies that manipulate the sense of touch. Current haptic systems use micromotors or other miniaturized mechanical devices (for example, for vibration and pneumatic actuation) and are mostly far from reproducing real materials' feelings. Reproducing the feel of everyday objects requires molecular control over the properties of materials and, ultimately, the design of materials which can change these properties in real-time. Stimuli-responsive organic materials, such as polymers and composites, can change their oxidation state, conductivity, shape, and rheological properties and thus present opportunities for future haptic technologies.

Bringing a sense of touch to virtual reality experiences and robotics could impact everything from physical rehabilitation to online shopping. Reducing the complexity (and therefore cost) and size of rehabilitation robots for home use is also a market opportunity.

OW12 Materials to replace per- and polyfluoroalkyl substances (PFASs)

PFASs are or ultimately transform into, persistent substances, leading to irreversible environmental exposure and accumulation. Due to their water solubility and mobility, contamination of surface,

[22] European Tyre and Rubber Manufacturing Association

ground- and drinking water and soil has occurred globally and will continue. It has proven very difficult and extremely costly to remove PFASs when released into the environment. In addition, some PFASs have been documented as toxic and/or bioaccumulative substances, both with respect to human health as well as the environment.

Industry, across all manufacturing sectors, urgently requires the development of material substitutes to PFASs that offer equivalent performance without the associated risks. Without innovation leading to alternative materials, the UK's ability to export to the EU will be seriously compromised and risk a large range of products being banned from the market. Alternatively, this can be seen as a huge opportunity for the UK to develop new materials and formulations to tackle this global problem.

However, there is currently no dedicated programme or initiative to address the monumental materials challenge which will impact all our industry sectors.

In addition, a broader policy issue will be to mandate the transparency of product composition by providing PFAS-free labels on all relevant goods. This will become essential when the EU PFASs ban comes into effect.

4.3 CORE THEME 3: BIOCOMPATIBLE MATERIALS (Table 4.3)

THE CHALLENGE

Biocompatible materials are natural or synthetic materials that can substitute a part of a living system (for example, synthetic organs) or function in close contact with living tissue (including materials for wound care and bioelectronic implants). They are designed to interface with biologically active systems for evaluating, treating, augmenting, or replacing any body tissue, organ, or function. Biocompatible materials cover several classes of traditional materials and can be used singly or in combination with each other to form most commercially available medical devices and implants.

Human and animal health are major societal priorities, and innovations in biocompatible materials offer significant advantages in therapeutics, regenerative medicine, and nutrition.

THE OPPORTUNITY

The medical and healthcare industry seeks materials that integrate efficiently with the human body while ensuring optimal performance. The widespread recognition of biomimetic and bio-responsive materials arises from the need to enhance the longevity of medical devices and regenerate injured tissues. Utilizing biomaterials in medical devices can enhance patient comfort, extend implant longevity, and reduce the risk of complications.

The market analysis of biocompatible materials reveals significant growth potential. The increasing prevalence of chronic diseases and the ageing population are major factors driving the demand for medical devices and implants. Rising awareness and acceptance of minimally invasive surgeries, as well as the growing demand for cosmetic and reconstructive surgeries, are also propelling the demand for biocompatible materials.

These materials are extensively used in orthopaedic, dental, cardiovascular, and other surgical procedures. There is an increasing demand for bioelectronic materials for implanted and wearable devices powered by biological energy (for sensing and therapeutics).

The market for biocompatible materials is also witnessing several other technology trends. For example, additive manufacturing, bioprinting (scaffolds and cells) and reverse tomography approaches (using UV light to generate 3-D structures from liquid) are becoming increasingly applied due to their ability to create complex geometries and customize patient implants.

The UK has a clear opportunity to lead in several key areas in the field. The global market for biocompatible materials is growing at a CAGR of 8.8% and is expected to reach USD 436.4 million by the end of 2033[23], creating significant economic opportunities for the UK.

THE PRIORITIES

Industry engagement has revealed clear priorities, including materials to enhance soft tissue and wound repair, bioactive and biocompatible materials for (active) implants, sensors, and materials for more efficient and controlled drug and nutrient delivery.

A focus will be developing materials appropriate for healthcare applications, possibly by applying nascent fabrication technologies, including additive manufacturing, bioprinting and reverse tomography, to create complex and small-scale geometries.

For agricultural applications, a focus will be on more efficient nutrient delivery and improving soil health.

TABLE 4.3 - CORE THEME 3: BIO-COMPATIBLE MATERIALS (Health, life sciences, bioengineering, food & agriculture)	
OPPORTUNITY WORKSTREAM	**Example Innovation Focus Areas**
OW13 Materials for soft tissue/wound repair and procedures	• Biosynthetic materials • Tissue scaffolds • Infection resistance, detection & treatment
OW14 Bioactive materials for soft implants	• Electronic/ionic communication pathways • Biocompatible coatings/surfaces for Implants • Shape memory materials (for example, stents dental) • Infection resistance, detection & treatment • 3D printable materials for soft implants • Smart implantables – failure detection and self-repair • Soft organic materials for bioelectronics
OW15 Biocompatible materials for hard implants	• Materials for bone regeneration/replacement/support • Joint implants • Materials for implants to combat metal-ion sensitivity (for example biocompatible ceramics) • Solid-state bioelectronic interfaces • Infection resistance, detection & treatment • 3D printable materials for hard implants • Smart implantables – failure detection and self-repair
OW16 Bioactive materials for wearables	• Biocompatible coatings/surfaces for wearable devices (including flexible sensing electronics – see OW29) • Infection resistance, detection & treatment (enhanced textiles)
OW17 Materials for drug delivery (including paediatric/geriatric applications) and nutrient delivery	• Substance-eluting materials (for drugs and nutrients) • Smart delivery - drug control • Smart Soils

OW13 Materials for soft tissue/wound repair and procedures

Chronic wounds are debilitating and expensive for patients and healthcare systems, with the annual cost of wound care in the UK estimated at over £8bn per annum[24].

[23] https://www.persistencemarketresearch.com/market-research/biocompatible-materials-market.asp
[24] BMJ; 2020 Dec 22;10(12): e045253. doi: 10.1136/bmjopen-2020-045253

Chronic wounds, burns, and other injuries require special care and attention. Moreover, traditional wound care methods often fail to provide sufficient support and rely on patients' body restoration mechanisms. Advances in medical technology must deliver solutions that improve wound management and treatment.

For example, regenerative medicine leverages the body's natural healing processes to accelerate wound closure and reduce complications. Advanced biomaterials such as tissue scaffolds, together with technologies that guide and stimulate tissue regeneration, offer a more effective and non-invasive approach to wound care.

Excess exudate is a common issue that slows down wound healing processes and increases the risk of infections, causing discomfort to patients. Hence, managing exudate is an essential aspect of wound care, but the traditional approach of using absorbent dressings is often inadequate. Innovations in exudate management solve this problem through advanced wound dressings, such as hydrogels and foams, which provide superior absorption capacity and fluid distribution.

Incorporating infection resistance, detection and treatment within these materials would further aid wound recovery, significantly improving patient outcomes and reducing healthcare costs.

OW14 Bioactive materials for soft implants

Appropriate selection of implantable soft biomaterials is a key factor in implant long-term success. The biological environment does not accept any material, so implants must be selected to optimise biological performance while maintaining adequate function and reducing the negative biological response.

Bioactive materials can be used in a wide range of implant applications, biodegradable implants, synthetic grafts and soft-part replacements (for example, valves).

Key challenges in the implantables field include the development of biocompatible coatings and surfaces, 3-D printable materials, and materials with smart capabilities including failure detection, and infection resistance, detection and treatment.

Further opportunities include materials for bioelectronics where biology-technology communication is required. For example, solid-state bioelectronic interfaces and materials to facilitate electronic/ionic communication pathways. The latter is an emerging field requiring significant development of new materials.

OW15 Biocompatible materials for hard implants

Again, implants must be selected to optimise biological performance, maintain adequate function, and reduce the negative biological response.

