Innovate UK

Materials and manufacturing vision 2050

Reimagining materials and manufacturing together

Materials and manufacturing vision 2050

The UK has clear potential to become a world-class destination of choice for advanced low-carbon manufacturing.

The 3 strategic imperatives will be:

- net zero and resource efficient
- resilient and responsive
- technologically advanced and digital

Key messages

UK manufacturing faces urgent challenges such as climate, resilience and productivity

UK manufacturing offers incredibly exciting opportunities and is a great career option

UK has the talent and innovation infrastructure to realise its vision of being world-class

UK materials and manufacturing will be mission critical for our economy and society. Share your thoughts and get involved. Visit us at:

www.ukri.org/reimagine-manufacturing

Foreword

With a long and proud history in manufacturing and materials, the UK continues to be an important global player in both. All sectors now face radical change, as the real impact of climate change and the practical actions needed to deal with it become more significant.

With radical change comes both opportunities and challenges for the UK and for our research, innovation and business system in particular.

The Innovate UK Materials and Manufacturing Vision 2050 sets out some thought-provoking considerations . It is aimed at stimulating interest, focus and action to make the UK a leading, world-class destination for advanced low carbon manufacturing. In fact, it is a complete reimagination of the role that materials and manufacturing should have within our economy and society in a strongly net zero focused world.

The following pages delve into challenges and opportunities facing the UK materials and manufacturing sectors over the next 30 years.

As the UK's innovation agency, we aim to inspire, involve and invest to support innovation.

We want to **inspire** you with this vision of the UK as a world leading manufacturing ecosystem. We have worked right across the UK to create this vision and we want to continue to involve you in the years to come. We want your help to evolve this living document and to challenge us where you think we've not got it right. The vision is not intended to be a prescriptive roadmap of activity – instead it will guide our decisions on what to support and where to invest; we hope it will do the same for you.

The Innovate UK Materials and Manufacturing team has worked to involve and consult many, many people across business, academia/ research, and government. I would like to thank all those people for their involvement, experience and ideas.

Now is the time to reimagine manufacturing together, and the Innovate UK Materials and Manufacturing Vison 2050 is going to be the best stimulus to do that, and become an enduring contribution to doing that in a productive way.

Indro Mukerjee
Chief Executive | Innovate UK

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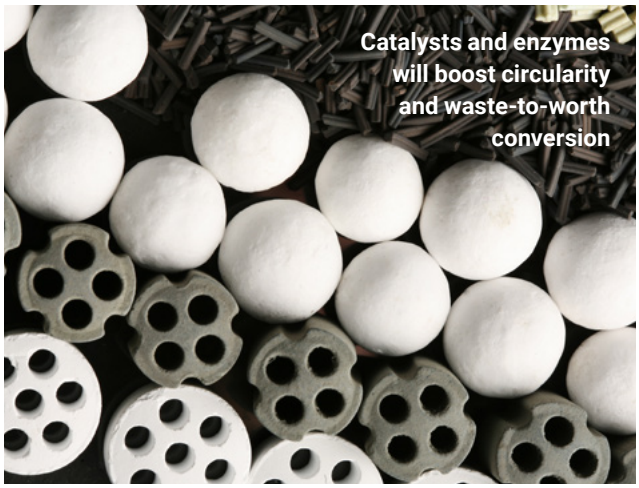
Executive summary

Reimagining materials and manufacturing together

The UK is one of the largest global manufacturing nations. Materials and manufacturing are pivotal to our economy and our society. These sectors are facing radical change. Our Materials and Manufacturing Vision 2050 and the analysis behind it demonstrates significant opportunities to make a real economic, environmental and societal difference to the UK. This document also shows how businesses must adapt and evolve in order to secure market position and grow.

Materials and manufacturing play a vital role in the UK economy through driving innovation, exports, job creation, productivity and growth. Over the next 30 years these sectors must adjust to meet climate change targets, adopt new technologies and adapt to changing customer demands. There are huge opportunities to transform the UK into a global destination for green and sustainable manufacturing and to develop and adopt new material applications to help meet the climate challenge.

This vision explores the manufacturing and materials-related challenges and opportunities likely to face key sectors of the economy by 2050 and the steps we may need to take together to ensure the UK prospers from these changes. We foresee a huge opportunity to boost manufacturing capacity and to make the UK a global centre for net zero and sustainable production. We foresee the UK as a green financing hub and a global destination of choice for advanced low carbon manufacturing founded on a networked ecosystem.



Catalysts and enzymes will boost circularity and waste-to-worth conversion

The vision will guide the decisions we make on how we invest in supporting new products, tools and processes over the coming years. We hope it will also help others to do the same. We must work together and invest collaboratively to achieve our aims.

The vision has grown out of extensive research from the best available information within over 170 documents and out of consultation with over 120 partners across industry and academia, and at UK Research and Innovation, Innovate UK, High Value Manufacturing Catapult, the Department for Science, Innovation and Technology and the Department for Business and Trade.

The view we present is not exact, and the vision is based on the best information available today. We welcome feedback and look forward to working with you as we further develop thinking on the future for UK materials and manufacturing.

Materials and manufacturing accounts for 61% of all business expenditure on UK R&D and in 2019 attracted 22% of all inward foreign direct investment in the UK economy

1 ONS National Accounts. **2** ONS Trade in Goods by CPA and ONS UK Trade.
3 ONS Workforce Jobs. **4** ONS Business Enterprises Research and Development (BERD)]

Bio-manufacturing and bio-plants will produce sustainable feedstocks and fuels at scale

Vision for materials and manufacturing 2050

Our vision is for UK materials and manufacturing in 2050 to be sustainable, safe, advanced, agile and resilient. We aim to stimulate diverse cross-sector debate, facilitate alignment, promote transparency, and inspire creative and transformative action.

Our vision is guided by three strategic imperatives that are mutually supportive. The UK will be an increasingly attractive place to manufacture goods with organisations in materials and manufacturing embracing innovation to be:

- net zero and resource efficient, understanding the environmental impact of every stage in the supply chain and manufacturing process and widely adopting sustainable practices
- resilient and responsive with the agility to mitigate risks arising from the changing global economy, interruptions to supply of critical minerals and materials, national and global disruptions, and climate change
- technologically advanced and digital to improve efficiency across supply chains, enable novel business models, support whole-system design and deliver highly customised products.

Our vision is guided by these three strategic imperatives. They provide the key insights for 10 areas of focus – five core areas and five enabling areas where we expect major change and where the UK has the strengths to take advantage. The core and enabling areas should be viewed as a system where the interactions and symbioisis between the areas are as important as developments within the areas themselves.

The future generation will be inspired to work in materials and manufacturing

Focus areas

The core areas are:

- materials for the future economy
- smart design
- resilient supply chains
- world class production
- longer in use and reuse

The enabling areas are:

- clean energy
- proactive regulations and policy
- future skills
- networked relations
- evolving value models

The core areas

Materials for the future economy

Materials, associated processing and new material applications will be the basis for cutting-edge products that reduce emissions, energy consumption and costs for UK manufacturing. The UK's strengths in standards, packaging, materials science, sensors, steel production, textile weaving and space technology mean it is well placed to take advantage.

Smart design

Effective design methods, design for resource efficiency, and design for maximum through-life value, with a digital thread over the lifecycle of products, will be at the heart of UK manufacturing. UK strengths in high-value design, complex systems with through-life engineering and digital technologies and information management can set us apart from global competition.

Resilient supply chains

Sustainable feedstocks, supply chain visibility, and co-location of waste and emission streams will support UK manufacturing. The UK has a strong reclamation culture and the materials recycling expertise to take advantage. It is also well placed to embrace servitisation and benefits from a strong research and technology organisation (RTO) network including the High Value Manufacturing Catapult.

World-class production

Flexible production capacity, minimal material waste, high-quality products, streamlined productivity, and agile and adaptable operations will allow manufacturing to thrive. The UK has many strengths that set it apart, including economy of scale for large factories, long tradition of foundation industries, focus on high-value manufacturing, and strong automotive and aerospace industries. In addition the UK benefits from a supportive network of research and technology organisations including Catapult centres to help scale businesses rapidly.

Longer in use and reuse

UK manufacturing will minimise materials use and waste, practise complete traceability, and use new remanufacturing services. The UK can take advantage of its design and recycling expertise, its leadership in monitoring with the internet of things and its growing and significant resale and reclamation markets. Value retention processes such as increased product longevity and remanufacturing can be a key component in driving down the cost of living.

The enabling areas

Clean energy

A decarbonised, affordable and secure energy system will power UK manufacturing. Strong offshore technologies, wind turbine, hydroelectric and solar industry, developing battery supply chain, and nuclear research and development give the UK a strong advantage.

Proactive regulations and policy

A trusted regulatory framework, coordinated policies, and agile and forward-looking standards will accelerate assurance within UK manufacturing. The UK's rich standards legacy, ethical environment and expertise in metrology and carbon accounting mean it is in a good position to take advantage.

Future skills

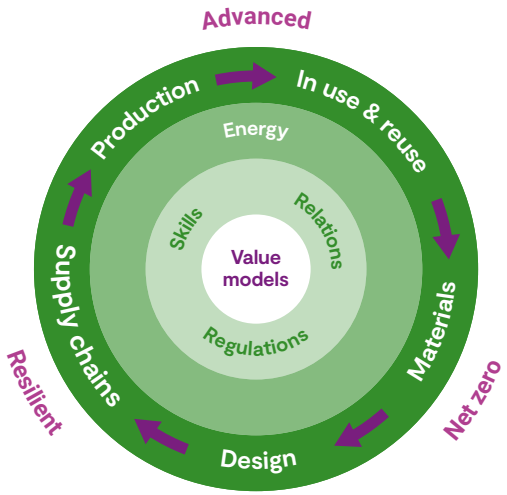
Courageous leadership, critical skills foresight, upskilling and diverse talent will drive manufacturing. Growing student numbers in STEM subjects, increased apprenticeships, technician training opportunities, a flexible workforce, and expertise in cyber security, computer technology and decision sciences give the UK a strong advantage.

Networked relations

Collaborative networks, open knowledge sharing platforms, and aligned investment will energise manufacturing. The UK has many advantages including a thriving network of researchers, developers and investors, a strong Catapults network, ambitious industrial policies, and leadership in areas such as food safety and traceability, use of data and cyber security.

Evolving value models

Innovative business models, agility to meet demand, green financing, and balanced trade will drive manufacturing. The UK is well set to take advantage with its net zero policy and strategy, commitment to growth in research and development, funding for new business models, and strength in high-tech manufacturing.



Introduction

UK materials and manufacturing will be globally competitive in 2050 by being technologically advanced, digital, safe, resilient, resource efficient and sustainable

Successful UK materials and manufacturing sectors are fundamental to economic growth, prosperity and competitiveness. They also improve the resilience and security of UK supplies and are key to achieving environmental and sustainability targets – including, as defined by the United Nations, "meeting the needs of the present without compromising the ability of future generations to meet their own needs"[1].

Materials and manufacturing will undergo radical change over the next three decades to meet sustainability targets and adapt to new technologies and changing consumer demands. We expect future manufacturing to not only meet net zero targets and minimise waste but also to make money from negative emissions and from recycling any waste produced. Future manufacturing will use new sustainable materials and chemicals and make personalised products with digitised, highly autonomous and adaptable systems. Some materials will even be produced in space. Products will have a longer life and will be supported by stronger services that promote that longer life and reuse.

We expect future manufacturing to employ a highly skilled and adaptable workforce that enjoys higher wages and increased job satisfaction.

We see huge opportunities for the UK to be at the centre of this global revolution in manufacturing. We can build manufacturing capability, and we can make the UK a global centre for net zero and sustainable production.

Why we need a vision

We have drawn up a vision of how UK materials and manufacturing could look in 2050 and drafted a model for the collaborative development of key priorities needed to reach this vision.

A common understanding will contribute to more aligned decision-making and quicker, more effective, and cheaper realisation of environmental, societal and economic benefits.

We aim to:

- propose aspirational and realistic manufacturing futures by using an open process to consolidate multiple studies into one model that has reproducible outcomes
- create a platform for debate and collaboration with communities and across sectors and maintain continuity through regular updates
- bring greater alignment and long term continuity around a future vision and pathways and create more attractive UK investment opportunities.

Self-calibrating tooling and no-code platforms will spur automated manufacturing

Why we care

Critical for the economy

Materials and manufacturing sectors play a vital role in the UK economy through driving innovation, exports, job creation and productivity growth. The UK is one of the largest global manufacturing nations, contributing £203 billion GVA to the UK economy in 2021[1] and accounting for 45% of total UK exports[2]. Almost 2.5 million jobs are supported with an estimated 5 million across the entire manufacturing value chain[3]. Small and medium sized enterprises account for 99% of registered businesses and 58% of employment.

Materials and manufacturing accounts for 61% of all business expenditure on UK R&D[4] and in 2019 attracted 22% of all inward foreign direct investment in the UK economy. 84% of manufacturing takes place outside London and the South East so is key to local economies across the UK and essential to support the government's levelling up objectives.

Supporting UK resilience

Resilient manufacturers produce a constant quality at reasonable cost and in time despite disturbances and uncertainties.

Today's supply chains are highly sophisticated global networks that can be exposed to disruptions in both supply and demand. Manufacturers have shown they can adapt and reconfigure when under stress to support demand for essential products and services. This was evident during the recent pandemic when manufacturers were able to adapt quickly to provide essential health supplies and produce vaccines and medicines.

Sectors are on the journey to embrace emerging and digital technologies, develop skills, and embed resilience in operations and the supply chain. All these developments need to accelerate to ensure global competitiveness.

Fermentation reactors will produce proteins and bio-stimulants at scale

Electrification with renewable energy will revive the UK foundation industries

Combatting climate change

Materials and manufacturing will play a role in achieving the UK's net zero target by 2050 and meeting global sustainable development goals.

UK manufacturing, construction and fuel supply industries account for 20% of total domestic emissions. In addition, waste and fluorinated gases account for an additional 6% and 3% respectively, and require reduction through the chain from manufacturing to the consumer.

However, UK choices and innovations inside the factory gate have a wider impact on emissions and waste.

An internal study by the Catapult network in association with Leeds University of direct, indirect and associated emissions from manufacturing, indicates that manufacturing could account for as much as 43% of total emissions associated with UK consumption of goods.

1 ONS National Accounts. **2** ONS Trade in Goods by CPA and ONS UK Trade. **3** ONS Workforce Jobs. **4** ONS Business Enterprises Research and Development (BERD)

Our vision

Manufacturing and materials face many challenges. The scarcity of resources, pace of technological change, global competition, skills availability, and the urgent need to decarbonise, move away from fossil-based feedstocks and embrace sustainability are all stresses that require leadership and constant transformation. These challenges need flexibility, innovative thinking, and collaboration, both nationally and internationally.

This publication is our attempt to look ahead 30 years to see where manufacturing and materials might be and to think about the kinds of support and efforts that we need to put in place to get us there and ensure these sectors remain at the heart of a prosperous and thriving UK.

Our vision is for UK materials and manufacturing in 2050 to be sustainable, safe, advanced, agile and resilient. We aim to stimulate diverse cross-sector debate, facilitate alignment, promote transparency, and inspire creative and transformative action.

Our approach

We have combined the best evidence available, the thoughts of our partners, and our own imagining of the future to create an analysis and a vision that will be a live document that can be adapted as the world changes and as people's views change.

We took key points from more than 170 documents and distilled them into a model of UK strengths, weaknesses, opportunities and threats. We then used this analysis to develop transformation maps that provide more detail on suggested milestones towards a vision.

The analysis includes a collection of logic models that visualise how to achieve our desired outcomes. The models are transparent and are pointing to a total of 35 innovation strands spanning the materials and manufacturing sectors as a whole. The innovation strands are based on current information and traceable to references. The priorities are based on an analysis of quantitative and qualitative evidence.

We sought input from across our network, including from UK Research and Innovation (including the Engineering and Physical Sciences Research Council), Innovate UK Knowledge Transfer Network, High-Value Manufacturing Catapult, the Department for Science, Innovation and Technology, the Department for Business and Trade, The British Standards Institution, industry representatives, and academia.

The vision is based on extensive research including input from more than 120 contributors from industry, government and academia. The approach is deliberately both sector and region agnostic. We recognise that sectors and regions will have specific priorities, however an agnostic approach allows synergies and common areas of opportunity to be identified that would not be visible with a less holistic methodology.