Hard bioactive materials can be used in a wide range of implant applications, including glass and ceramic ophthalmic implants, metals and nanotubular surfaces for bone support and replacement, biodegradable implants, synthetic grafts, and dental applications.

Key challenges in the implantables field include the development of biocompatible coatings and surfaces, materials to combat metal-ion sensitivity, materials for bone/cartilage regeneration, 3-D printable materials (for example, joint replacements), and materials with smart capabilities including failure detection, and infection resistance, detection and treatment.

OW16 Bioactive materials for wearables

Wearable medical devices that can collect various types of physiological records are becoming increasingly important in health monitoring, disease discovery, disease avoidance, and treatment compliance. They have the potential to significantly lower the overall public sector health cost and improve patient outcomes.

Of particular interest are biocompatible coatings/surfaces for wearable devices, improved sensing capabilities and paediatric and geriatric-specific applications.

OW17 Materials for drug & nutrient delivery

Drug delivery technologies enable the development of many pharmaceutical products that improve patient health by enhancing the delivery of a therapeutic to its target site, minimizing off-target accumulation and facilitating patient compliance.

Only recently has the importance of dosage form design been recognized as a vital component of effective therapy, with patient outcomes improved through the incorporation of rate-controlled dosage forms. Conventional formulations have provided vehicles for introducing agents into the body. New therapeutic systems could offer greater versatility, particularly when they permit localised treatment of specific tissues and controlled-release methods for systemic delivery. These new dosage forms need to be diverse, precise, and adaptable in many therapeutic situations.

For example, membrane-controlled therapeutic systems provide controlled release of a drug in solution over a specified period, using osmotic activity as an energy source. These new systems must overcome issues related to conventional sustained-release and other controlled-release dosage forms that rely on pH to release the medication and, therefore, overcome the problems associated with unpredictable release patterns.

Systems specifically designed for paediatric and geriatric applications will enhance compliance and deliver bespoke therapies.

These systems can also be applied to nutraceutical ingredients, a significant global market, and animal husbandry, where substance-eluting materials can improve the efficient delivery of drugs and nutrients.

In addition, similar material innovations can also improve soil health and productivity. For example, substance-eluting materials in soils can significantly improve nutrient delivery, combat viruses and other crop pathogens, and increase filter efficiency while nano-catalysts can reduce pollution in arable farming, forestry, and natural ecosystems.

Improving overall soil health is also a priority for agricultural systems, including the development of materials for smart soils.

4.4 CORE THEME 4: MATERIALS FOR SUSTAINABLE STRUCTURAL COMPONENTS (Table 4.4)

THE CHALLENGE

Structural materials are used in a range of technological, electrical, and engineering applications and a range of environments including extreme environments. Across multiple sectors, the industry's clear sustainability requirements and the increasing manufacture of inexpensive, transportable, and adaptable technological tools will continue to fuel the demand for innovative materials.

Inadequate technological advancements in structural materials will inhibit industry's growth across multiple sectors.

THE OPPORTUNITY

From applications in defence, transport and aerospace to construction and energy, innovation in structural materials will be crucial, including their response to specific environmental degradation factors (such as fatigue and corrosion). Structural materials also underpin many sustainability impact innovations and are, therefore, significant across almost all sectors.

Significant market segments rely on structural materials, and innovation in these materials can potentially increase the UK's share of growing global markets. For example, the global lightweight materials market value is estimated to be USD 276.4 bn by 2030 at a CAGR of 8.3% during the forecast period (2023-2030)[13]. Lightweighting is a key priority across many sectors, from transport and construction to health. The Green Cement market value is estimated to be USD 73.1bn by 2030 at a CAGR of 10.76[13]. Reducing the carbon footprint of cement, whilst specific to the construction industry, has massive global ramifications in reducing CO_2 emissions.

Bringing together innovation for enhanced structural material characteristics with new modelling technologies and AI/Machine Learning methods will also improve functionality. For example, modelling mechanical properties to design materials that are application-specific or modelling to maximise the sustainability impact of lightweighting. Another key focus area is in the modelling of degradation though processes such as corrosion or wear, which links to innovation in surfaces and coatings. In particular, there may be opportunities to re-think how application-specific materials are designed, using data and modelling in the early stages of materials development.

The UK has an opportunity to harness its materials research expertise to underpin economic growth through the support and development of structural materials-producing and structural materials-reliant industries.

THE PRIORITIES

An overall goal of innovation in structural materials is often to balance sustainability, cost and performance. Industry highlighted prioritising materials for lightweighting, designing materials for circularity, improving performance (especially in extreme environments), additive manufacturing and multi-use, multi-performance materials (*for example,* multiple *applications* of a material standard, reducing the overall complexity of materials systems).

TABLE 4.4 - CORE THEME 4: STRUCTURAL MATERIALS (Sustainable, stronger, lighter, smarter materials for construction, manufacturing, transport, aerospace, energy, technology)	
OPPORTUNITY WORKSTREAM	**Example Innovation Focus Areas**
OW18 Materials for sustainable structural systems, ranging from metallics to composite systems	• Sustainable, high-specific strength/stiffness materials • Sustainable, high-performance adhesives and resins for deconstructable high-strength materials (applications across aerospace, maritime, automotive and construction sectors) • External Thermal Insulation Composite Systems (ETICS) • Inorganic fire-resistant insulating panels • Insulation (vapour open & vapour closed) • Cladding for brick structures (aesthetics & function) • Lower temperature melting glass with improved strength • Sustainable/recyclable lightweight engineered components (for example, wind turbine blades)

	• Extreme high-temperature materials (Ceramic matrices) to withstand higher operating temperatures and reduced cooling requirements for high-efficiency, land-based gas turbines and transport applications • Bio-based lightweight materials • Self-healing structural materials • High-dampening materials for vibration reduction in transport (for example, aircraft) as well as applications such as equipment and machinery (at all scales) • Reduced waste/sustainable component manufacture • Novel feedstock materials such as continuous fibres, nanoparticles, ceramics or functional fillers for additive manufacturing • Green alloys (including steels and aluminium) • Standardising grades of alloys across sectors to allow for multiple use • Corrosion-resistant steel • Improved materials and digital innovations (made smarter) for additive manufacturing (for example, improved metal powder purity and materials for wire arc additive manufacturing) • Improved models of degradation and corrosion, including general corrosion, creep, oxidation, stress corrosion cracking and fatigue
OW19 Specialist structural materials for extreme environments - temperatures, radiation, multi-extremes (for example, nuclear fission and fusion reactors and gas turbines) (For Advanced Nuclear Fuels, see OW7)	• Structural materials for irradiated environments including high-purity, low-activation steels and irradiation-tolerant shield materials • Rapid development alloys, ceramics and structural materials for novel coolants for high-temperature environments • High-temperature superconductors • Advanced moderator materials (for example, next-generation graphite moderators) • Magnetic field materials for plasma applications (for example, plasma-facing materials for stable confinement) • High-temperature structural materials for gas turbines
OW20 Materials for hydrogen storage, sensing and distribution	• Cost-effective compressed gas storage (for example, advanced pressure vessels made of fibre-reinforced composites capable of reaching 700 bar pressure) for transport • Materials for cryogenic applications (for example, cryo-hydrogen storage technologies - cryogenic vessels that operate the system at low temperatures (<20 K) • Materials-based hydrogen storage technologies (including sorbents, chemical hydrogen storage materials and metal hydrides). For example, porous coordination polymers (PCPs) / metal-organic frameworks (MOFs), Covalent organic frameworks (COFs) and other porous crystalline nanomaterials (such as metal-organic polyhedrons (MOPs) or conjugated microporous polymers (CMPs) • Solid-state materials with high volumetric and gravimetric hydrogen densities to increase the capacity of glass micro vessels, microporous, and nano-porous media, as well as

	safety and refilling-time demands for hydrogen storage vessels • High-sensitivity, high-selectivity hydrogen sensors (for example, thick-film, micro-fabricated point-contact hydrogen sensors)
OW21 Low carbon construction materials including concrete	• Sustainable cement maintaining mechanical and thermodynamic properties, fire resistance, workability and durability • Alternative cement routes (for example, geopolymers) • New regulatory/testing framework for supporting and accelerating innovation solutions

OW18 Materials for sustainable structural systems

Materials with exceptional strength-to-weight ratio, corrosion resistance and durability have extensive applications in the construction of robust and durable structures. Examples of lightweight structural materials include composites, metals and alloys.