This vision is a snapshot in time and the result of work to date. There are many views and there are evolving near and long-term priorities. We need collaborative work to better understand areas where there is less certainty or lack of agreement on priorities.

Our model and analysis will be kept live and regularly refreshed as new information becomes available and alternative views are analysed.

In-orbit material labs will evolve into microgravity production platforms

Who we are

We are Innovate UK, the UK's innovation agency. Our plan for action for UK business innovation, Building the future economy, explains how we will help deliver the government's innovation strategy. It outlines how we will support businesses and invest in opportunities that will support the future economy. Understanding and shaping the future is a critical part of our role.

In this, we work closely with the High Value Manufacturing Catapult, and the wider Catapult network, independent centres supported by us to bridge the gap between academia and businesses and to provide access to world-class research and development facilities.

The UK government's Innovation Strategy recognises businesses need to both create new products and services and improve efficiencies to compete and thrive in evolving markets. It also recognises that innovation creates huge value for society, including improving wellbeing and quality of life for UK citizens.

We will use the vision to support our own decision-making on areas we support. We will work closely with our partners across UKRI to combat the challenges and meet opportunities. We also hope others, including government and industry, will find this vision useful and use it to inform their own decision-making.

Novel batteries and magnets will reduce dependence on critical minerals

International benchmarking

An international benchmarking study has been completed alongside this visioning work. This identifies international research and innovation collaborations with the potential to unlock opportunities for UK next-generation materials and manufacturing. A key output of the study is a shortlist of the top opportunities for international collaboration, including specific technology areas.

This report covers:

- key motivations and win-win principles for international research and innovation collaboration
- strengths of the UK advanced manufacturing and materials sector
- UK technology priorities and key opportunities for international collaboration
- key partner countries
- implications for the selection and funding of future international collaboration.

It concludes that strategic international research and innovation collaboration in the advanced manufacturing and materials sectors is more vital than ever for the UK to strengthen its global position in the future net-zero economy.

Working within the framework of the National Security and Investment Act 2021, this work will be used in tandem with the opportunities identified in the vision and other sources to support our investment decisions.

Our approach

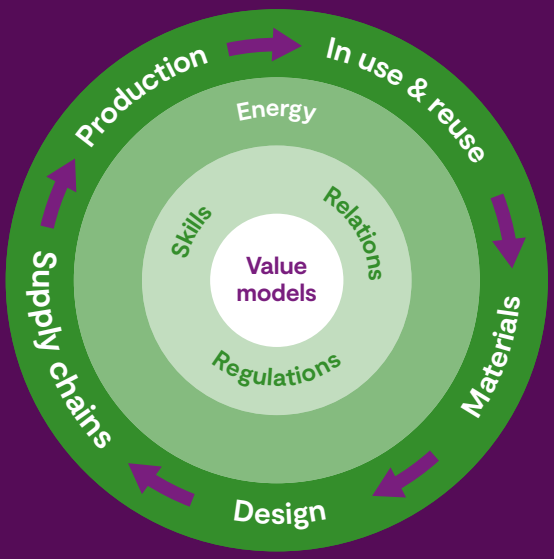
170+

Recent documents researched

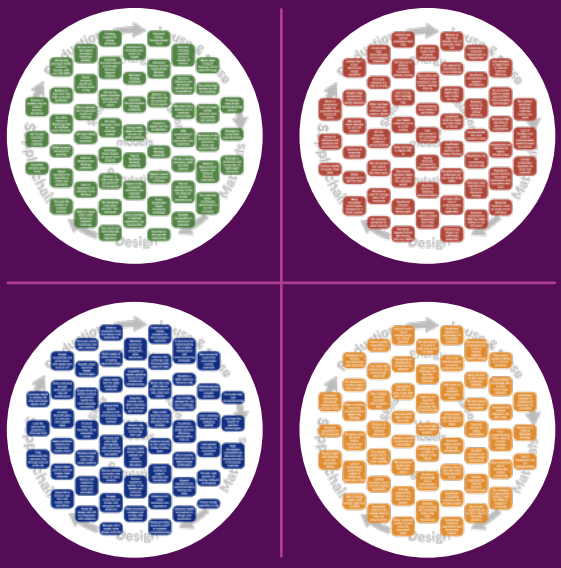
120+

Individual stakeholders consulted

Systems approach

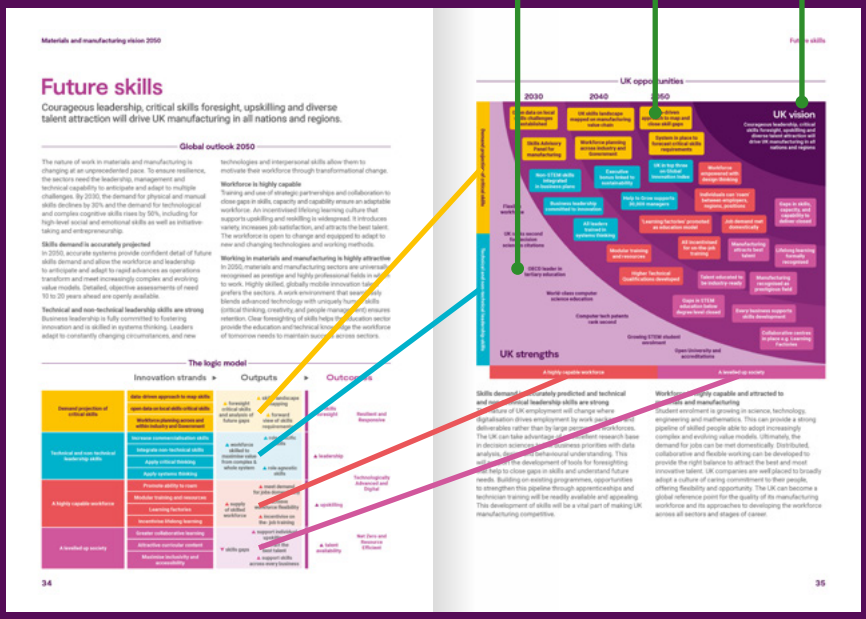


SWOT analysis



Innovation strands

UK strengths Milestones Vision statements



35 Innovation strands identified

Sector agnostic vision

10 connected logic models

10 transformation maps

Vision for UK materials and manufacturing

Our vision is for UK materials and manufacturing in 2050 to be sustainable, safe, thriving, agile and resilient, and able to adapt to rapid advances and to support their operating environment. Materials and manufacturing will be technologically advanced and their impact will be net zero and sustainable.

Our vision is influenced by three strategic imperatives that are mutually supportive. The UK will be an increasingly attractive place to manufacture goods with organisations in materials and manufacturing embracing innovation to be:

- net zero and resource efficient by understanding our environmental resources and the impact of every stage in the supply chain and manufacturing process and widely adopting sustainable practices
- resilient and responsive with the agility to mitigate risks arising from the changing global economy, interruptions to supply of critical minerals and materials, national and global disruptions, and climate change
- technologically advanced to improve efficiency across supply chains, enable novel business models, support whole-system design and deliver highly customised products.

The vision will require systemic change involving society, the economy and technical capabilities.

Organisations will embrace emerging technologies, develop skills, encourage diversity, embed resilience in operations and the supply chain, and build sustainability. This requires flexibility, collaboration and innovative thinking.

Companies will need to adapt and evolve to deliver the right products and services for a sustainable and increasingly digital world. The UK will need to design, manufacture, sell and use products, with associated digital threads, that deliver ever more value during their lifetime.

New value and business models will be in place to meet economic, environmental and societal demands.

The UK can develop new world-leading, reliable and cost-effective sectors, and become an increasingly attractive place to manufacture goods. The case for building capability in strategically key manufacturing and domestic supply chains will be strengthened.

Our strategic imperatives

Net zero and resource efficient

A net zero and resource-efficient UK sector will understand environmental impact across the full lifecycle, including emissions embedded in raw materials, in distribution, in manufacture, in use and at end of life, whether these activities occur in the UK or overseas.

Regulatory requirements will make clean and resource-efficient business models the most profitable. UK businesses will be recognised as global leaders in sustainability and this will enhance their competitiveness.

Businesses will seek to extract the full value from resources, minimise waste and deliver a circular economy. Activity will ultimately be regenerative, restoring rather than exploiting resources, such that manufacturing makes a net-positive contribution to achieving climate targets.

Design engineering will be optimised to reduce material use and human-centred to help reduce and manage demand. Recycling and reuse will be increased, and product life will be greatly improved. Product use and sharing will increase, and materials that we see as 'waste' today will be valued. These materials will be sold into new markets or adapted as a feedstock for production of chemicals, low-carbon fuels and materials (for example through catalytic or biotechnological processes), reducing reliance on virgin feedstocks.

Resilient and responsive

Companies will clearly see and be aware of the risks of disruption across all their operations. Manufacturers will adopt autonomous systems that allow them to rapidly adapt to maintain and even improve operations during periods of disruption with limited investment of time and money.

Resilience of supply will improve to meet society's needs and mitigate the risk from interruptions to supply of critical minerals and materials, national and global disruptions, and climate change. Critical minerals, materials and products will be more secure, being increasingly sourced, substituted, made or reused in the UK.

Companies will be responsive to market patterns, capable of rapidly repurposing production to meet demand. Digital and other technologies will be used to maximise resilience against cyber and other threats.

Gaps in skills needed to deliver will be closed through anticipating those needs and upskilling. Strategic partnerships and collaboration will be built to expand capacity and strengthen capability.

Organisations will have the leadership, management, and technical capability to anticipate and exploit multiple challenges, ensuring resilience in the face of a highly uncertain and demanding world.

Technologically advanced and digital

Digital technologies and a digital thread will allow companies to view every stage in the supply chain and manufacturing process. Manufacturing facilities and supply chains will be connected, networked, and fully integrated, allowing live analysis and optimisation.

The UK will be a leader in the development and export of industrial digital technologies and the associated information management, and their application will be widespread.

Processes will be easily customised and provide customers with products they want at the right time and cost. The efficiency, productivity and accuracy gains will catalyse UK manufacturing, leading to extensive reshoring of strategically important supply chains. Emerging and enabling technologies will be rapidly and widely embraced.

Improved competitiveness will be supported through national and international research, innovation and collaboration, enabling the UK to export solutions globally, providing new jobs, industrial growth, and economic benefit.

The UK can develop world-leading and innovative sectors, and become an increasingly attractive place to manufacture goods

Manufacturing system must transform

We will need transformation across the manufacturing system to achieve the vision. End-to-end design engineering for through life and sustainability, sustainable materials and feedstocks, and circularity and resource efficiency are important for emissions and waste reduction, resilience and technological advance.

Manufacturing is vast and complex, so systems thinking is essential to identify the relevant trends and challenges, including their mutual interactions and dependencies. We have identified 10 areas of focus – five core areas and five enabling areas. However, we have retained a single perspective guided by the three strategic imperatives. The areas sit next to each other, and they work together. Throughout our analysis, we have used the three imperatives – net zero and resource efficient, resilient and responsive, and technologically advanced and digital – to provide key insights.

Areas of focus

The core areas are:

- **Materials for the future economy** – discovery, scaling, accelerating adoption of advanced, bio-based and sustainable materials, and the associated processing
- **Smart design** – through-life and multidisciplinary design engineering with support of digital tools to de-risk and prototype new ideas
- **Resilient supply chains** – procurement of raw materials and components, and the repurposing of emissions, solid waste and industrial water back into manufacturing
- **World-class production** – automated and adaptive manufacturing, productivity enhancement, predictive maintenance, biomanufacture and resource efficiency
- **Longer in use and reuse** – sustainable consumption of resources and reuse, repair, recycling, remanufacture, and ultimate disposal products and materials

The enabling areas are:

- **Clean energy** – development and adoption of a decarbonised manufacturing system founded on a reliable, affordable and clean energy supply
- **Proactive regulations and policy** – agile regulatory and policy framework and promotion and protection of intellectual property
- **Future skills** – anticipating and planning for the technical, leadership, innovation and commercial expertise and diversity required
- **Networked relations** – connections between all communities and individuals working on innovation
- **Evolving value models** – understanding, design, customisation, and adoption of increasingly complex or even disruptive organisational business and value models.

Joining the dots

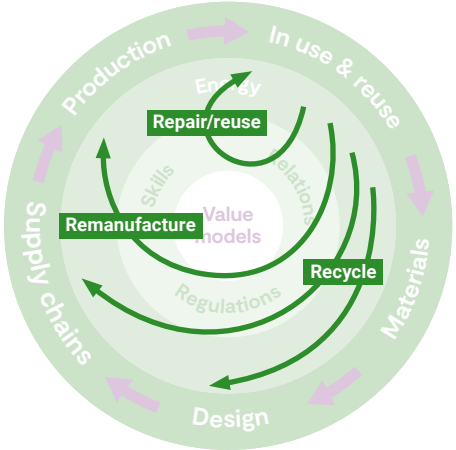
We must keep a broad perspective across all the areas we have identified and bring them together in a systems approach. Breakthroughs often occur when different paths of innovation unexpectedly come together or when diverse technology communities connect. Creativity is at the heart of new technology, and new connections can bring exceptional new value. For example, bringing together new space technologies, material science, and autonomous operations could pave the way for material production in space. This could deliver materials with new and exciting properties and help us to replenish scarce resources.

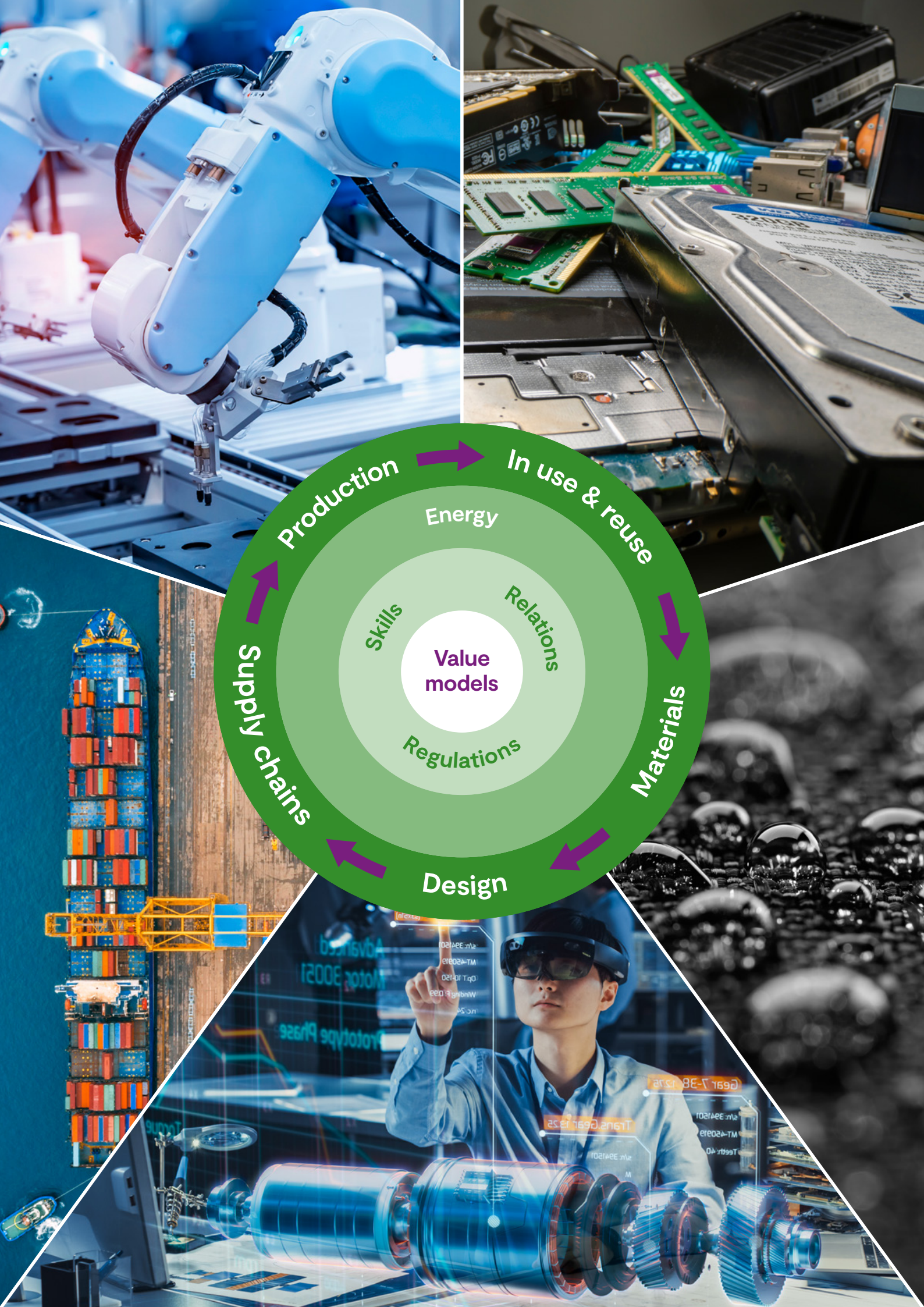
We also recognise that some trends and themes can be in conflict and that technological advance can have unintended consequences. These can pose serious challenges to the environment, to society, or to the resilience of the economy. Examples could include economic growth leading to higher consumption and impacting efforts to achieve net zero and sustainability targets; automation leading to job polarisation and unemployment; and advanced coatings hampering efforts to improve recycling. Innovation should aim to break the orthodoxies that often lie behind the tensions and prevent these situations where gains in one area adversely impact another.

We carried out an extensive analysis of the literature in each area to draw our conclusions on the likely global changes of coming years, the UK's strengths and weaknesses, and the associated UK opportunities. We present each of the areas in the following sections. One graphic (logic model) explains how the changes we envision relate to the strategic imperatives we have identified and a second graphic (transformation map) shows relevant milestones on the way to 2050.

Tightening the loop

Circularity is essential to achieving both net zero and resource efficiency targets as well as improving supply chain resilience. Our vision is that recycle loops will tighten in favour of remanufacture, repair and reuse. This will involve all areas of the materials and manufacturing system.




Production
In use & reuse
Materials
Design
Supply chains
Energy
Relations
Regulations
Skills
Value models

Materials for the future economy

Materials, associated processing and new material applications will be the basis for cutting-edge products that reduce emissions, energy consumption and costs for UK manufacturing.

Global outlook 2050

The rapid discovery with broad adoption and efficient processing of advanced and sustainable materials underpin decarbonised economies and have strengthened resilience in supply chains.

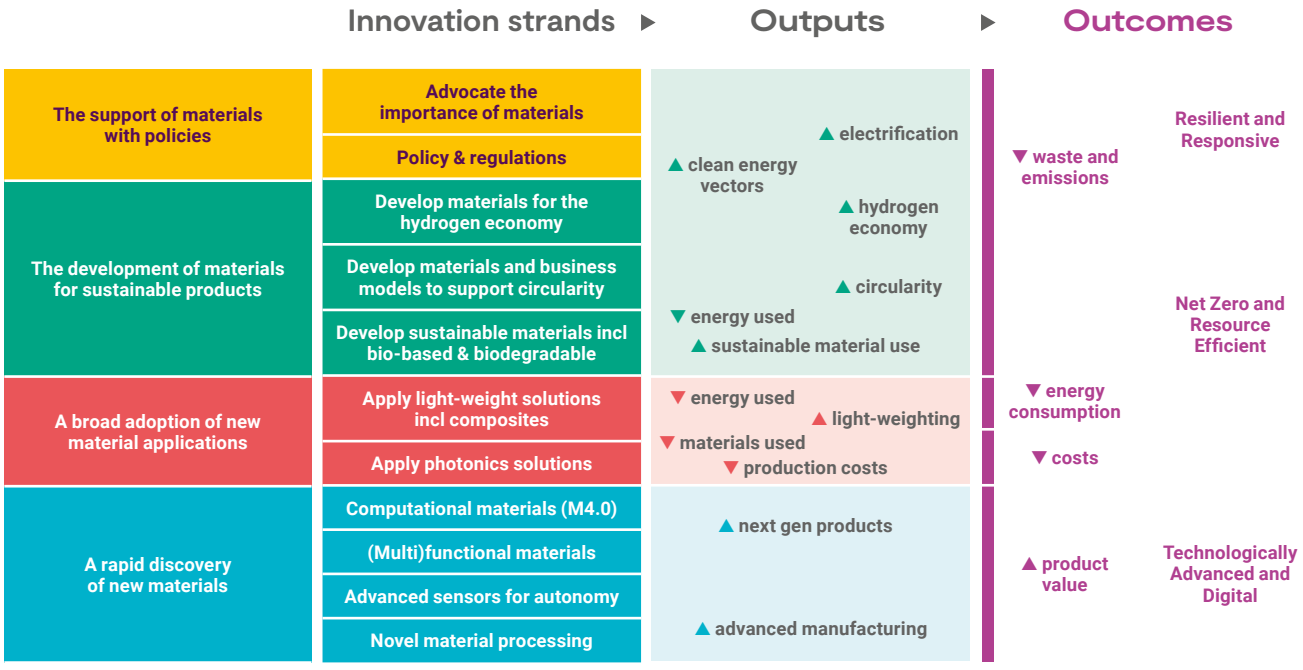
Materials science underpins manufacturing
Materials science and engineering underpin manufacturing through the development of new products and coatings, and creation of new processes to produce those materials. This is recognised in a supportive and dynamic policy framework, regularly updated to reflect developments.

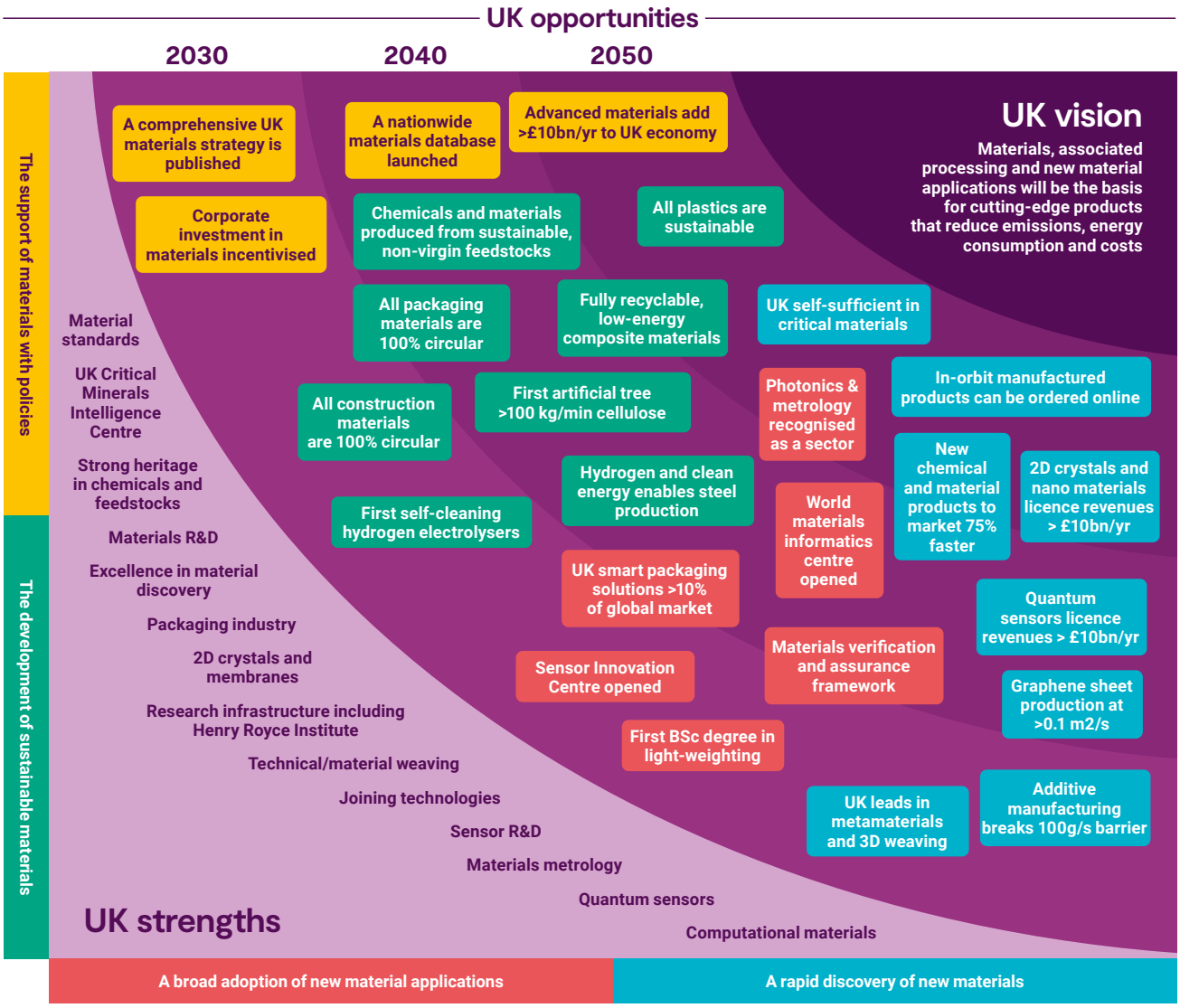
Materials are fully sustainable
Sustainable materials radically transform the design and use of consumer goods and packaging. All packaging and construction materials are designed to be 100% reused or recycled. Chemicals are mainly produced from non-virgin fossil carbon feedstocks, enabled by new catalytic processes, engineering biology and industrial biotechnology. All plastics are sustainable, and all food packaging is biodegradable or edible. The global hydrogen economy is spurred by the discovery of new materials and by the retrofit of legacy gas distribution and transport systems.

New material applications are broadly adopted
Novel material applications are rapidly de-risked and adopted. Aerospace leads light-weighting and spins out revolutionary energy-saving materials for cross-sector adoption. The broader adoption of photonics and low-cost sensors spurs autonomous manufacturing. New catalysts and membranes provide breakthroughs for energy. Design engineers are inspired by new possibilities from functional materials that are driven by interconnectivity, automation, and machine learning – the so-called Materials 4.0 era.

New materials discovered more rapidly
Materials informatics, including machine learning tools and techniques, and physics-based modeling has improved the discovery and development of new materials. New chemicals and materials innovation will be accelerated through the increased adoption of digital technologies in research organisations. Advanced metallurgy, 3D weaving, 2D crystals, nano materials, metamaterials and in-orbit manufacturing are business as usual. Low-cost sensing technologies and high-tech quantum sensors are fundamental technologies in advanced manufacturing. Smart materials continue to be developed with in-built sensors and the ability to diagnose and repair themselves.

The logic model





Materials science underpins manufacturing

The development of next generation materials will need to be incentivised and aligned around common challenges. UK expertise in data science can support material provenance and forensic performance analysis. With organisations like National Physical Laboratory, UK can use its leadership in materials science research, materials data quality, and engineering to accelerate the development of standards. This can be supported with a UK materials strategy and a nationwide intelligent materials database that matches problems with solutions and suppliers.

Materials are fully sustainable

Consumer goods and packaging will need to be increasingly sustainable. The UK has expertise in design for sustainability and the development and production of sustainable chemicals, materials, and smart packaging at scale. The UK can generate significant revenue through licensing of novel materials, in particular for materials that are critical to the hydrogen economy. Environmental and regulatory policies can encourage investment in new and sustainable materials, and incentivise the widespread use of recycled materials.

New material applications are broadly adopted

It will be essential for new materials and novel applications of existing materials to be rapidly and widely adopted. UK aerospace is leading in light-weighting and the adoption of composites and will spin out revolutionary energy-saving materials across sectors. UK can integrate its expertise in photonics and precision sensors in advanced autonomous production systems. The adoption of sustainable construction materials can transform the UK industry and grow exports.

New materials discovered more rapidly

It will be increasingly important to accelerate the discovery of new materials. The UK leads in metamaterials, advanced metallurgy, electrochemical machining, 3D weaving, and in-orbit manufacturing and holds the most valuable patents for 2D crystals, nano materials, sensors and sensor fusion. The UK establishes itself as the global centre for materials informatics and computational materials for designing next-generation materials (Materials 4.0).

Smart Design

Effective design methods, design for resource efficiency, and design for maximum through-life value will be at the heart of UK manufacturing.

Global outlook 2050

Sophisticated design tools are widely adopted to augment human capabilities with technology. Data-supported lifecycle-thinking with an associated digital thread is standard, maximising the value a product delivers and minimising the emissions locked in at the design stage. New approaches to product development are in place to provide high-quality and low-risk solutions to highly complex and rapidly evolving societal and environmental challenges.

Designing the right things

Design engineering is truly multidisciplinary. Open access and secure collaborative platforms facilitate "real-time", agile product creation, engaging consumers and the full supply chain. Digital twins provide a single source of truth across all manufacturing functions. They are used for better prediction and optimisation, for streamlining and transforming processes, and for improving decision-making, increasing agility, and reducing risk.

Circular economy principles are widely adopted. They make product upgrade, retrofit, remanufacture and repair standard practice and remove the "make-use-dispose" mindset. Design for maximum product value through-life, including re-use and recyclability, are standard practice. Regulatory targets have driven the consumer demand to understand social, economic and environmental footprints. The mindset is changing from 'design things right' to 'design the right things'.

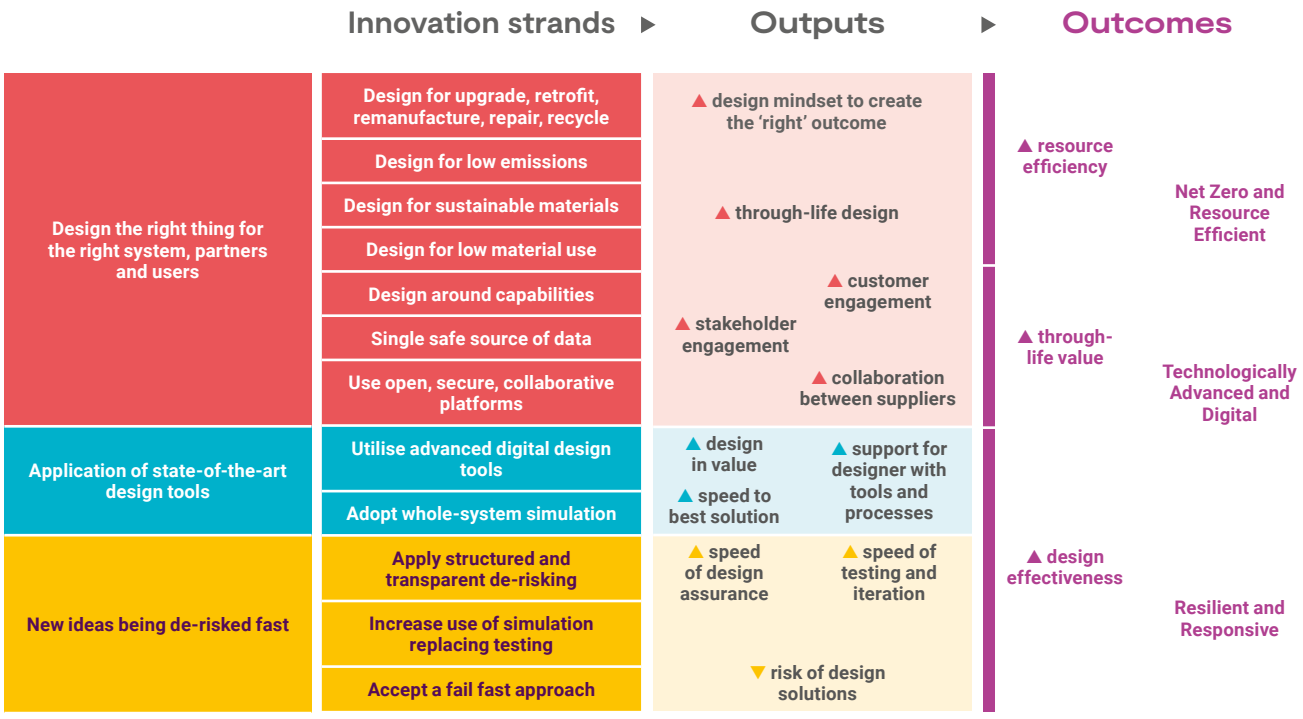
State-of-the-art design tools applied

The design engineer's imagination is augmented by next-generation tools enabling the best solutions to be rapidly and organically found for a given set of constraints. Practical and intelligent algorithms allow thousands of design options to be developed to ensure an optimum solution to meet increasingly complex requirements. Improved understanding of degradation processes and their prediction enables optimised through-life design. Artificial intelligence is universally deployed, guiding the design engineering process and automating analysis, allowing the design engineer to focus on creative tasks.