From the built environment to transport, defence, and even health sectors, industry highlights the need for lightweighting structural components while maintaining other performance characteristics.

For example, different applications present specific challenges for lightweight materials, such as thermal resistance/conductivity (required in transport, nuclear fusion/fission and gas turbine applications) and acoustic insulation and fire resistance (both required for construction applications).

Another key challenge is making structural components more sustainable, especially in terms of their ability to be reused or recycled. The former is related to Materials 4.0 (for example, digital material passports), and the latter is related to the ability to deconstruct materials and infrastructure for recycling.

Deconstructing lightweight structural materials such as composites will require innovations in high-performance resins and adhesives to reduce delamination and degradation of composite layers whilst improving overall toughness and mitigating the risk of sudden failures. Another challenge for composites is their susceptibility to environmental factors such as moisture, heat, and chemicals, which degrades their mechanical properties over time. The requirement for long life cycles is particularly relevant to the construction industry. Innovation in high-performance resins and adhesives will make materials resistant to these factors and offer improvements in durability and longevity (as well as deconstruction).

Other innovation opportunities include bio-based lightweight materials (especially for high corrosion, UV radiation and wear applications) and the integration of nanotechnology to improve functionality. For example, improving thermal and dimensional stability (for use in high-temperature applications), and electrical conductivity (making them suitable for electronics and energy storage applications). Others include self-healing capabilities in materials for autonomous repair of structural components and carbon fibre-reinforced polymers (for demanding thermal applications). There may also be opportunities to expand the applications of carbon fibre-reinforced polymers by enhancing their cut strength and reducing the poor adhesion of surface coatings, which are characteristics required by the automotive sector. There is also a challenge in the lack of a domestic carbon fibre supply chain.

A specific example of innovation in this field is the need for sustainable structural boards and inorganic insulation panels for construction. This sector requires bricks, panels, and customised parts with a very high strength-to-weight ratio, thermal and acoustic insulation properties, and fire resistance. These components are used in various buildings and construction applications. Traditional construction components release high CO_2 emissions during manufacturing. New products must combine strength with other characteristics such as insulation, temperature resistance, and an adjustable degree of porosity.

Following a number of high-profile building fires, there is public and industry pressure to develop improved inorganic fire-resistant panels that can be used for external insulation cladding.

While there are multiple opportunities for developing lighter and more sustainable materials across multiple sectors, steel and aluminium remain key structural components in many industries, from construction to transport.

Steel is one of the most important engineering and construction materials. However, the industry now needs to cope with pressure to reduce its carbon footprint. Innovation here must focus on process, refining products for vastly improved sustainability (including circularity) and materials to improve the efficiency of electric arc furnaces.

Enhanced corrosion-resistance properties are also an area ripe for innovation.

Innovations in high-purity steel for nuclear applications are covered in OW16.

Aluminium is the second most used metal in the world after steel with an annual consumption of 88 million Tonnes[15]. It is also the fastest-growing metal market, which has grown twice as fast as other metal markets[15]. Its characteristics, such as lightweight, recyclability, conductivity, non-corrosiveness, durability, design flexibility, and production efficiency, have helped establish it as a metal of choice for various applications across various market segments including transport, construction, machinery and electronics. Another key advantage of aluminium is that it can be recycled without loss of quality and the recycling process is low energy. However, recycling is more problematic for cast aluminium-silicon alloys which typically contain up to 11% silicon and small amounts of copper, iron, and nickel for improved strength. A large proportion of aluminium going into new products such as electric vehicles, is an aluminium silicon alloy. Major challenges are to develop new recycling technologies and practices to maximize scrap quality, improve efficiency and reduce cost, and develop aluminium alloys that are easily and fully recyclable.

Additive manufacturing and advanced forming processes use metals and alloys across multiple sectors and applications, ranging from low-volume functional parts and one-off parts to near-net-shape part production for nuclear components and wire arc additive manufacturing. Advances are required for various techniques, such as powder bed fusion and direct energy deposition, by improving powder purity, reducing size distribution and developing low-cost additive manufacturing metals and alloys to make the technologies more affordable. Innovations in advanced forming processes (such as forging) are also intrinsically linked to 'made smarter' approaches using digital technology.

OW19 Specialist structural materials for extreme (including nuclear fission and fusion reactors and gas turbines)

The nuclear sector constantly seeks new technologies to make nuclear power plants more reliable, cost-effective, and safe, extend their operational life, and develop novel reactor systems and systems that can work more effectively within a low-carbon electricity grid.

Nuclear reactions also pose challenges in generating extreme conditions, specifically related to radiation, but also long-term demands through elevated temperature and long-term corrosion damage.

The key materials innovation opportunities related to fusion are in structural steel, magnetics, high-temperature superconductors, novel rapid development alloys, ceramics and structural materials for novel coolants. Structural materials suitable for high temperatures and extreme irradiated environments are also required.

There is also a researcher demand for access to a test reactor to test materials and materials models and to irradiated material examination capabilities and materials (including an irradiated materials databank). These capabilities are also important in the development of advanced nuclear fuels (OW7).

OW20 Materials for hydrogen storage, sensing & distribution

Hydrogen storage is a key enabling technology for the advancement of hydrogen and fuel cell technologies in applications including stationary power, portable power and transportation. Hydrogen exhibits the highest heating value per mass of all chemical fuels while being regenerative and environmentally friendly. It is increasingly considered essential to a sustainable world energy economy because it can store surplus renewable power, decarbonise transportation and serve as a zero-emission energy carrier. It can be stored physically as a gas or a liquid. Storage as a gas typically requires high-pressure tanks, whereas liquid storage requires extreme cryogenic temperatures. However, hydrogen poses significant technical and engineering challenges for conventional high-pressure or cryogenic storage, where leakage is a particular challenge. There is a clear cross-over here with innovations in surfaces and coatings (see section 4.5). Hydrogen can also be stored on the surfaces of solids (by adsorption) or within solids (by absorption).

Innovation opportunities centre around cost-effective compressed gas storage, using advanced pressure vessels capable of reaching 700 bar pressure, cryo-compressed hydrogen storage and materials-based hydrogen storage technologies including adsorption of hydrogen on solid surfaces and through chemical reactions (for example, solid-state materials with high volumetric and gravimetric hydrogen densities are durable alternatives to gas-phase hydrogen storage).

Safety is a crucial issue in hydrogen energy applications due to the unique properties of hydrogen. Accordingly, a suitable hydrogen sensor for leakage detection must have high sensitivity and selectivity, rapid response/recovery, low power consumption and stable functionality, all of which require further improvements on the available hydrogen sensors. Different hydrogen sensing mechanisms include resistive, capacitive, optical and surface acoustic wave-based sensors, with their sensing performances based on different nanostructures and material combinations. Further exploration of materials for hydrogen sensors is required.

OW 21 Low carbon construction materials (including concrete)

Embodied carbon in buildings accounts for 11% of our national total emissions, with concrete, a default choice for many structures, accounting for 8-10%[25]. The estimated value of the UK's precast concrete sector is £3.7 bn, growing at around 5% per year, while the UK ready-mixed concrete sector is worth over £3 bn[26]. There are over 1,900 concrete plants in the UK supporting 29,000 employees. As a carbon-intensive material, developing sustainable (low-carbon emissions) concrete is a top priority in achieving net zero.

Sustainable (low-carbon) concrete must consider all phases of a concrete construction's life cycle, i.e. structural design, specification, manufacturing and maintenance, and it includes all aspects of performance (including mechanical properties, fire-resistance, workability, durability, thermodynamic properties). There are several alternative environmental requirements with which green concrete structures must comply including at least 30% CO_2 emissions reduction overall, at least 20 % of the concrete includes waste products (previously landfilled or disposed of in other ways), CO_2-neutral

[25] World Green Building Council
[26] IBIS Concrete Construction Product Manufacturing in the UK - Market Size, Industry Analysis, Trends and Forecasts Report

production (using waste-derived fuels), non-reduction in recycling ability and no increase in hazardous substances in wastewater[27].

To address this challenge and drive CO_2 down further, new materials must be developed. Some initiatives have been established (for example, through the UKRI Transforming Construction Industrial Strategy Challenge and the current Innovate UK Small Business Research Initiative (SBRI) Decarbonising Concrete funding call). However, low-carbon technologies are unavailable on a suitable scale and require substantial further research and investment[28] and an environment that will accelerate translation. This is now an urgent priority as large construction companies (for example, Laing O'Rourke) are mandating the switch to low-carbon concrete on all new UK projects. However, innovation is inhibited by standards and practices (such as risk aversion to the use of "new" construction materials by the insurance industry) and access to test capabilities for SMEs.

4.5 CORE THEME 5: MATERIALS FOR SURFACE ENHANCEMENT & PROTECTION (Table 4.5)

THE CHALLENGE

Manufactured surfaces are constantly subject to wear and tear, corrosion, UV radiation, temperature extremes and other detrimental elements that necessitate coatings to provide enhanced durability. Surface engineering treatments can also enhance the overall performance of surfaces. 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. Processes range from painting to metal coating.

Furthermore, several in-use coatings are now restricted (for example, under Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) regulations) and require replacement solutions.

In addition to developing materials for such applications, understanding and predicting surface degradation remains a significant challenge.

THE OPPORTUNITY

Corrosion is a global problem with implications across almost all sectors. The global cost of corrosion is estimated to be US$2.5 trillion, which is equivalent to 3.4% of the global GDP (2013)[29], not including individual safety or environmental consequences. Reducing corrosion in materials based on existing technologies could realise between 15% and 35% savings. Through innovation in this field, economic benefits could be even greater.

Surface-surface interactions are also important in developing more efficient processes and devices, especially in combatting friction and wear and developing self-lubricating technologies that can operate in various environments.

Harnessing Materials 4.0 approaches, AI and new modelling techniques could vastly improve our understanding of corrosion, surface-surface interactions, and the behaviour of surfaces and coatings across all environments.

This would underpin the development of enhanced protection coatings, barriers, and surface treatments and new materials to improve or extend the overall performance of surfaces.

[27] British Standard BS 8500-1:2006; The British Standards Institution (BSI) – updated standard for concrete to allow the specification of a wider range of lower carbon concretes to help decarbonise construction projects.
[28] The Institution of Structural Engineers Concrete Technology Tracker
[29] International measures of prevention, application, and economics of corrosion technologies study; NACE International; http://impact.nace.org/economic-impact.aspx

The UK has an opportunity to take a lead in this area, which has major global implications.

THE PRIORITIES

Materials that help protect and enhance surface performance and longevity are clear priorities across sectors.

TABLE 4.5 - CORE THEME 5: MATERIALS FOR SURFACE ENHANCEMENT AND PROTECTION	
OPPORTUNITY WORKSTREAM	**Example Innovation Focus Areas**
OW22 Materials for surface protection & enhancement	• Corrosion protection – multiple surfaces • Thermal barriers • Coatings to extend operational lifetime in extreme environments (for example, hydrogen storage) • Impact-resistant coatings (for wind/steam turbine blades) • Vapour-open and vapour-closed coatings & surfaces • IR-reflective coatings (for example, passive houses; thermal and electromagnetic camouflage) • Hydrophobic and omniphobic surfaces • Self-cleaning surfaces • Smoothing • Antimicrobial surfaces • Stain-resistant building coatings
OW23 Materials for tribology/surface engineering (wear-resistant coatings & lubrication)	• Developing self-lubricating materials • Developing aerodynamic surfaces
OW24 Enhanced materials design through improved models of degradation and corrosion	• Modelling and testing for surface degradation and corrosion for development of higher-performance materials

OW22 Materials for surface protection and enhancement

Materials that provide improved protection against corrosion caused by a range of environmental factors (including thermal, chemical and radiation) are a priority.

New modelling approaches to corrosion and corrosion-resistant materials is also required, leading to improved material design and application.

In addition to protection, "smart surfaces" that use materials to enhance a product's overall functionality, such as active cooling paints or anti-soiling and self-cleaning surface treatments are highlighted as innovation opportunities as are surfaces with hydrophobic, omniphobic, smoothing, antimicrobial or thermal barrier properties.

OW23 Materials for Tribology/Surface Engineering

Tribology is the science of interacting surfaces in relative motion, focusing on friction, wear, and lubrication. It encompasses how interacting surfaces and other tribo-elements behave in relative motion in natural and artificial systems, including bearing design and lubrication. Tribology plays a crucial role in reducing energy consumption, extending the lifespan of machinery, and enhancing human comfort and safety.

A priority is tailoring materials to control the friction and wear of materials. Applications include healthcare and energy sustainability, including reducing friction in offshore wind turbine blades, valves and gears, developing self-lubricating materials and manufacturing aerodynamic surfaces.

OW24 Enhanced materials design through improved models of degradation and corrosion

Understanding the nature of degradation and corrosion is vital to developing new materials that exhibit enhanced performance and longer life-cycles.

It is a major industrial and economic opportunity area which also links to the Materials 4.0 cross-over theme and across multiple applications and sectors.

4.6 CORE THEME 6: MATERIALS FOR ELECTRONICS, TELECOMS, SENSING & COMPUTING TECHNOLOGIES (Table 4.6)

THE CHALLENGE

The device manufacturing industry is growing rapidly, leveraging the latest technology advancements in fabrication processes and component design. For example, wireless electronics eliminate the need for physical connectors, cables, and bulky components, reducing weight and increasing mobility. Technologies like Bluetooth, Wi-Fi, and near-field communication (NFC) enable faster power transmission and make devices lightweight and more streamlined.

However, ICTs use between 5% and 9% of all energy consumed globally, with energy consumption by digital devices and infrastructure increasing by between 6% and 9% per annum[30]. With numbers and demand for higher computing power increasing daily, reducing power consumption whilst increasing computing power is a major priority for the industry.

All areas within this core theme are developing rapidly and offer many avenues of innovation. Identifying and focusing on key areas where the UK can truly excel will be key.

THE OPPORTUNITY

Opportunities include innovations around designing and manufacturing electronic components with improved efficiency, durability, sustainability and extended operating environments.

Organic electronics is a relatively new field with applications in display, photovoltaic and transistor technologies, and biomedicine. Its advantages include low power consumption, reduced or non-use of rare elements and greater circularity/sustainability. Their flexibility offers significant potential in the wearable bioelectronics market as well as more flexible solar PV installations (which also links to section 4.1).

Another opportunity area highlighted for the UK includes innovations in materials for the generation, manipulation, control, and detection of light. Such technologies have wide-ranging applications, and the market is growing across sensing, communications, and light emission technologies (lasers, LEDs, modulators, and photodetectors). Key innovations here include the development of dielectric materials (especially improving new process efficiency such as atomic layer deposition).

THE PRIORITIES

As with almost all industry commentary, sustainability and cost reduction are high priorities in materials innovation in these areas. Other priorities relate to reducing or optimising power consumption and energy dissipation and materials innovations that expand operating parameters (especially temperature).

Specific materials innovation priorities include silicon alternatives, ultra-wide bandgap materials and high-purity materials for power electronics, more efficient and optimised organic electronics (for

[30] Source: EnerData; Global Energy Data

example, electron transport and electron injection materials), increasing computational power whilst decreasing energy consumption, and controlling the way heat moves through crystalline materials.

In terms of light generation, manipulation and detection, materials innovation priorities focus on achieving higher efficiency devices. For example, plasmonics, unlike conventional optics, enable unrivalled concentration of optical energy well beyond the diffraction limit of light. However, a significant part of this energy is dissipated as heat. Plasmonic losses present a major hurdle in the development of plasmonic devices and circuits. A priority for materials innovation is, therefore, to develop enhanced performance plasmonic materials.