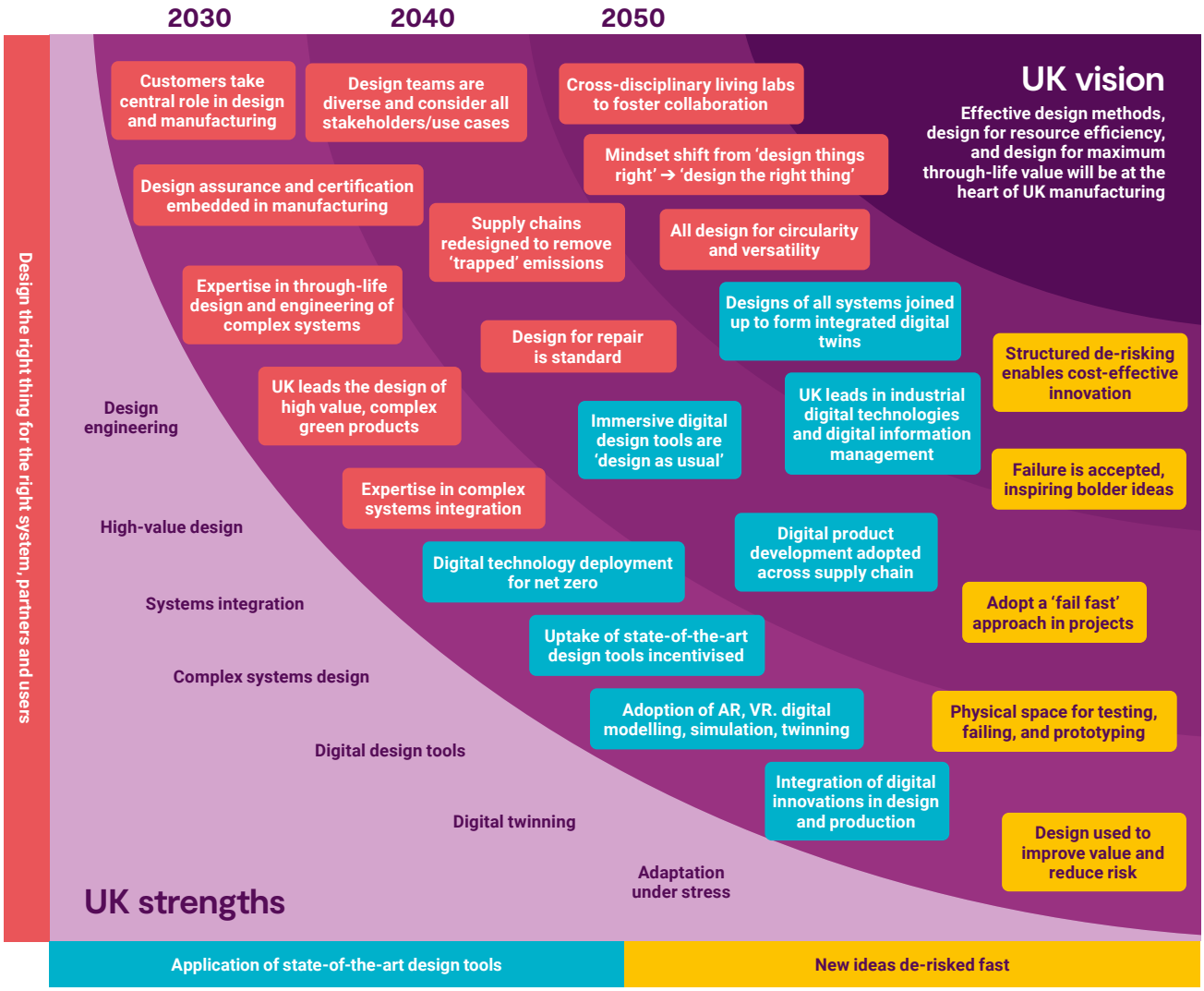
New ideas de-risked fast

Product assurance is rapid and dynamic and supported by advanced analysis and digital testing. This allows validation and certification to run concurrently with design engineering to greatly accelerate the delivery to market of innovative products and services.

The logic model



UK opportunities



Designing the right things and applying state-of-the-art design tools

Design engineering underpins modern manufacturing sectors and is pivotal to minimising emissions, waste and improving resilience. Agility, accuracy and efficiency at the design stage, supported by new technology, can minimise the 70% of a product's lifecycle costs locked in at the design stage. Regulatory targets and increasing product complexity can all be supported by having design engineering at the core of the process from an early stage.

UK has capability in through-life design and engineering of complex systems. This will build understanding of the total emissions that go into making all the materials and parts in a final product. UK expertise in through-life design will enable optimisation of the product, enhancing the resilience of material supply, and reducing emissions. The UK's design engineering specialism has the potential to set it apart from global competition, maximising both the value a product delivers to consumers and the value businesses derive from ideas. There is the opportunity to anchor design in the UK by being the design authority on large programmes.

The UK is well-positioned to lead resource-efficient and generative design by combining technologies such as topology optimisation, biomimetics and additive manufacturing.

New ideas are de-risked fast

Expertise in high-value design engineering and complex systems integration puts the UK in a strong position for value-added growth from embedding digital innovations in design engineering and production. The product design process can be agile and digital, with design engineers working across multiple disciplines to optimise solutions. The UK's respected regulatory framework can be developed to support rapid and flexible design assurance to improve speed to market and reduce the risks associated with commercialisation. Digital design and simulation tools can make the UK more attractive to investors by bridging the 'valley of death' that novel products and services often face.

Resilient supply chains

Sustainable feedstocks, supply chain visibility, and co-location of waste and emission streams will support UK manufacturing.

Global outlook 2050

Change to process, demand or supply brings uncertainty and increases the risk of disruption. This uncertainty increases costs and waste and reduces or, in some cases, stops value creation. Businesses manage this uncertainty through scenario planning, contingency mapping and the taking of calculated risks. By enabling companies to deal with uncertainty, we create more resilient supply chains, which, in turn, create more value with less cost and less waste.

Supply chains are robust

By 2030, we see almost ubiquitous use of analytics to significantly increase visibility across the whole supply chain. By 2040, this drives aligned decisions and reduces waste and cost. In 2050, we see a robust manufacturing supply chain with deep understanding of threats and opportunities.

Some risks, such as natural disasters, remain and require mitigation. Redundancy in the supply chain continues to be necessary, although applied in a transparent way, minimising waste whilst mitigating the risk. Similarly, some geo-political risks beyond the control of companies are mitigated by reshoring strategically key manufacturing supply chains.

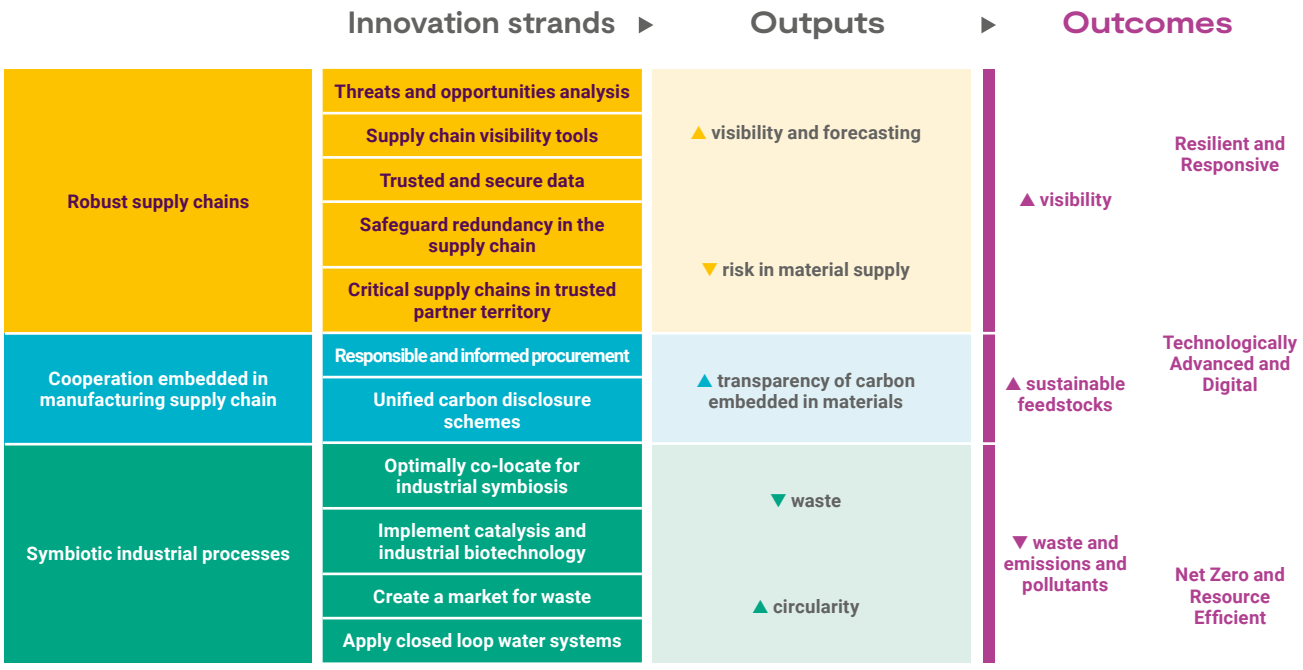
Supply chains are highly cooperative

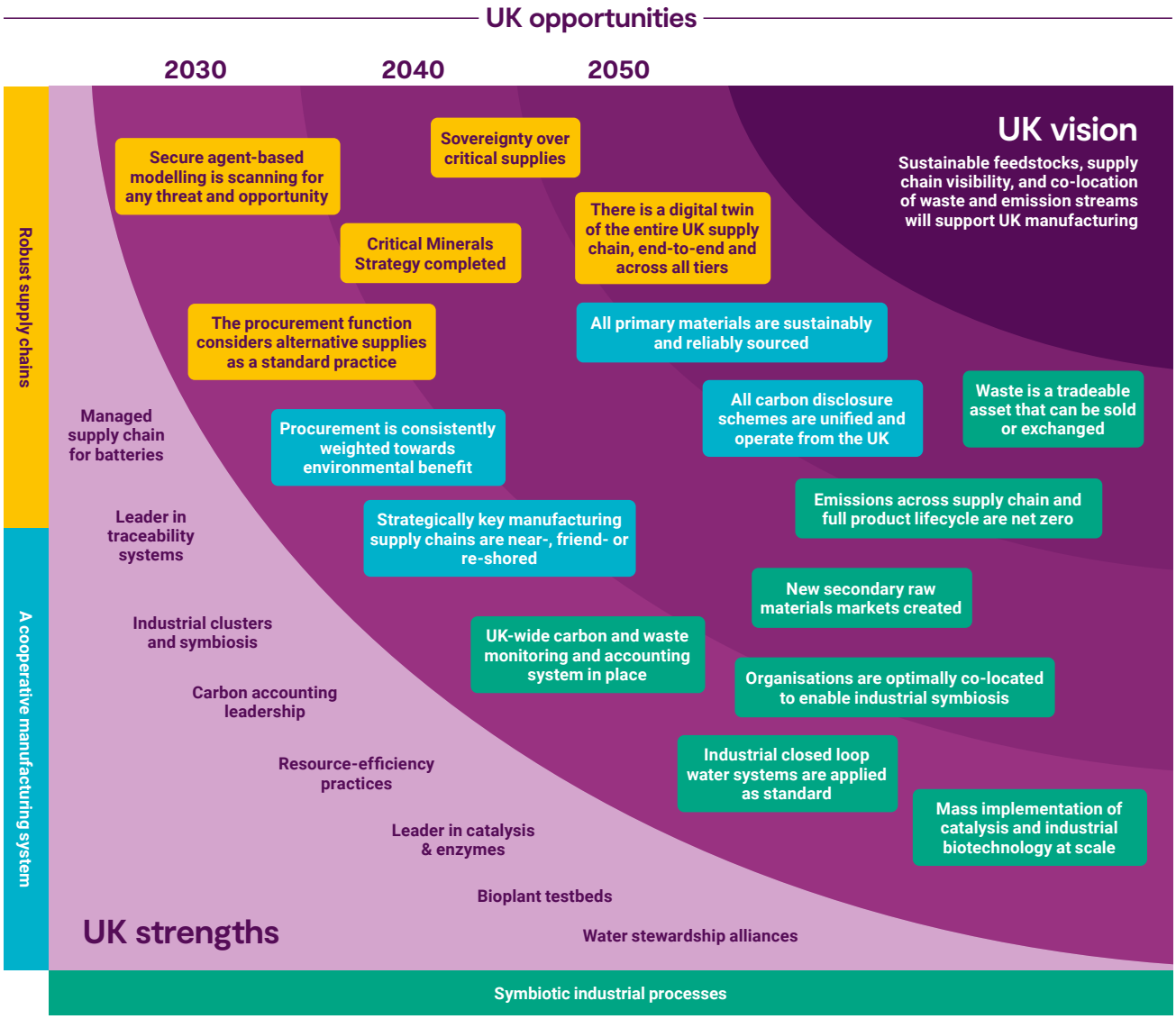
The resilient supply chain of 2050 is highly cooperative. Flows of information and data are secure but shared across organisational boundaries and allow system-level optimisation. By 2030, procurement of equipment and components is consistently weighted towards environmental benefit and, by 2040, all primary materials are sustainably and reliably sourced. Carbon disclosure schemes are common and recognised. Trusted and transparent data flows openly to and from suppliers, producers and end-users.

Industrial processes are located together

By 2040, waste sites and feedstock sites are commonly located together. Industrial closed loop water systems are applied as standard and water leakages are eliminated. By 2050, catalysis and industrial biotechnology have enabled the use of biomass and recycled feedstocks for the production of chemicals and materials rather than virgin feedstocks. Dependency on imported primary raw materials is reduced creating new supply chains in secondary raw materials.

The logic model





Supply chains are robust

Improving visibility through complex supply chains, transparency of data including global information on materials, and forecasting using agent-based models and digital twins will result in significant productivity gains, cost savings and improved resilience. UK manufacturers are well placed to co-develop and adopt these technologies, working with UK leaders in software design and development. The UK will build its own machines, critical components and software more locally, eliminating the historic dependence on other countries. The UK will secure its need for critical materials, find alternatives to rare earth metals, and replace chemicals with bio-based feedstocks. To implement this safely, trust will be critical, and the UK's leading position in cyber security and broader security approaches will be a critical advantage for UK manufacturers.

Supply chains are highly cooperative

Carbon accounting and disclosure schemes will allow buyers to make informed decisions, including end customers. The UK is a recognised leader in developing standards. UK companies are well placed to develop and adopt novel approaches to help them make informed supply chain decisions, giving them an edge in markets moving towards sustainable products. The UK can implement mechanisms and business models to facilitate and incentivise data sharing.

Industrial processes are located together

The UK's strong reclamation culture can be exploited across multiple sectors to enable the UK to adopt more closed-loop systems. Early adoption helps not only because green credentials give a commercial advantage in the market, but also because it reduces risk and secures supply of materials, allowing for cost reduction whilst delivering stronger reliability to the market.

World-class production

Flexible production capacity, minimal material waste, high-quality products, high productivity, and adaptable operations will allow UK manufacturing to thrive.

Global outlook 2050

In 2050, manufacturing is fully optimised to seamlessly flex capacity and meet dynamic demand. Autonomy is commonplace, and reliable self-maintaining systems support rapid adaptation. High-precision manufacturing leads to optimal use of resources and revolutionises product life. Low energy manufacturing techniques are the norm. Water use is optimally reduced across manufacturing operations and in materials production. Technology and automation are readily adopted and ensure high-value employment.

Distribution of manufacturing is optimised
In 2050, distributed manufacturing with production near-shored or where practicable reshored to networks of dispersed manufacturing facilities exists in parallel with larger factories with versatile, adaptable, and targeted, centralised manufacturing. The balance is optimised to specific requirements.

Production capacity is always sufficient
Analytics accurately predict production demand, and the capacity of factories is more adaptable to changes in demand. Greater visibility of the supply chain of machinery and components improves resilience. National foundation industries revive, mainly due to cleaner and cheaper energy solutions and the recycling of materials.