Another field with significant potential for UK innovation is integrated sensing and communication (ISAC) systems using the terahertz (THz) band. These THz systems have significant advantages over lower radio frequencies, such as high-quality image resolution, penetration of infrared opaque materials, do not produce ionising radiation and are low-energy and, therefore not harmful to humans. Immediate priorities are the development of materials with specific properties for THz devices.

Energy dissipation is also an area ripe for materials innovation. In most computational devices, one key limitation to increasing speed and memory is the need to dissipate the heat generated by the chips.

Phonons are especially relevant in the behaviour of heat in crystals, but their behaviour is chaotic and thus difficult to predict and control. Finding ways to manipulate the behaviour of the phonons in chips, so the heat can be removed easily, is critical to the development of next-generation computing technologies.

TABLE 4.6 - CORE THEME: MATERIALS FOR ELECTRONICS, TELECOMS, SENSING & COMPUTING TECHNOLOGIES

OPPORTUNITY WORKSTREAM	Example Innovation Focus Areas
OW25 Materials for power electronics	• Silicon alternatives • Compound semiconductors • Ultra-wide bandgap materials (for example, gallium oxide and diamond) – design, fabrication & optimisation • Field effect transistors • High-purity metals, alloys and ceramics for semiconductors • Silicon-alternatives
OW26 Materials for organic electronics	• Embedded microbial energy generation in organic circuits • Electron transport materials for higher-efficiency organic light-emitting diodes and semiconductors • Electron injection materials for enhanced metal-organic interfaces in electronic devices
OW27 Materials for optimised computing (including quantum and neuromorphic computing)	• Materials for high computational power and lower energy consumption (including efficient digital signal processing • Materials systems for quantum that operate at ambient temperatures • Negative capacitance, 2D materials to reduce/optimise power dissipation • Ambient and high-temperature superconductors for ICT applications • Improved quality of topological insulators (for example, for optimised memory and spintronics applications) • Dope alloys to enable more precise deposition on wafers • Materials for neuromorphic technologies (nascent)

OW28 Materials for data storage	• Materials for high-density, energy-efficient data storage using technologies such as spintronics, magnetics and photonics • Low-Energy solid-state memory materials
OW29 Materials for telecommunications (including radio frequency and optical)	• Materials for more efficient RF circuits (reduced size, cost and power consumption) • Development of new materials for THz comms & sensing (6G high-data-rate transmission) • Development of new optical fibres to improve data capacity • Scalable production micro-LEDs • Development of inductive resonant coupling coils for high-energy transmission • Electromagnetic coatings with improved electromagnetic interference reduction
OW30 Materials for advanced electronic sensors and instrumentation (including robotics, haptics and the Internet of Things)	• Materials to enable dielectric atomic layer deposition and inspection for semiconductor memory • Plasmonic-enhanced materials to reduce radiative losses and energy dissipation and improve tuneability, for • Materials to enable higher efficiency laser and maser-emitting diodes • Development of wavelength-specific materials for biophotonic laser diodes • Intelligent, high-performance piezoelectrics • Low-dimensional hybrid/heterostructure nanomaterials with novel sensing properties • Materials to improve phonon control • New materials for biophotonic lasers for imaging and diagnosis • Flexible sensing electronics for wearable health devices

OW25 Materials for power electronics

Priorities in this field include developing silicon alternatives and other semiconductor materials or composites, such as graphene and nanomaterials, for high performance and efficiency. For example, high-performance power-switching gallium nitride (GaN) semiconductor materials deliver vertical current conduction GaN devices that extend application voltages from 1000V to over 10 000V, and semiconductor-grade carbon nanotubes support room-temperature deposition on any substrates. These technologies have applications in consumer electronics, electric vehicles (EVs), industrial motor control, energy grids, wireless and computing applications, and sensor components.

3D-printed electronics rely on conductive inks and often flexible films and advancements in printing technologies allow the production of flexible hybrid electronics. They are used in lighting, automotive, healthcare, and electronics industries.

OW26 Materials for organic electronics

Organic Electronics offer massive advantages over traditional inorganic electronics. They are cost-effective, flexible, indissoluble, optically transparent, lightweight, and consume low power. Moreover, the application of organic materials to the manufacture of electronic devices enables manufacturers to use safer, fewer, and more abundantly available raw materials.

Opportunities exist in various domains, such as circuits with microbial components (for power supply) and devices with biodegradable and recyclable materials. Materials innovations include electron transport materials, electron injection materials, and light-emitting materials.

OW27 Materials for optimised computing (including Quantum and neuromorphic computing)

Graphene-based transistors, quantum computing, DNA data storage, neuromorphic technology, optical computing, and distributed computing will drive computing advances in the near and medium term. Materials innovations will be central to these.

For example, technologies enabled by quantum science have the potential to transform health care (such as quantum magnetic field sensors enabling functional brain imaging), transportation, and communications, enhance resilience to cyber threats (such as quantum optical communications enabling encrypted communications), and facilitate the discovery of next-generation materials.

Opportunities include finding silicon alternatives and developing system-on-chip technologies, metamaterials, negative capacitance 2-D materials, and dope alloys.

OW28 Materials for data storage

The era of data-centric computing is here. The demand for ever-increasing capacity means developing new material solutions to increase cost-effective high-density data storage is critical.

Key innovations include spintronics, especially antiferromagnetic materials (characterised by electrons that behave like tiny magnets and are capable of recording memory with this magnetism alone without the added boost of an electric current). Photonic circuit approaches for rewritable data storage that can be integrated into computing architectures are another key innovation area as is low-energy solid-state memory.

OW29 Materials for telecommunications (including radio frequency and optical)

Alloys and optical materials dominate the field with opportunities in new optical fibres, more efficient RF circuits and THz comms and sensing.

As telecom capacity demand grows, silica glass fibre performance will need to be significantly enhanced to transmit more and more data.

Wireless data transfer is a normal part of everyday life, and the future promise of ever-more connectivity places ever-increasing demands on the available bandwidth for data transfer. These demands are giving rise to new communication technologies, such as visible light communication, also known as LiFi, which exploits micro light emitting diodes (micro-LEDs) based on gallium nitride (GaN) to transfer data at ultra-high speeds via high-speed modulation of light intensity combining energy-efficient lighting with data transfer. New materials manufacturing is required to develop this technology.

OW30 Materials for advanced electronic sensors and instrumentation (including robotics, haptics and the Internet of Things)

Advanced sensing materials are key to enabling the Internet of Things (IoT). IoT sensors require lower power consumption, higher sensitivity, better selectivity, lower complexity, higher throughput, and higher cost-effectiveness, which represents a new challenge in sensing materials development.

Developments in both sensing materials (to sense defects, porosity, channel traffics, and hybrids) and data processing (such as pattern recognition), together with newly emerging in-situ measurements and theoretical calculations (such as binding energy, charge transfer, or bandgaps), have all contributed to the continued development of high-performance sensors. Notably, sensors based on novel nanomaterials exhibit ultrahigh selectivity, specificity, low power consumption, multifunctionality, and miniaturized size.

Key innovations include low dimensional nanomaterials with novel sensing properties, nanomaterial hybrids/heterostructures with enhanced sensing properties (such as selectivity, operating temperature, sensitivity, frequency response, linearity range, stability, or accuracy), Porous coordination polymers (PCPs) / metal-organic frameworks (MOFs), covalent organic frameworks (COFs) and other porous crystalline nanomaterials (such as metal-organic polyhedrons (MOPs) or conjugated microporous polymers (CMPs), and their hybrid-based chemical sensors), synthesis and characterization of nanomaterials and fabrication, phonon control, electromagnetic coatings and more efficient digital signal processing.

Applications that combine lasers with advances in other technologies, such as optics and sensors, are seeing significant growth. These fields require a range of active and passive materials that can direct, filter or manipulate certain portions of light. Photonic sensors detect precise emissions of light or energy within the photonic spectrum, including some UV and IR wavelengths. They convert these emissions into information about the environment in which the sensor is operating. They also require materials innovations in power, wavelength, and optical design.

The UK has research expertise in this field and could lead in specific areas of autonomous sensing.