Production leaves less waste
Portable surface metrology, self-calibrating tooling, and high-integrity welding support net-shape production – a one-step manufacturing method removing the requirement for additional finishing processes. Zero-defect high-precision manufacturing leads to higher resource efficiency, reduced wear, increased product life, and less overdesign. Low-weight, compact assemblies, and compliant structures reduce material costs and the bill of materials. Processes are optimised for energy efficiency, minimising demand.

Work is more productive
Robotics, co-bots, and exoskeletons make the workplace more productive, and automation creates high-value employment. Trends towards remote working and virtual meetings lead to an optimised hybrid working model. No-code programming has democratised automation. Next-generation production techniques are rapidly adopted.

Machines are more reliable
Digital twins and predictive analytics are commonly used to design and operate reliable systems. Critical challenges of business continuity planning, cyber security and threats of ransomware are resolved. There are autonomous and self-maintaining plants operated virtually.

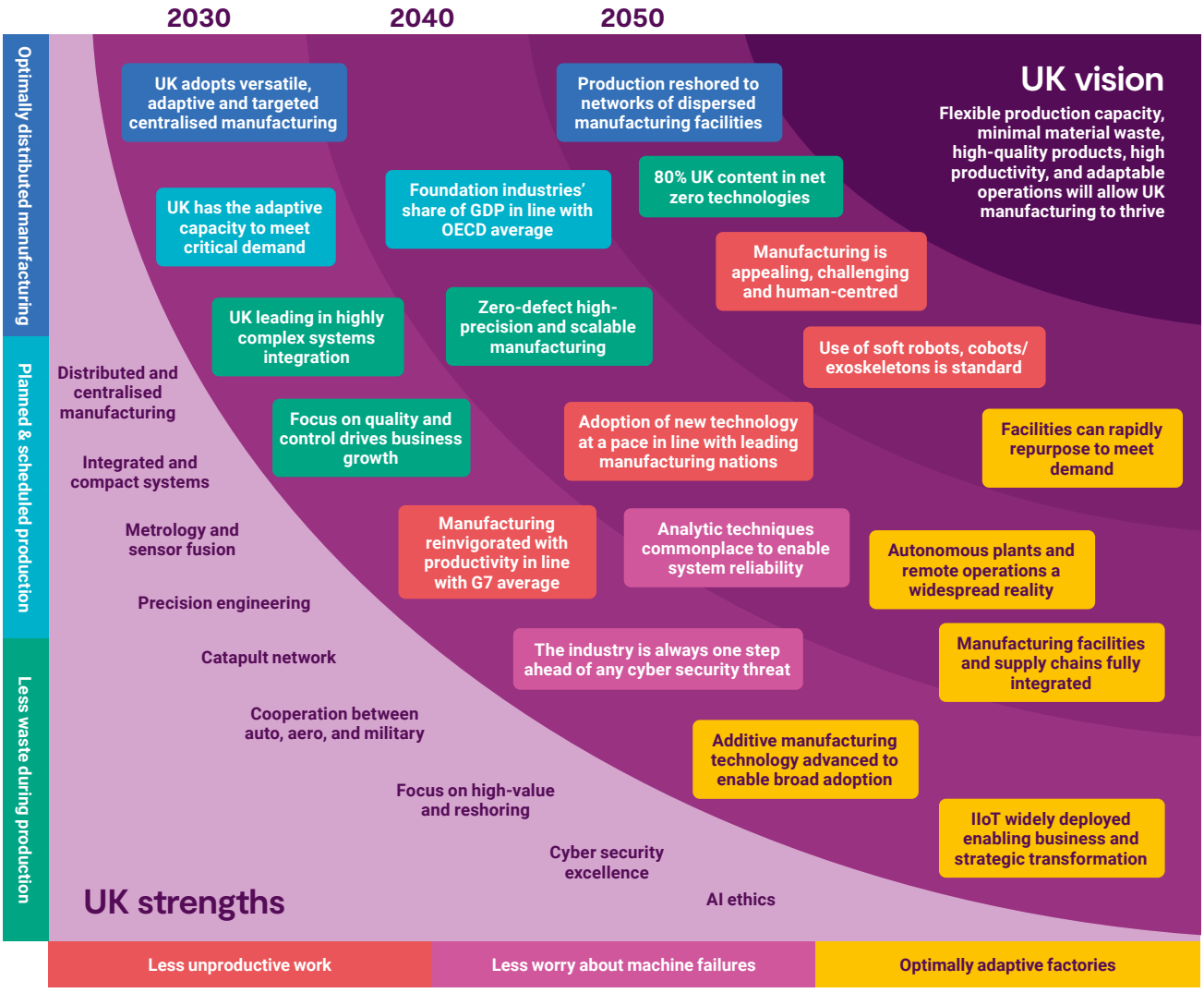
Factories are optimally adaptive
Synthetic sensors, industrial internet of things, sensor fusion, artificial intelligence, and edge computing support adaptive factories, leading to a full integration of manufacturing facilities and supply chains. Process integration has expanded to larger self-healing network alliances. A critical enabler in this new Industry 4.0 (even 5.0) world is a reliable, fast, and low-power wireless network.

The logic model

Innovation strands	Outputs	Outcomes	
Optimally distributed manufacturing	Distribute manufacturing Centralise factories	▲ optimised distribution	▲ capacity Technologically Advanced and Digital
Planned & scheduled production	Optimised scheduling Increase capacity Revive foundation industries	▲ optimised capacity	
Less waste during production	Advance process control Reclaim materials and fluids Improve production quality & control Develop precision engineering Integrate products	▼ overdesign ▲ net shape ▼ swarf metals ▼ machining fluids ▲ product longevity ▼ defects ▼ weight ▼ wear ▲ compactness	▼ material waste ▲ product quality
Less unproductive work	Focus on people Improve systems intelligence Deploy robotics	▲ healthy workplace ▲ automation	▲ productivity Net Zero and Resource Efficient
Less worry about machine failures	Cyber security Predictive maintenance	▲ secure and available production equipment	
Optimally adaptive factories	Interoperable processes & networks Wireless, sensor fusion Responsive reconfiguration Industrial and operational autonomy Agile additive manufacturing	▲ system integration ▲ system intelligence	▲ adaptivity Resilient and Responsive

Advanced metrology will enable cutting-edge precision engineering

UK opportunities



UK wind turbine manufacturing will be advanced, productive, and a force for good

Distribution of manufacturing is optimised
UK manufacturing consists of many small and some very large manufacturing sites and is well placed to grow and adopt two forms of manufacturing in parallel – distributed manufacturing and large centralised factories alongside each other. There is a huge opportunity to reshore high-value design and production and to create high-value jobs in the UK.

Production capacity is always sufficient
UK manufacturing can design and build more production machinery and tooling and reduce its dependence on other countries. Being at the forefront of the energy transition and the hydrogen economy UK manufacturing can revive its foundation industries.

Production leaves less waste
Zero-defect and high-precision manufacturing radically improve product quality, reduce wear, and eliminate overdesign. The UK can leverage its strengths in material science and metrology to design and make, for example, mechanical microdevices for medical applications. Expertise in highly complex products and systems integration is an opportunity to further reduce waste.

Work is more productive
The UK is well placed to adopt a human-centred approach that will make manufacturing an appealing place to work and learn, attracting the talent to increase high-value productivity. The UK's leading role in implementing AI responsibly will minimise unintended ethical consequences. There is an opportunity to lead design and best practice for human-robot interaction in manufacturing. The UK will leverage the Catapult network and the Innovate UK Knowledge Transfer Network to replicate good practices and boost the productivity of SMEs.

Machines are more reliable
UK expertise in building military equipment with cyber security and broader security approaches ensures always being one step ahead of any cyber security threat. It will make UK manufacturing more robust and can generate new security related services. More predictive maintenance and wireless sensor fusion will improve system reliability and integration. The UK's strength in AI, metrology and photonics can play a critical role in developing self-calibrating tooling and self-maintaining equipment.

Factories are optimally adaptive
Meeting the unpredictable demand for new products requires adaptivity. The UK has strong experience in the automotive and aerospace industries as well as the industrial internet of things, sensors and additive manufacturing. This makes UK manufacturing well placed to lead the transition towards Industry 4.0, leading to industry 5.0, building self-configurable factories that can rapidly repurpose themselves.

Humans and intelligent machines will seamlessly work together

Longer in use and reuse

UK manufacturing will minimise materials use and waste, practise complete traceability, and use new remanufacturing services.

Global outlook 2050

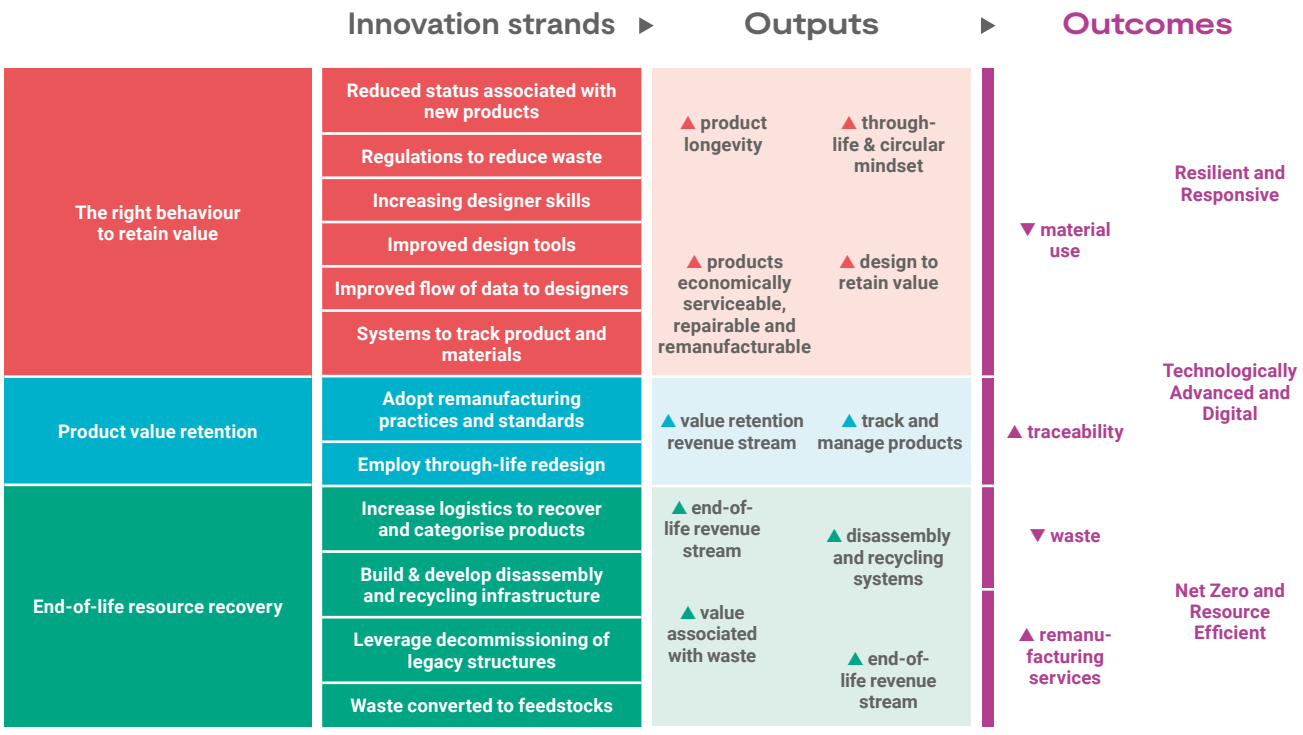
2050 products have a life two-to-three times longer than in 2020. This is driven by changes in customer demand and by legislation and regulation. Fewer products containing less material deliver the same or greater value for the customer for longer, supporting a reduction to near zero in the flow of waste.

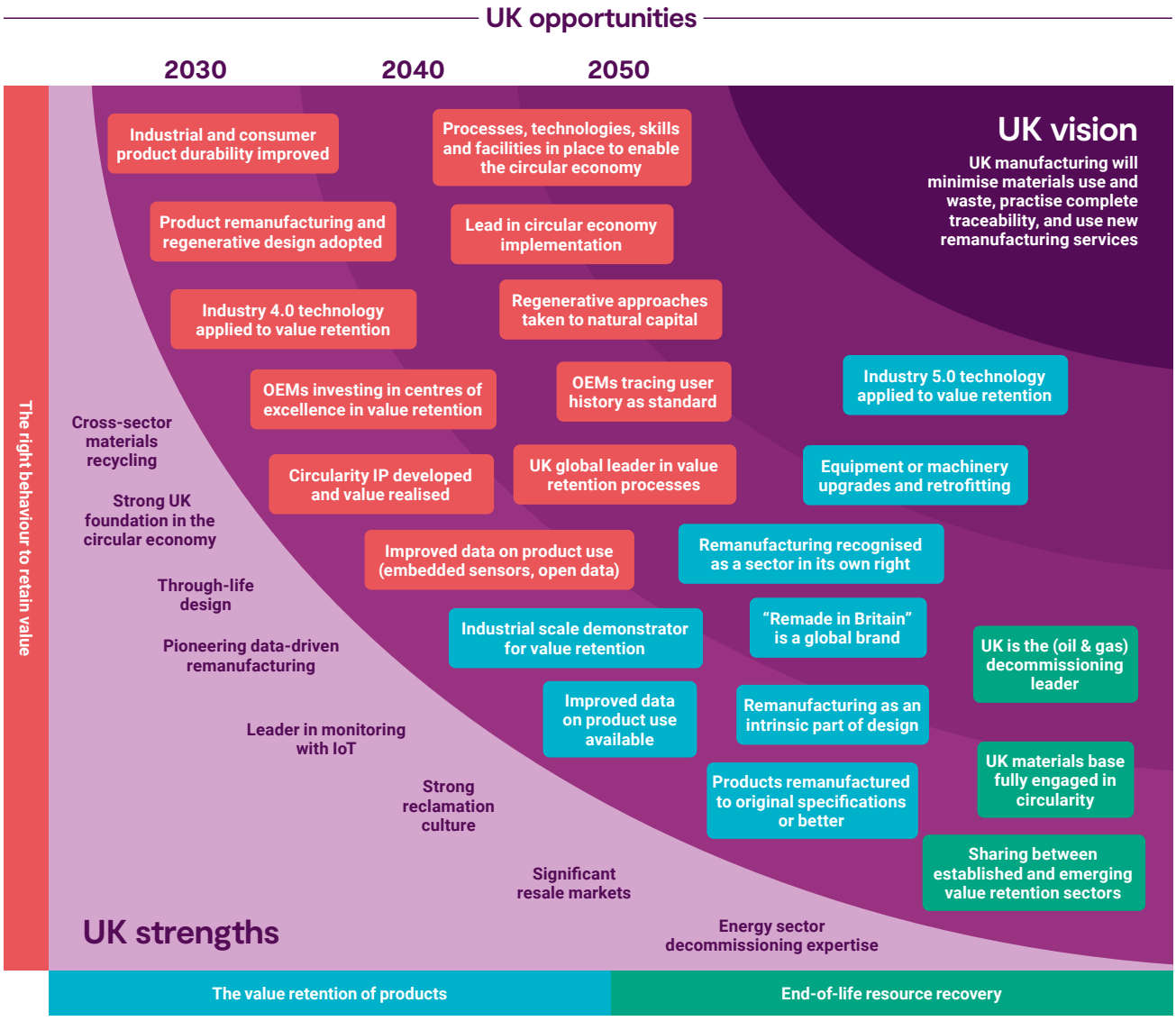
Customers and producers value product life
Customers place much higher value on product life, and social status associated with new products is significantly diminished. Progressive regulation to incentivise repair and reuse and make waste uneconomic has put greater responsibility on design engineers and manufacturers to deliver serviceable and repairable products with increased useful lifetimes and better value for customers. Next generation coatings are widely applied enabling prolonged life and functionality. Consumers will be increasingly incentivised to seek products that deliver more value through life.

Good understanding of through-life value
Design engineering to retain value and to track and manage products through life, including proactive maintenance, has greater importance. Revenue from service and repair is significant, and supporting service is a key product differentiator. Remanufacturing has seen a 10-fold increase in the market and is a viable sector supported by standards and codes of practice. Products are designed for disassembly, service, remanufacture and end-of-life. Design engineers have adopted new skills and new systems are in place (see smart design above).

Procedures in place for end of life of products
Manufacturers have procedures to recover and categorise products to confirm whether they can be serviced, remanufactured, or need to progress to end-of-life processes. They have either developed their own, or subcontracted, disassembly and recycling systems. These are also revenue earners. Where products cannot be recycled, end-of-life strategies ensure no detrimental impact on society or the environment.

The logic model





Customers and producers value product life
A change in design process and approach will be needed to deliver products that last longer and are more easily reused. We will need design engineers with revised skills but importantly also the supporting tools and processes. The UK's design engineering, software and manufacturing capabilities mean it is well positioned to deliver these future tools and exploit the significant future value they will offer.

Good understanding of through-life value
Product monitoring and tracking has enormous potential for growth. Communications industries and systems engineers will need to develop the sensor technologies required. The UK has strengths and is a leader in monitoring with internet of things so is well positioned to develop and deliver systems.

Procedures in place for end of life of products
Maximising the useful life and value of products is already worth £53 billion to the UK and supports around 475,000 jobs. There are significant growth opportunities. The UK is well placed to build on strong research activity, excellent standards development and well-established remanufacturing industries in sectors such as aerospace. Decommissioning, materials and waste sorting recycling expertise across multiple sectors strengthens this position. The UK can establish systems to efficiently extract and reclaim critical minerals and materials from waste.

Clean energy

A decarbonised, affordable and secure energy system will power UK manufacturing.

Global outlook 2050

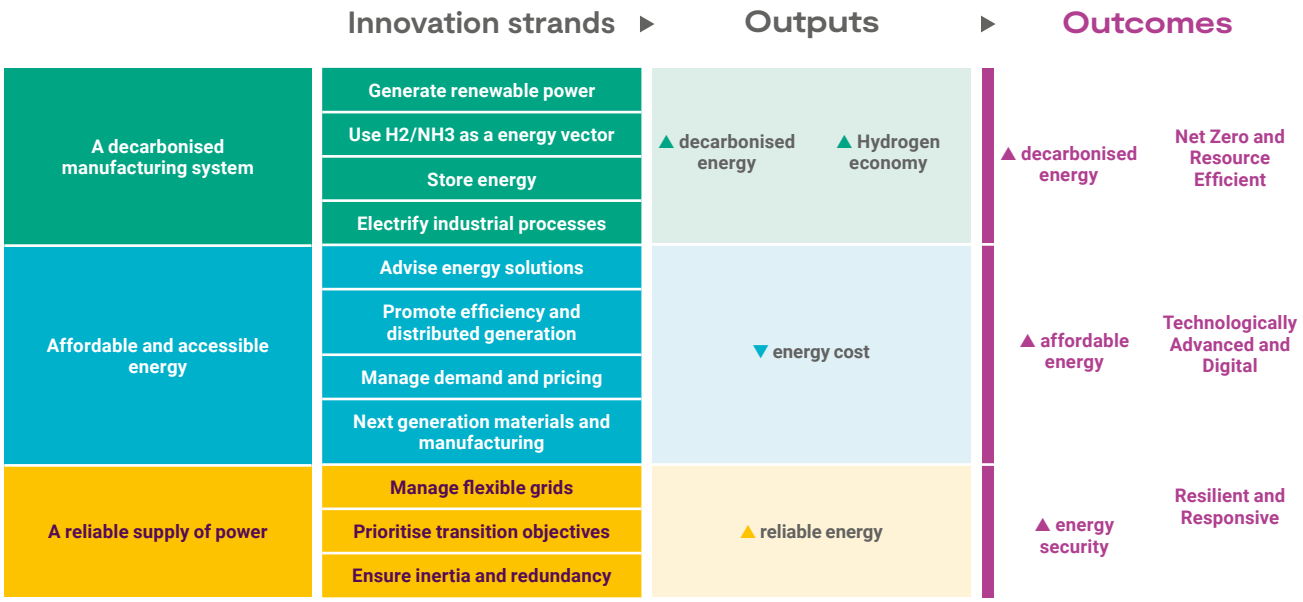
The generation and use of clean energy is essential to reaching net zero. Decarbonisation is driven by electrification and increased use of hydrogen and ammonia as a fuel. Resilience and reliability is ensured by a supply that includes distributed power generation as part of a network of smart grids. Competitiveness is enhanced by increased efficiency, more affordable and secure energy and intelligent pricing mechanisms.

Manufacturing is decarbonised
Power is generated from low-carbon sources supported by cost-effective long-duration energy storage systems. Clean energy grids are used to fuel industry, and zero or low carbon transport is the norm throughout the logistics chain. Electrification of industrial processes drives decarbonisation and achievement of net zero. Greenhouse gas mitigating measures are identified that can be implemented quickly. The dichotomy between clean, affordable and reliable energy is no longer a compromise. Business models that monetise negative emissions are the norm.

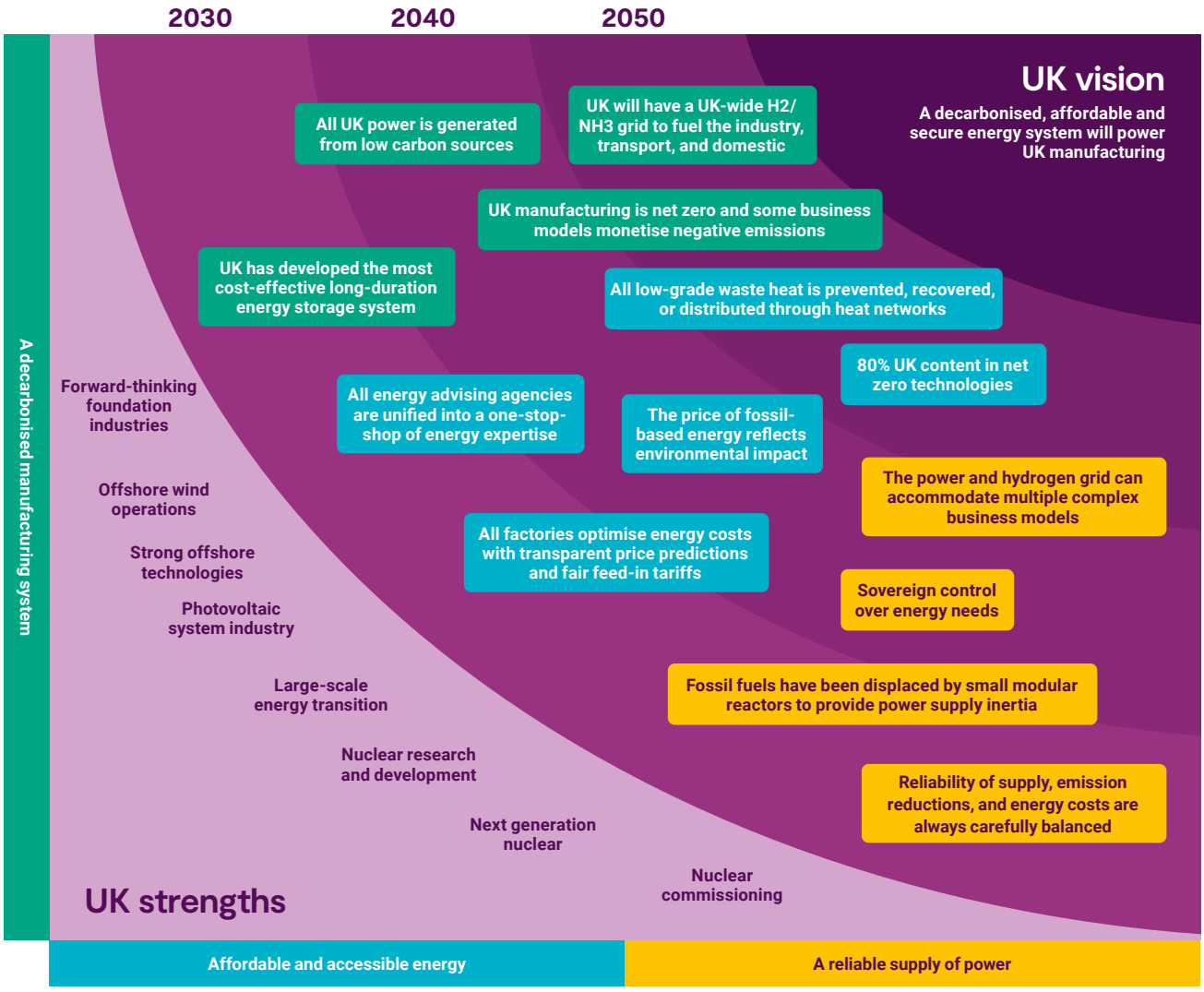
Energy is accessible and affordable
Countries accelerate the use of renewable energy sources to mitigate volatilities in supply of fossil fuels. Low-grade waste heat is prevented, recovered, or distributed through heat networks. Factories optimise energy costs with transparent price predictions and fair feed-in tariffs.

Power supply is reliable
Countries are becoming less reliant on single-source oil and gas. Power and hydrogen delivered from the factory to the grid accommodate multiple complex business models. The reliability of supply, emission reductions, and energy costs are always carefully balanced. Smart distributed energy supply ensures resilience and minimises losses.

The logic model



UK opportunities



Manufacturing is decarbonised

The power supply to all manufacturing needs to be generated from low carbon sources. The UK is well positioned to build on a strong industry to ensure a smooth energy transition. Expertise in whole system integration design and management can be leveraged to develop cost-effective long-duration energy storage. The UK has the opportunity to develop a hydrogen/ammonia grid to fuel industry and transport, supported by electrification of industrial processes. The UK can continue to build capability in the design, manufacture and through-life services to support the introduction and operation of future UK decarbonised energy supply and distribution systems.

Energy is accessible and affordable

Energy efficiency measures need to be universally adopted. The UK is well paced to develop and implement these measures building on network expertise and leading system integration capability. The UK can build heat networks to prevent, recover or distribute all low-grade waste heat. Factories can optimise energy costs with transparent price predictions and fair feed-in tariffs.

Power supply is reliable

UK manufacturing needs a resilient power supply. The UK has capabilities to establish power and hydrogen factory-to-grid systems that accommodate multiple complex business models. Building on UK strengths fossil fuels can be fully displaced by renewables and small modular reactors to provide power supply inertia. Former refinery complexes can be transformed into clean energy parks. Manufacturers can create opportunity through local clean power generation with any excess being fed-in to the grid.

Proactive regulations and policy

A trusted regulatory framework, coordinated policies, and agile and forward-looking standards will accelerate assurance within UK manufacturing.

Global outlook 2050

Regulatory frameworks are trusted to promote innovation and to protect intellectual property. The frameworks are forward-looking and facilitate innovation by creating markets and a conducive environment to incentivise new manufacturing business models. The benefits of standards and regulations are recognised, and their use is stimulated by electronic access.

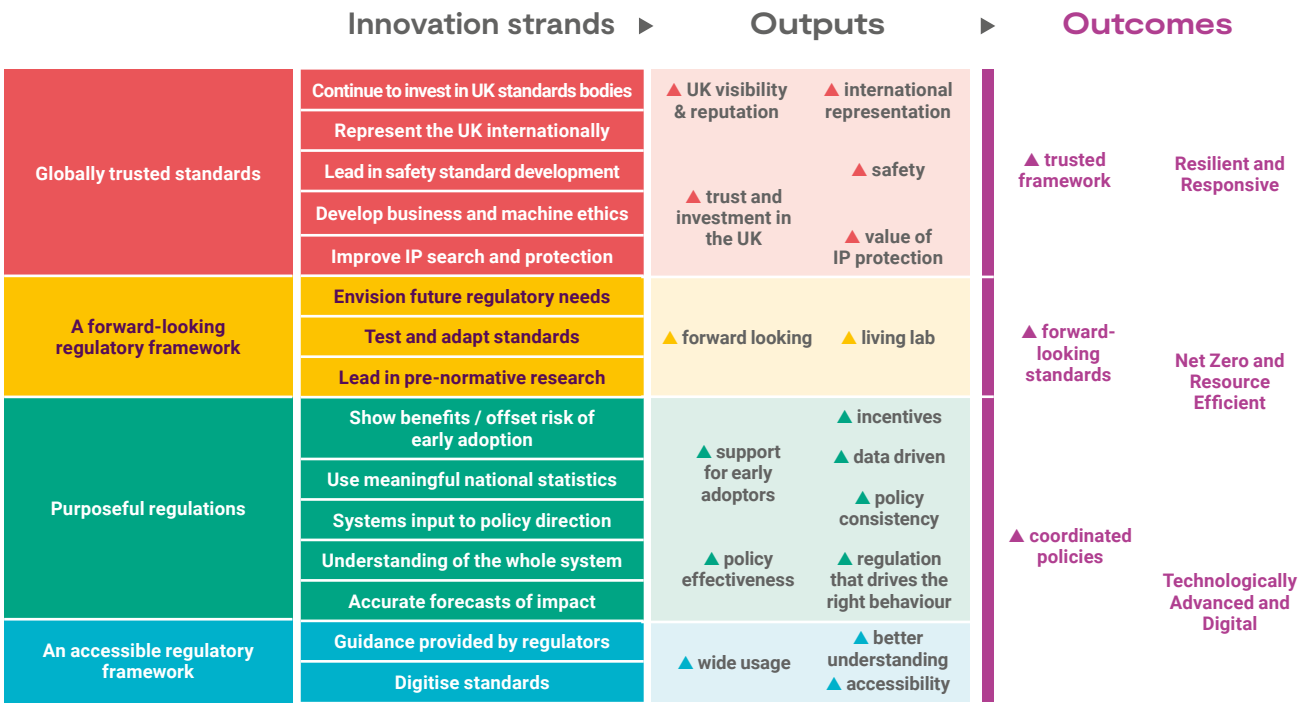
Trust in standards grows
The trust in how regulatory and policy frameworks are developed is growing, both technically and politically. The frameworks deal effectively with counterfeiting and the challenges arising from artificial intelligence and machine ethics, such as 'explainability' in particular to ensure users understand and trust the output from machine learning algorithms.

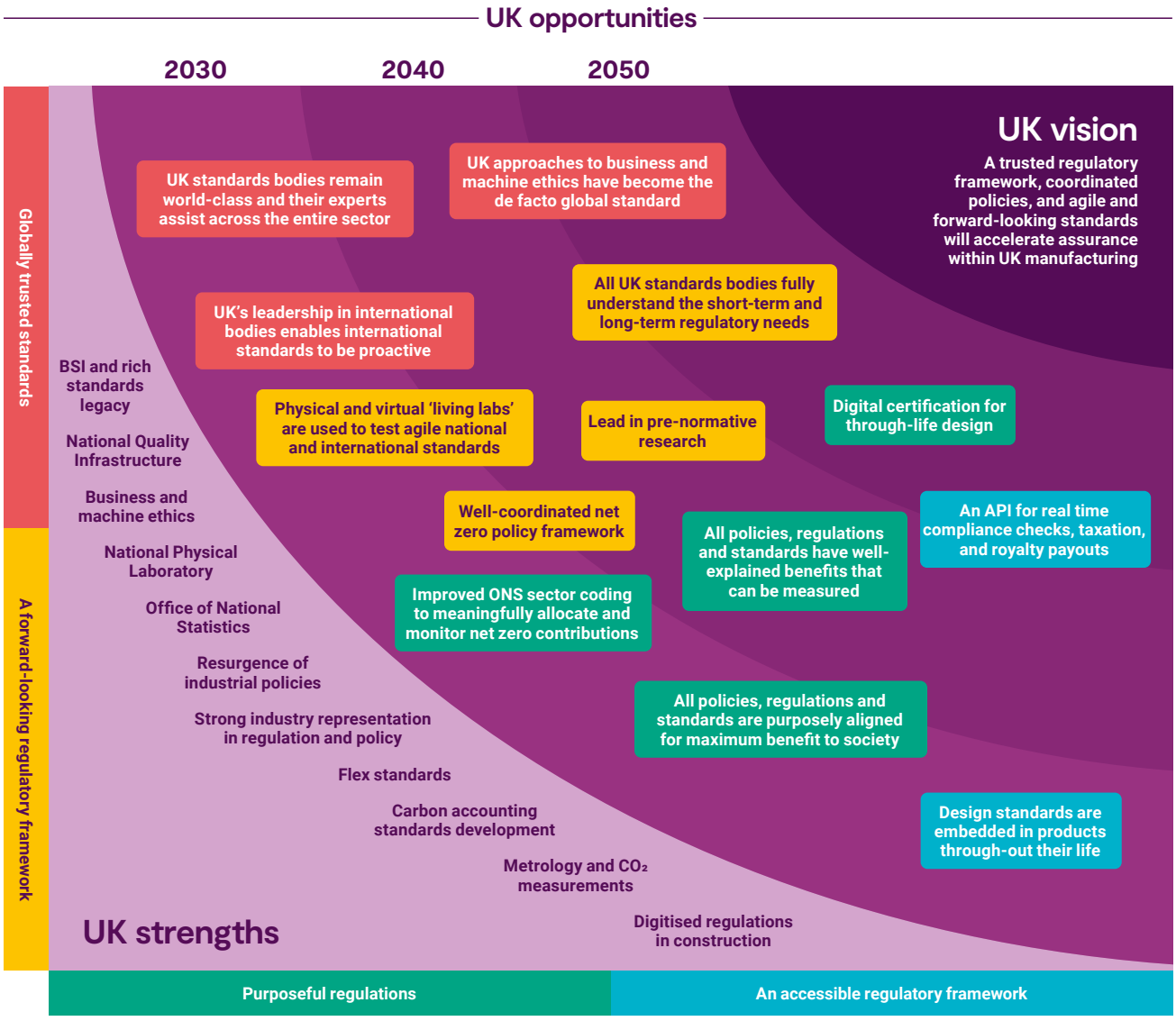
Regulatory framework is forward-looking
Standards bodies understand the short-term and long-term regulatory needs. Critical challenges have been addressed, such as promoting disruptive inventions, domination by large businesses, long standards approval timelines, and standardised life cycle assessment. Pre-normative research is recognised as critical to provide confidence in the absence of formalised standards. Codes, standards and specifications converge across industrial sectors, to recognise and reduce restrictions associated with sector specific requirements.