5. CROSS-OVER THEMES

Across the industry cluster workshops, the outputs also identified several cross-over themes which are non-application specific. Cross-over themes are priority areas of interest that cut across all or most core themes.

For example, sustainable products designed for improved circularity, recycling, reuse, or recovery are high on the industry's agenda across all sectors. They offer economic and environmental opportunities in addition to regulatory/legislative compliance.

Similarly, materials 4.0 (including digital security and trust, digital standards, lab automation, and data/image storage and sharing) and a lack of efficient tools and processes for optimizing materials design and use were identified across all industry cluster workshops as an essential innovation.

Further, the innovation process for translating new materials from laboratory to market can take 10 to 20 years and is very expensive. Key enablers across the materials innovation space include:

- An Integrated end-to-end innovation approach
- More agile scale-up ecosystems relevant to material classes
- An enabling policy and regulatory environment

All industries identify an appropriately skilled workforce as crucial to delivering and adopting materials innovation. The requirements are wide-ranging, including building on existing skills, developing new skills, and delivering skills.

Innovation will require considering the skills required to deliver specific materials across all priority areas. While some skills capabilities, such as digital skills, will be cross-cutting, specific skill requirements will vary across core themes. These could include new types of career pathways and qualifications, upskilling or reskilling the existing workforce, or completely new job roles.

CROSS-OVER THEMES

1. Sustainability & Circular Economy: designing and producing materials for sustainability and circularity.
2. Materials 4.0, Digital Thread, AI, intelligent discovery, design and manufacturing: using digital thread/AI, big data and new modelling techniques to accelerate materials discovery and application; digital twinning; digital material passports.
3. Skills, including re-skilling, up-skilling and developing new skills capabilities.
4. Critical minerals & materials for supply chain resilience and sovereignty.
5. Manufacturing & scale-up: capabilities for testing, verification and scale-up.
6. Policy, regulations & standards: enabling materials innovation.

Further details of the cross-over themes are provided in Table 5.1.

TABLE 5.1 - CROSS-OVER THEMES IDENTIFIED FROM INDUSTRY CLUSTER WORKSHOPS

CT1	SUSTAINABILITY & CIRCULAR ECONOMY	• Sustainability • Recycling • Reuse • Recovery • Multi-purpose/fewer components – simple by design • Unified life-cycle analysis • Alternatives to restricted substances
CT2	MATERIALS 4.0, DIGITAL THREAD & AI	• Accelerated materials discovery and application using big data and AI • Improved modelling techniques • Digital Twinning • Digital passports • Lab automation • Data storing and sharing
CT3	SKILLS	• Skills provision • New skills • Up-skilling
CT4	CRITICAL MINERALS/MATERIALS	• Supply chain resilience & sovereignty
CT5	MANUFACTURING & SCALE-UP	• Rapid test facilities and protocols (links to standards and regulations) • Mid-scale facilities for manufacturing trials and/or qualification
CT6	POLICY, REGULATIONS & STANDARDS	• Embedding sustainability in regulations • Common standards & tools. For example, Life Cycle Analysis • Rapid certification

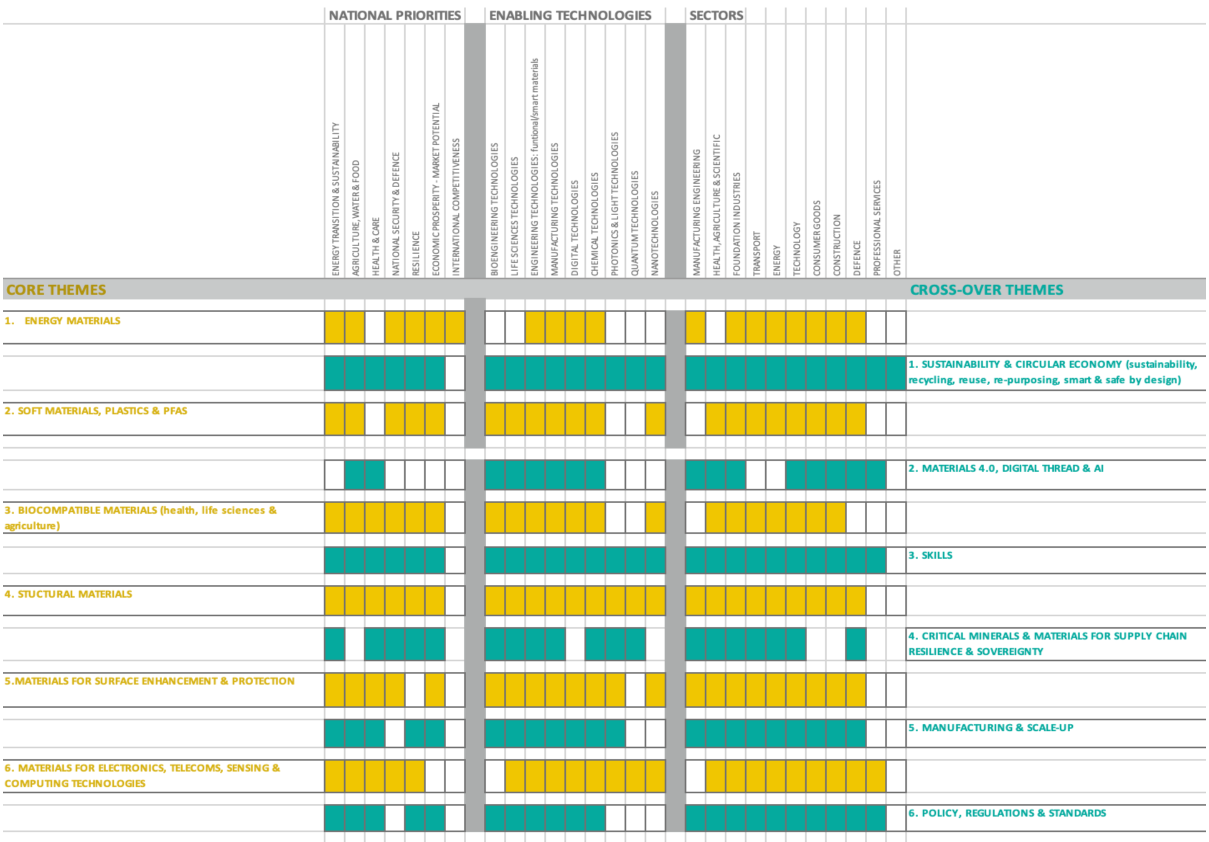
6. ASSESSING CROSS-SECTORAL RELEVANCE OF CORE THEMES AND CROSS-OVER THEMES

The core themes and cross-over themes have been mapped against:

- The high-level national priorities outlined above (Section 1)
- Enabling technologies where the UK has existing expertise (identified from the industry cluster workshops)
- Sectors (as identified in the econometrics study; Section 2 above and Appendix 1)

Table 6.1 highlights the cross-sectoral and cross-disciplinary nature of the emerging priority themes and how they relate to broad societal priorities.

TABLE 6.1 - CORE THEMES AND CROSS-OVER THEMES MAPPED AGAINST NATIONAL PRIORITIES, ENABLING TECHNOLOGIES/EXPERTISE AND SECTORS



7. NEXT STEPS & CALL TO ACTION

Opportunity workstreams will conduct deep dives into the focus areas, identifying priority materials innovations for the UK based on the challenges and opportunities identified by industry. They will provide the required detail necessary to deliver a comprehensive strategy.

Each opportunity workstream will consider how the cross-over themes can enable the materials innovations identified by the workstreams and, where appropriate, which cross-over themes will underpin specific materials innovation. For example, what skills and capabilities are required for particular innovations or the importance of specific materials' sustainability characteristics?

Each opportunity workstream will deliver a sub-strategy, which will be incorporated into the National Strategy for Materials Innovation.

If you are interested in contributing to the Expert Working Groups to provide the necessary clarity for the opportunity workstreams and put in place the recommendations to deliver them, please submit an expression of interest:

https://forms.office.com/e/5LXSqANknQ

Appendix 1

SIC Codes and Sector and Value Chain Definitions

Table A1 – Top 10 materials innovation SIC codes

Primary UK SIC (2007) description	Rank of Most Common SIC	% of Total Companies
Other research and experimental development on natural sciences and engineering	1	8%
Other manufacturing n.e.c.	2	7%
Manufacture of other plastic products	3	5%
Other professional, scientific and technical activities (not including environmental consultancy or quantity surveying) n.e.c.	4	4%
Other business support service activities n.e.c.	5	4%
Research and experimental development on biotechnology	6	3%
Manufacture of other chemical products n.e.c.	7	2%
Manufacture of other rubber products	8	2%
Engineering related scientific and technical consulting activities	8	2%
Manufacture of other special purpose machinery n.e.c.	10	2%

Source: Glass.ai, Bureau van Dijk

Table A2 – Sectoral definitions

Sector Group	Description
Foundation Industries	Companies that are critical to the manufacturing supply chain, providing essential materials and components used across various aspects of the economy. Including companies involved in the production of metals, ceramics, chemicals, cement/concrete and paper. They are called "foundation" because their outputs are fundamental to the construction, manufacturing, and production processes in many other industries, acting as the building blocks for a wide range of products and infrastructure projects.
Construction	Companies involved in the construction of new buildings and repairs or alterations to existing properties in Great Britain measured by the amount charged for the work, including work by civil engineering companies.
Consumer Goods	Companies involved in the manufacture of consumer products including but not limited to cosmetics, cleaning products and textiles.
Transport	Companies involved in the manufacture of aerospace products and components
Defence	Companies involved in the manufacture of products primarily for military use including fighter aircraft, helicopters, large aircraft wings, missiles, jet engines, submarines, warships, amphibious vehicles, armoured vehicles, armour, weapons and munitions, surveillance and communications equipment.
Health & Life Sciences	Companies involved in the application of biology and technology to health improvement, including biopharmaceuticals, medical technology, genomics, diagnostics and digital health.
Technology	Companies involved in telecommunications and data, computing (including quantum and neuromorphic), semiconductors and chips, other electronic components and products, and scientific equipment.
Manufacturing Engineering	Companies involved in mechanical, chemical, electrical, and industrial engineering as applied to manufacturing of goods and intermediates that are not included in the foundation industries. Including equipment manufacturers.
Energy	Companies involved in the production, storage and distribution of energy including traditional energies (oil and gas), renewable energy and nuclear energy.
Professional Services	Companies involved in providing materials innovation related consultancy services

Table A3 – Value chain definitions

Value Chain Group	Description	Example Companies
Research Organisations and Technology Industries	Any organisation involved in materials research and development and/or licensing	Ceres Power, The Electrospinning Company, CPI, AMRC, TWI, Lucideon, NCC, BDC, WMG / IfM
Consultant	Any organisation involved in offering materials-related consultancy or advisory services	Avalon CSL, Frazer-Nash, ScotChem
Test House	Any organisation involved in materials testing or monitoring	NPL, Element Materials Technology, NDT Consultants, Sonomatic, Westmoorland Mechanical Testing, Resonate Circuits
Producers	Any organisation involved in the development and/or production of chemicals and/or virgin materials	Huntsman, Solvay (Syensqo), NSG, OutoKumpu, Tata Steel, GSK, Croda, Timet, Scott Bader
Materials Processors & Intermediates	Any organisation involved in a process that adds value to an existing material	Vitrex, Hexcel, Bodycote, Chemring, M. Wright, James Dewhurst, Technical Fibre Products
Parts & Structures	Any organisation using materials to produce parts, structures or components	Teledyne, Spirit Aerosystems, GKN, NIFCO, Fluid Power Equipment, Plessey Semiconductors, IQE, ZF Automotive, Safran, Thales
OEM	Any organisation assembling parts and structures to produce end products and systems	Rolls Royce, Unilever, Airbus, Boeing, JRL, Nissan, Siemens, Vestas, Weir Group, Hitachi, Toshiba, Seagate, Smiths, Sunseeker
Equipment Producer	Any organisation providing manufacturing and processing equipment and tools	Cygnet Group, Renishaw, Surface Measurement Systems, RHI Magnesta, Oxford Instruments
Distributor	Any organisation involved primarily in the wholesale or distribution of materials products	Plastribution, Sheet Materials Wholesale, Vulcan Materials Company, Neonickel
Recycling	Any organisation involved in recycling and reprocessing materials	Veolia, Gen 2 Carbon, EMR

Source: NMIS Study Team

Appendix 2

National Materials Innovation Strategy Industry Cluster Workshop Outputs

Key

Issue specific to this cluster
Issue is cross-sectoral
Cross-over themes
Cross-over theme – skills

APPENDIX 2 PRIORITIES IDENTIFIED BY WORKSHOP

1. BUILT ENVIRONMENT

	Priority Area: Application/material classification	Priority Area: Application/properties/challenge
1.1	Coatings & Surfaces	Anti-corrosion (for example, steel) Self-healing road surfaces
1.2	Energy Harvesting	Photovoltaic/Energy Surfaces
1.3	Insulation	Vapour-open and vapour-closed applications
1.4	Retrofitting	Over-cladding for brickwork to allow airflow and moisture to be released
1.5	Construction - structural	Green cement or alternatives Corrosion-resistant steel
1.6	Passive houses	Sealable Letterboxes and cat flaps
1.7	Simplifying construction/deconstruction	Multi-application materials – using fewer components
1.8	Digital Thread	Materials Passports
1.9	Passive monitoring	In situ monitoring, failure detection
1.10	Standards & Accreditation	Need to take into account sustainability
1.11	Skills	Upskilling existing workforce

	2. CHEMICALS	
	Priority Area: Application/material classification	**Priority Area: Application/properties/challenge**
2.1	Hydrogen	Storage – cryogenic Water-splitting @ scale and for salinated Water – catalysts
2.2	Carbon Capture and Utilisation	Separation of CO_2 from waste streams (efficient scrubbing of emissions)
2.3	Lightweighting	Various applications: Additives for composites & polymers = morphology control Bio-adhesives Sustainable/recyclable
2.4	Modular construction & lightweighting	Carbon fibre Polyester (white fibre) Composites Structural adhesives
2.5	Coatings - industrial	Industrial applications
		Stain-resistant
		Thermal properties (IR-reflective surfaces)
2.6	Textiles	Biodegradability Vegan textiles for automotive applications Stain-resistant
2.7	Batteries	Solid electrolytes Electrodes Compliment Li-ion?
2.8	Bio-feedstocks	Catalysts
2.9	Semiconductors for automotive	
2.10	Electrical conduction	Replacing Copper
2.11	Low-Energy ICT solid state memory	
2.12	Energy Harvesting	Piezo electrics Photovoltaic
2.13	Vegan ingredients	
2.14	Non-animal testing	
2.15	Civil nuclear	Alloys
2.16	Extreme environments	
2.17	More functionality with fewer inputs	
2.18	Recyclability of components	
2.19	Multi-application structural	Polymers – sustainable: recycling, additives Multi-function polymers/Polymer Liquid Formulations
2.20	Multi-application functional	sustainable: recycling, additives Multi-function components (reducing overall number of materials, better recyclability)
2.21	Recovery from waste	
2.22	Rare earth element recovery	
2.23	Skills	Materials/chemical scientists Green chemistry embedded in training Digital skills

	3. **ELECTRONICS, SOLAR & PV**	
	Priority Area: Application/material classification	**Priority Area: Application/properties/challenge**
3.1	Batteries/Fuel cells	Recycling Reclaiming key elements/minerals Battery-grade graphite, nickel, cobalt, manganese, SiC, Low-cost fuel cell catalysts – Pt replacement Electrodes & electrolytes
3.2	Comms, Sensing, Data transmission	Autonomous sensing Lightweighting/ low SWaP Energy-efficient comms THz comms & sensing 6G high-data-rate transmission Superscale data centres and transmission Spintronics and magnetics for data storage Quantum technologies – positioning, navigation & timing Neuromorphic technologies - Photonic & quantum components
3.3	Computing	Low-loss electronics System-on-Chip System stack layers coupling
3.4	Solar PV/ Renewable energy transmission	Light weighting for aerospace/space applications Structural solar PV Solar cell transparency Grid inverter efficiency PV device interconnects, substrates, thermal management
3.5	Sustainable, higher efficiency semiconductors	Ultra-wide band gap materials (e.g. GaO and diamond) Sustainable, low-cost substrates Phonon control
3.6	Electrical/thermal insulation	Dielectrics performance SF6 replacement (non-Green House Gas) ETICS/piezoelectric performance Intelligent piezoelectrics
3.7	Electromagnetic coatings and devices	Enhancing design freedom between form factor, bandwidth, efficiency
3.8	Hydrogen	Storage, transport
3.9	Metrology	Complex, dynamic systems
3.10	Motors	REE replacements
3.11	Skills	Need for specialist engineers Materials scientists