Regulations maximise benefits
Policies, regulations and standards have well-explained benefits that can be measured, and the regulatory frameworks are purposely aligned for maximum benefit to society. Critical challenges have been addressed, such as public purpose, definition of 'green', definition of 'value added', misinformation, and incrementalism. Policy incentivises organisations to value carbon and other materials for use as feedstock for production of chemicals and materials.

Regulatory framework is easily accessible
Design standards are embedded in all products throughout their life. Further digitisation and use of software integration allows real-time compliance checks. Governments broaden their engagement to support organisations to match their challenges with solution providers.

The logic model





Standards are trusted globally
Trust in the regulatory system needs to transform to support dynamic innovation. The UK is in a good position to drive this transition with a consistent policy framework supported by leading standards bodies. UK approaches to business and machine ethics can become the de facto global standard. The UK can leverage its global soft power and provide leadership in international bodies supporting a drive to global alignment.

Regulatory framework is forward-looking
Policies, regulations and standards need to be more proactive and dynamic. The UK's legacy in standards development, stable regulatory framework and digitised regulation experience give a strong platform. Physical and virtual 'living labs' can be used to develop and test agile national and international standards. The UK can lead the development of artificial intelligence to support causal platforms to protect and use patents and to better match problems, solutions and inventors.

Regulations maximise benefits
All policies, regulations and standards need to have well-explained benefits that can be measured. The UK can build on experience in regulation to ensure systems are in place to enable benefits tracking, carbon accounting standardisation, and GHG measurements. The UK's expertise in metrology will bring GHG measurement standards into practice. The ONS sector coding can be adopted to meaningfully allocate and monitor net zero contributions across the manufacturing sectors.

An easily accessible regulatory framework
The regulatory framework needs to transition to provide real time compliance checks. The UK's strength in standards development gives the opportunity to lead the use of technology such as distributed ledgers and application programming interfaces (APIs) for real time compliance, taxation, and royalty payouts. It can also enable design standards to be embedded in all products throughout their life.

Future skills

Courageous leadership, critical skills foresight, upskilling and diverse talent attraction will drive UK manufacturing in all nations and regions.

Global outlook 2050

The nature of work in materials and manufacturing is changing at an unprecedented pace. To ensure resilience, the sectors need the leadership, management and technical capability to anticipate and adapt to multiple challenges. By 2030, the demand for physical and manual skills declines by 30% and the demand for technological and complex cognitive skills rises by 50%, including for high-level social and emotional skills as well as initiative-taking and entrepreneurship.

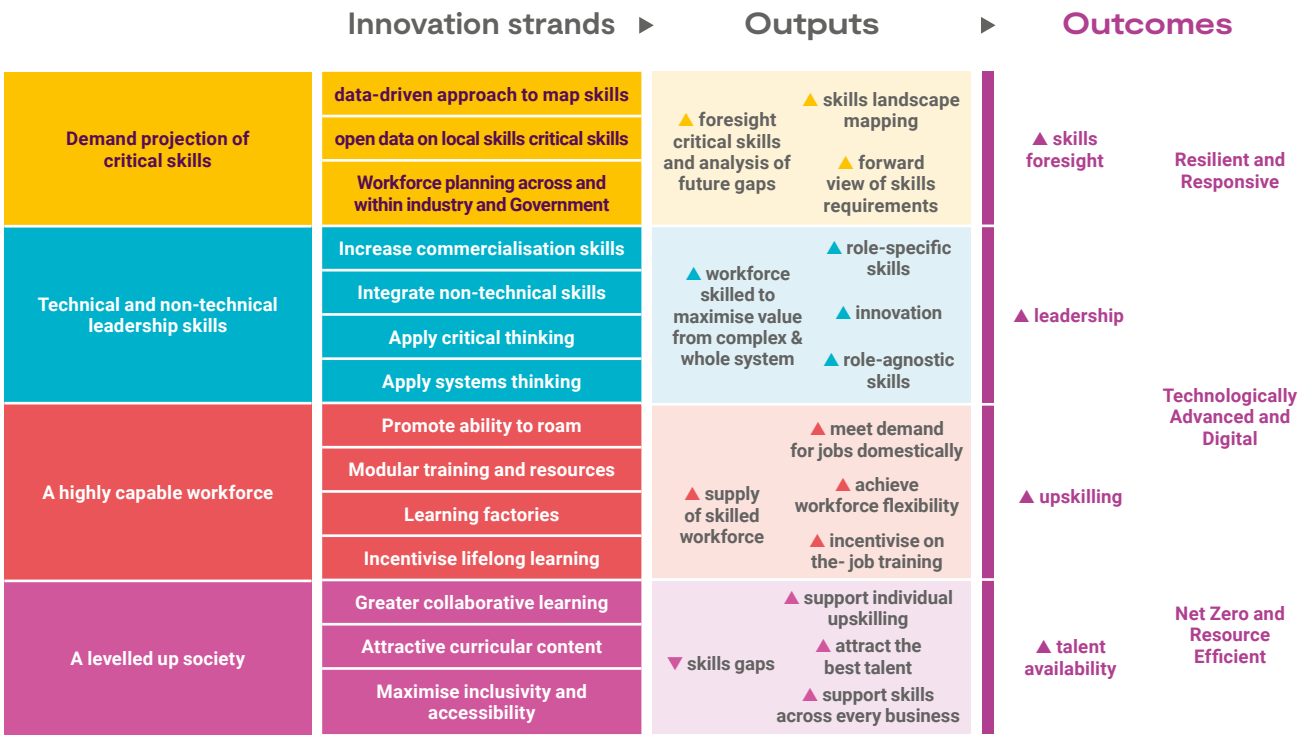
Skills demand is accurately projected
In 2050, accurate systems provide confident detail of future skills demand and allow the workforce and leadership to anticipate and adapt to rapid advances as operations transform and meet increasingly complex and evolving value models. Detailed, objective assessments of need 10 to 20 years ahead are openly available.

Technical and non-technical leadership skills are strong
Business leadership is fully committed to fostering innovation and is skilled in systems thinking. Leaders adapt to constantly changing circumstances, and new technologies and interpersonal skills allow them to motivate their workforce through transformational change.

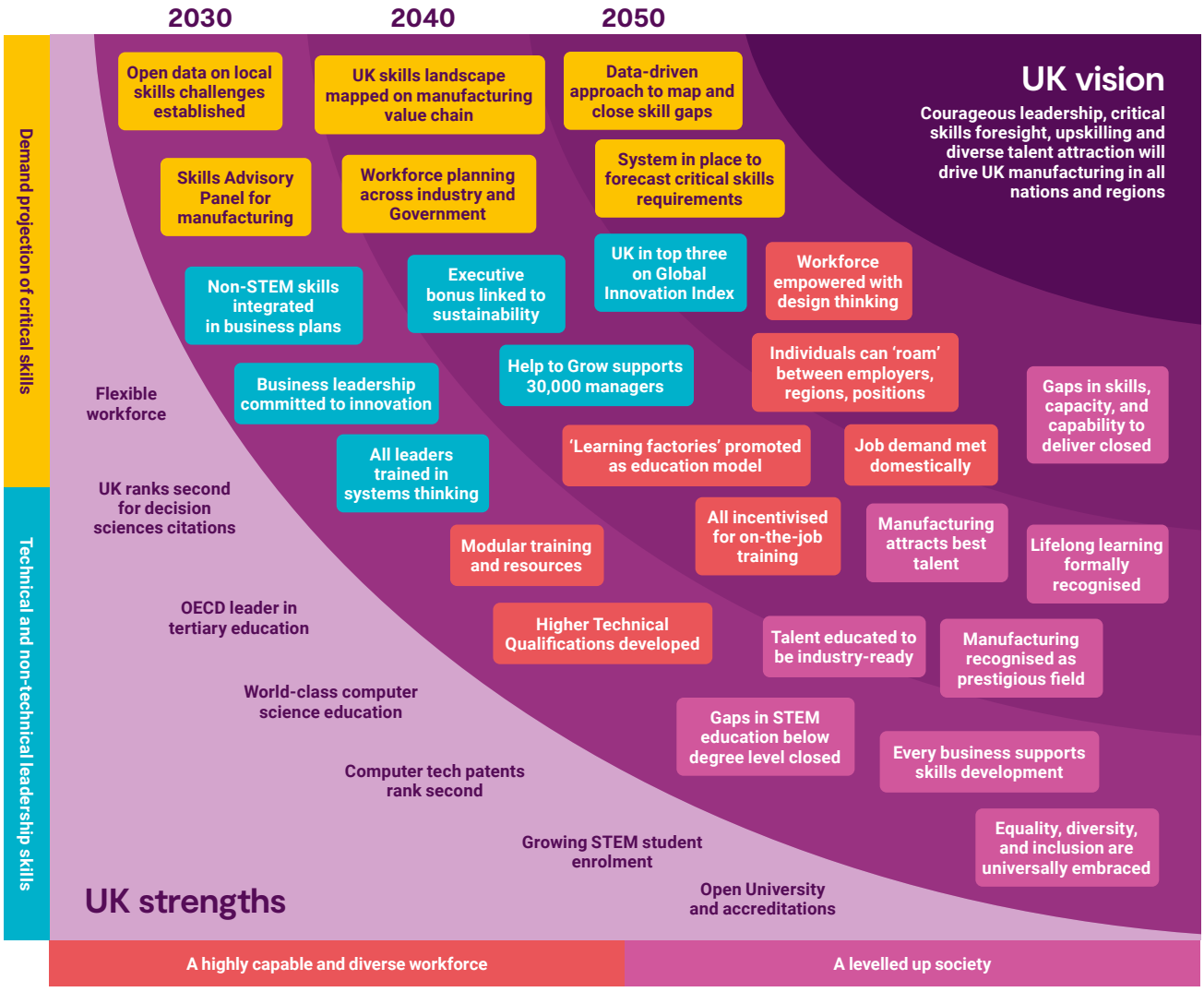
Workforce is highly capable and diverse
Training and use of strategic partnerships and collaboration to close gaps in skills, capacity and capability ensure an adaptable workforce. An incentivised lifelong learning culture that supports upskilling and reskilling is widespread. It introduces variety, increases job satisfaction, and attracts the best talent. The workforce is open to change and equipped to adapt to new and changing technologies and working methods.

Working in materials and manufacturing is highly attractive
In 2050, materials and manufacturing sectors are universally recognised as prestige and highly professional fields in which to work. Highly skilled, globally mobile innovation talent prefers the sectors. A work environment that seamlessly blends advanced technology with uniquely human skills (critical thinking, creativity, and people management) ensures retention. Clear foresighting of skills helps the education sector provide the education and technical knowledge the workforce of tomorrow needs to maintain success across sectors.

The logic model



UK opportunities



Skills demand is accurately projected and technical and non-technical leadership skills are strong

The nature of UK employment will change where digitalisation drives employment by work packages and deliverables rather than by large permanent workforces. The UK can take advantage of an excellent research base in decision sciences to link business priorities with data analysis, design and behavioural understanding. This will support the development of tools for foresighting that help to close gaps in skills and understand future needs. Building on existing programmes, opportunities to strengthen this pipeline through apprenticeships and technician training will be readily available and appealing. This development of skills will be a vital part of making UK manufacturing competitive.

Workforce is highly capable and attracted to materials and manufacturing

Student enrolment is growing in science, technology, engineering and mathematics. This can provide a strong pipeline of skilled people able to adopt increasingly complex and evolving value models. Ultimately, the demand for jobs can be met domestically. Distributed, collaborative and flexible working can be developed to provide the right balance to attract the best and most innovative talent. UK companies are well placed to broadly adopt a culture of caring commitment to their people, offering flexibility and opportunity. The UK can become a global reference point for the quality of its manufacturing workforce and its approaches to developing the workforce across all sectors and stages of career.

Networked relations

Collaborative networks, open knowledge sharing platforms, and aligned investment will energise manufacturing.

Global outlook 2050

Collaboration is essential to deliver thriving, clean and resilient sectors. To collaborate effectively we will share a common vision, work from common assumptions, appropriately share data and information with trusted partners, and create the environment for step-change innovation.

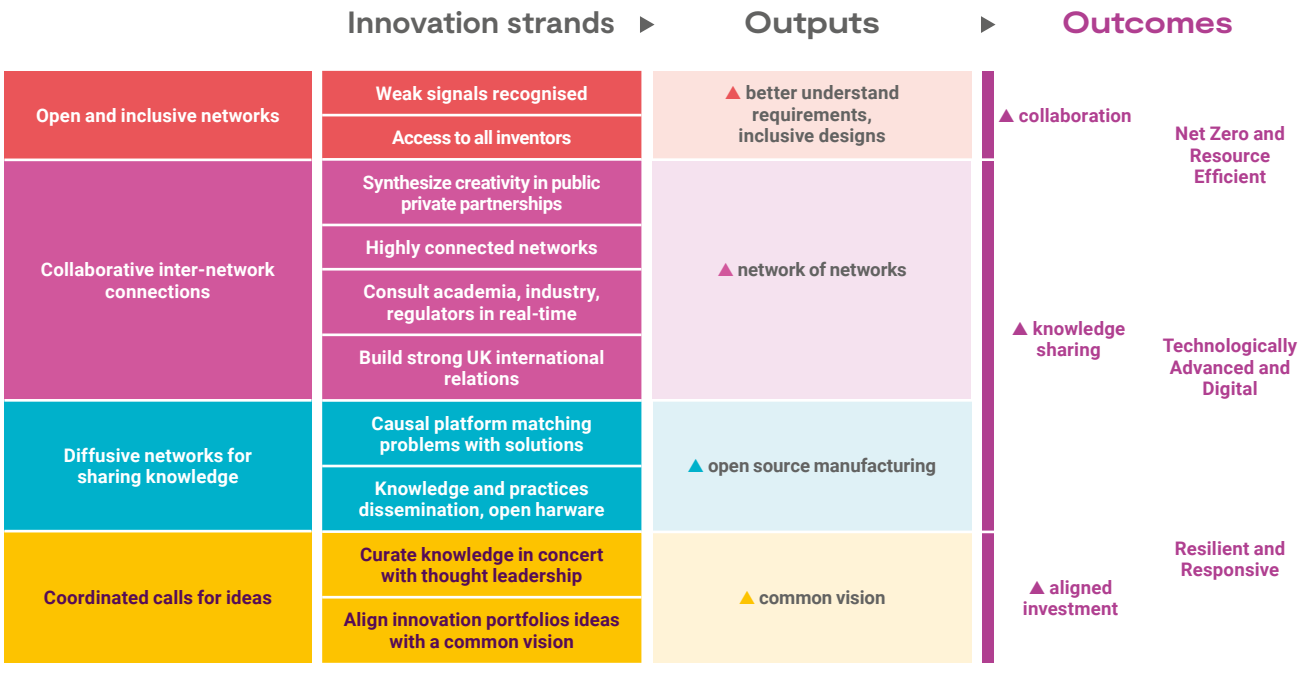
Networks are open and inclusive
A thriving and diverse innovation ecosystem drives better understanding of product and service requirements and ensures inclusive designs. Creative solutions are encouraged and evolved rapidly. Organisations that embrace the approach deliver better products and capture a larger market share.