4. **ENERGY**		
	Priority Area: Application/material classification	**Priority Area: Application/properties/challenge**
4.1	Energy efficiency	High efficiency heat exchangers Phase transition materials for heat (energy) storage High thermal capacity storage
4.2	Energy transmission	Low resistance conductors for energy networks e.g. HTc Supercons
4.3	Nuclear	Novel reactor systems High-Temperature Near net shape components
4.4	Engineering Biology	Solid state – Biology links Biocatalysts
4.5	Batteries	H_2O-based electrochemistry Carbon-based electrodes Solid State batteries - recyclable High conductivity-low porosity plates for flow batteries Electrolysis efficiency
4.6	Magnets	For fusion Alternatives for motors/generators
4.7	Polyfluorinated alkyl substances	Non-fluorinated Ion-exchange membranes Non-fluorinated o-ring/gasket materials for harsh chemical environments
4.8	Extreme environments	Non-fluorinated o-ring/gasket materials for harsh chemical environments Coatings to extend operational lifetime
4.9	Hydrogen-based power	Catalysts Storage & transportation
4.10	Lightweighting	Photovoltaic Wind turbine blades
4.11	Sustainability/circularity	Valorisation of lignin Recyclable structural components Reducing/replacing/recycling rare earth elements CO_2 capture Power to X

5. EQUIPMENT & MACHINERY		
	Priority Area: Application/material classification	**Priority Area: Application/properties/challenge**
5.1	Heavy duty application tyres	Abrasion resistance
5.2	Recycling-ready materials	Dismantlable composites
5.3	High electrical conduction	Motor coils & wiring
5.4	Extreme environments	Abrasion-resistance
5.5	Refrigeration	Compliance with F-gas regs
		High-electrical resistance fluids for coolant applications (high temperature and also down to -50C
5.6	REE Replacements	Batteries Magnets
5.7	Industrial automation	Self-lubricating gears
5.8	Gas turbines	Ceramic matrices
5.9	RF circuits	Metamaterials – RF manipulation Vacuum-compatible, high-strength ceramics
5.10	Plasma & Power tubes	Consistency/tightness of properties
5.11	Semiconductors	High purity metals, ceramics, alloys
5.12	Lightweighting	Gas storage Load-bearing applications (e.g. composites) Simpler/more dismantlable components
5.13	Alternatives to polyfluorinated alkyl substances	Replacement
5.14	Recycling	Conveyor belt recycling
5.15	UN17 Goals	
5.16	Skills	Engineering

6. FOUNDATION INDUSTRIES		
	Priority Area: Application/material classification	**Priority Area: Application/properties/challenge**
6.1	Nuclear	Alloys – extreme environments, rapid development
6.2	Structural	Wind turbine blades Concrete replacement Lower melting glass with improved strength Heat storage Inorganic fire-resistant insulating panels Switchable glazing
6.3	Photovoltaic products	PV integrated glazing Continuously produced photovoltaic systems on steel/metal substrates
6.4	Lightweighting	Glass
6.5	Digital	Material passports Data sharing to achieve circularity
6.6	Responsive devices	Intelligent components for in situ sensing, monitoring, repair
6.7	Sustainability	Carbon capture and utilisation site of emissions manufacturing Extend capacity use (most metals used below capacity) Improved recycling (tramp elements, glass, deconstructing composites, cast aluminium) Repurposing Waste stream recycling Reducing components, more multifunction materials Electrification Incorporate sustainability into standards
6.8	Skills	Engineering Steel Up-skilling existing workforce Ageing workforce

7. HEALTH		
	Priority Area: Application/material classification	**Priority Area: Application/properties/challenge**
7.1	Solvents/reagents	Alternatives to restricted reagents
7.2	Multiple Applications	Restricted substances alternatives (e.g. cobalt)
7.3	Sustainable packaging (from health products & pharma to agricultural products)	Viable packaging Recycling – less complicated and/or depolymerisation whilst maintaining properties
7.4	Structural metal implants – metal ion sensitivity	Reduction of metal ion sensitivity
7.5	Infection resistance & treatment	Detection and response to infection Infection-reducing surfaces, coatings/surfaces & drug release
7.6	Implants	3D printable metals
		Inbuilt sensing of early failure
		Infection resistant permanent implants
		Detection and response to infection
7.7	Drug delivery incl geriatric and paediatric specific applications	Drug eluting/time release mechanisms/efficiency
7.8	Crop nutrient delivery	Efficient, targeted nutrient delivery
7.9	Bioactive structural applications	Bone/cartilage regeneration
7.10	Soft tissue repair	Biosynthetic Shape memory
7.11	Digital Thread	Wearables Implantables Tracking & accountability of products Predictive simulation for medical devices/in vitro
7.12	Responsive devices: Implantables wearables	"Self-powering" devices Diagnostics Remote drug delivery management Inbuilt sensing (e.g. early failure, infection)
7.13	Regulations	High hurdles in health (e.g. Medical Device Regulations) Epidermal vs implantables
7.14	Recycling & re-use	Prosthetics/medical devices components
7.15	Personal Protective Equipment recycling	On-site technologies
7.16	Alternatives to polyfluorinated alkyl substances	
7.17	Testing	Clinical trial capabilities
7.18	Skills	Bio-interfaces – skills in understanding bio-engineering cross-over

8. PACKAGING, FASHION, CONSUMER GOODS		
	Priority Area: Application/material classification	**Priority Area: Application/properties/challenge**
8.1	Paper	Novel products
8.2	Textiles (automotive applications)	Biodegradable Vegan Stain-resistant coatings
8.3	Cosmetics	Non-animal testing
8.4	Sustainable packaging	Internal bottle coatings suitable for recycling Alternatives to polyfluorinated alkyl substances Plastics: control of morphology – via additives, processing Circularity: focus on technologies that have similar or more properties with fewer components Compostables and biodegradables are niche products
8.5	Recycling paper products	Better separation of paper & cardboard during recycling to allow much more effective recycled products

9. **TRANSPORT**		
	Priority Area: Application/material classification	**Priority Area: Application/properties/challenge**
9.1	Metal recycling	Alloys Cast aluminium
9.2	Lightweight structural – aerospace, automotive	Carbon fibre – manufacture, biobased & recycling Batteries Composites – fewer components, bio-resins Composite metallics/alloys – purity, strength
9.3	Multi-application (suitable for disassembly & reuse)	Multifunction/morphable
9.4	Rubbers – across applications e.g. Tyres, conveyor belts, road surfaces	Recycling, in situ repair Tyres for heavy-duty vehicles
9.5	Batteries	Lightweighting - Solid state/increased energy density
9.6	Heavy duty transport	Batteries & fuel cells
9.7	Extreme Environments	Temperature Pressure Corrosion Multi-extremes
9.8	Hydrogen Ammonia Internal combustion engine	Generation Storage
9.9	Sustainable structural components for aerospace	Bio resins
9.10	Isothermal applications	Resins/adhesives
9.11	Aerodynamic surfaces	
9.12	Hi-performance electricals	
9.13	Recycling	Wind turbine blades
9.14	Responsive components	Thermal management Embedded structures for signal & power distribution Structural health monitoring (SHM) bonded structures
	Moveable structures	
9.15	Digital Thread	Materials Passports Digital twinning
9.16	Skills	Up-skilling existing workforce Not enough engineers Digital skills