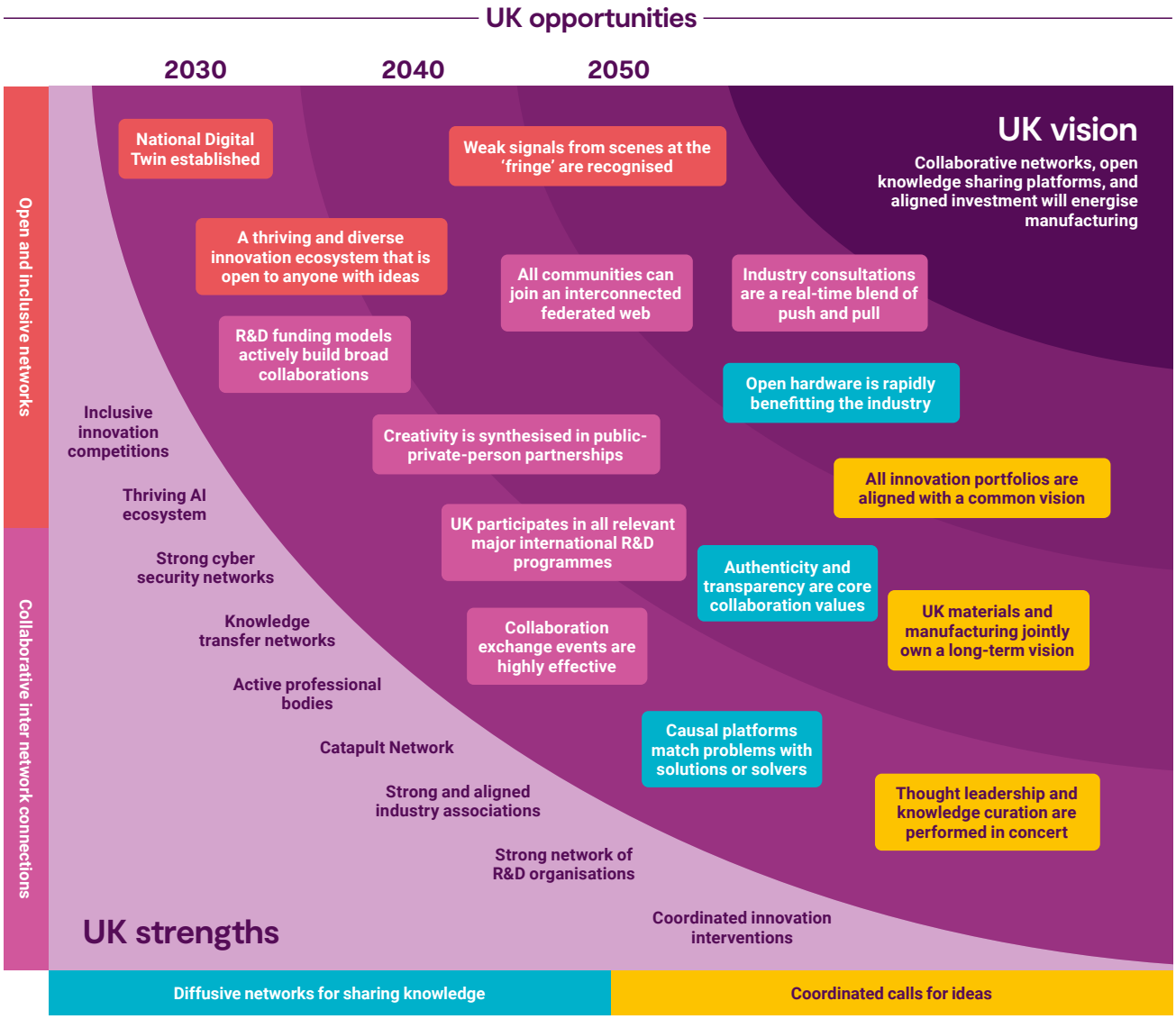
Interconnected collaboration unlocks investment
Collaboration delivers collective capabilities across industry sectors, academia, investors, public sector and beyond. Collaboration within networks but also inter-network allows all communities to create an interconnected federated web by 2035. Collaboration on standards, legislation and policy shapes markets that deliver societal aims alongside economic opportunities cost-effectively and quickly. A collaborative approach creates certainty that unlocks investment needed to reach the shared vision.

Open and diffuse networks share knowledge
In 2050, open innovation is pervasive and harnesses a diffuse network for knowledge-sharing and problem-solving. Open-source manufacturing is standard and there is wide use of causal platforms and solver networks. Open hardware rapidly benefits sectors by 2040.

Collaborative innovation programmes deliver
Collaboration, a stretching but achievable vision, and milestones for effective innovation programmes have delivered thriving, clean and resilient sectors.

The logic model





Networks are open and inclusive, and interconnected collaboration unlocks investment

Improving visibility through the supply chain and forecasting will provide critical communication routes. Making some of this information more open and available to more potential solution suppliers will deliver better understood requirements, more inclusive designs and ultimately better products and services. UK manufacturers are well placed to co-develop and adopt these technologies, working with UK-based leaders in software design and development. To implement safely, trust will be critical, and the UK's leading position in cyber security and broader security approaches will be a critical advantage for UK manufacturers.

Open and diffuse networks share knowledge

The UK has well established communities and support to build new communities. This includes sectors working with academia and regulators. Further development of this, and closer working with regulators on an agile and supportive regulatory environment, will give the UK a competitive advantage through the rapid changes of the coming decades.

Collaborative innovation programmes deliver

Networked relations can achieve a truly common vision, with common assumptions leading to better aligned investments. Whilst complex to coordinate and deliver, the benefits are significant and mean goals are reached more quickly and at a lower cost for all. The UK has demonstrated its willingness to put forward bold ambitions, and communities have formed to share information and co-develop roadmaps and strategies. There is significant value to gain by going to additional levels of detail with trusted partners and maintaining them.

Evolving value models

Innovative business models, agility to meet demand, green financing, and balanced trade will drive manufacturing.

Global outlook 2050

In 2050, society demands that businesses optimise environmental, economic, and societal impacts of their products and operations. Customers specify what they want, leading to universal demand for individual and customised products. Users are integral to conception and design. Manufacturing has responded to meet these complex requirements with flexible and adaptable systems. This requires the understanding, design, customisation, and adoption of increasingly complex business models.

New business models are swiftly de-risked
A research and innovation framework supports change, shares best practice, and allows organisations to swiftly de-risk new business models.

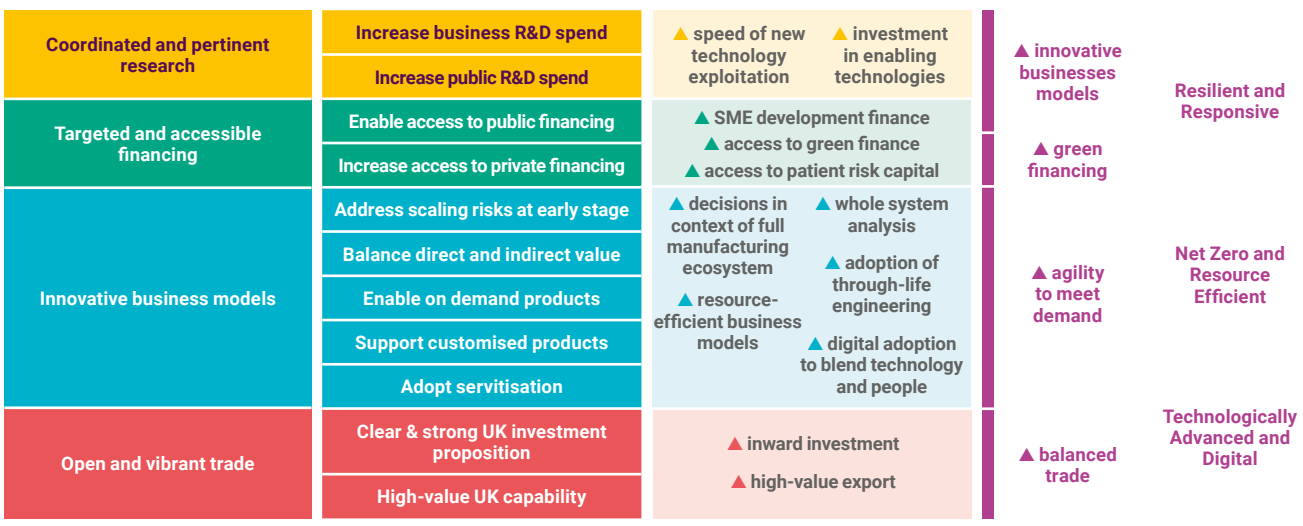
Financing encourages adoption of new business models
Public and private sector financing models are in place to de-risk and incentivise full adoption of transformational business models.

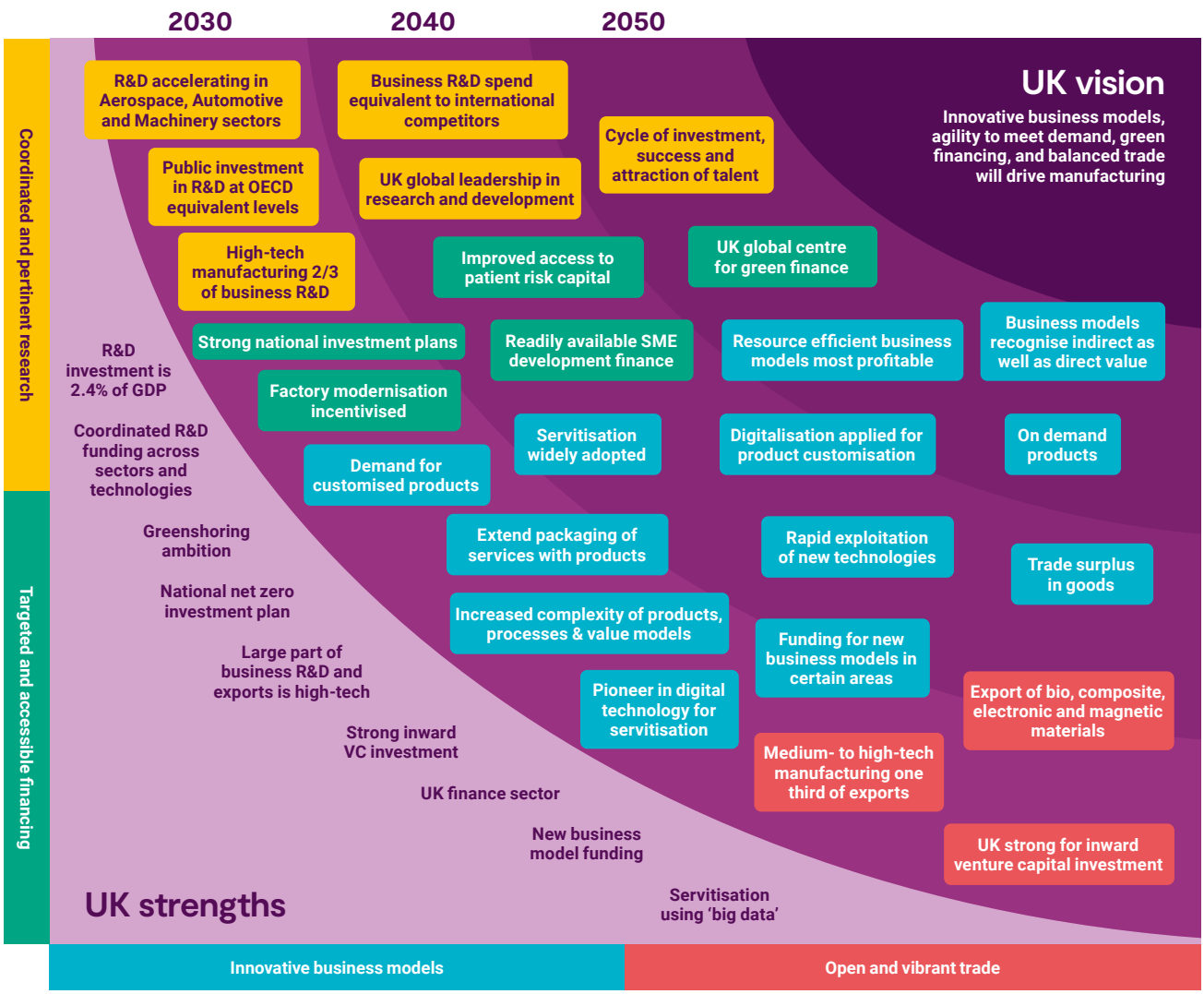
Innovative business models dominate
By 2050, the consumer expects a service or solution to meet a set of requirements rather than to buy and own a distinct product. Business models that were based on selling product are replaced by ones based on selling benefits. In other words, manufacturers retain ownership and responsibility, including for ongoing performance.

It is recognised by 2030 that sustainable and resource-efficient business models are the most profitable. The benefits of selling services around products – servitisation – and 'through-life engineering' practices, enabled by digital technology and underpinned by digital threads, are accepted. Customers buy service contracts for a greater percentage of products (up to 50% of household spend). This model allows manufacturers to realise significant and consistent value from longer-life products and greater amortisation of costs, benefits that can be shared with the customer. The selling of services around products becomes dominant in multiple markets, requiring greater understanding of customer needs whilst design engineers can make quite different trade-offs in product design.

Trade is open and vibrant
Manufacturers with a leading position in product customisation through digitalisation increase market share in both domestic and export markets. Efficient business models enable flexibility in where, how and what manufacturers produce, rapidly meeting changing demand.

The logic model





New business models are swiftly de-risked and financing encourages adoption of new business models

The UK's respected research base and national commitments and a vibrant private investment market can grow research and development and provide the environment to ensure organisations can transform with managed and understood risk. The UK can build on existing export strengths to deliver these business models to new markets and secure long-term growth.

Innovative business models dominate and trade is open and vibrant

The increased servitisation of products plays to UK strengths. UK companies lead the way in this business model. The UK also has a very strong service sector providing transferable skills and capabilities that can unlock value. A stable policy framework and long-term targets, such as net zero, give confidence to UK companies to invest in next-generation business models and to meet the opportunities presented by the changing demands of customers.

The route ahead

The vision and analysis demonstrate significant opportunities to make a real economic, environmental and societal difference to the UK. It shows how businesses must adapt and evolve in order to secure market position and grow sustainably.

- **The time is right to reimagine manufacturing**. We must act now to hit climate targets, secure sustainable supply, and improve productivity and prosperity
- **The UK has exciting opportunities**. We have world-class manufacturing, materials excellence, creativity and design expertise, digital excellence, leadership in standards and regulation, and an enviable RTO network
- **The vision is challenging but can be achieved**. The best talent working effectively together can enable the UK to become a destination of choice for advanced low carbon manufacturing

The stepping stones on our route ahead are below.

Net zero and sustainable products and services

Innovate UK will work with government and industry to support net zero and sustainable supply chains and systems.

Manufacturing supply chains and wider systems are critical to achieving net zero and sustainability targets. Creating products that can be tracked, serviced, maintained and ultimately recycled will deliver a high-value economy low on energy and material-use. Collaborative behaviour and close sharing of information will allow informed choices, including on embodied emissions. Drives towards resource efficiency and circular supply will create new business models and investment opportunities.

Supply chain resilience

Innovate UK will help to support new tools and processes to deliver supply chain resilience.

Secure and stable supply delivers customer value whilst also eliminating costs. Increasingly sophisticated analysis and tools will be deployed to create visibility throughout supply chains, informing decisions and mitigating risks. Management of waste will become increasingly important, with significant new market opportunities in converting waste back to feedstocks.

Consumer goods and hardware will be designed for repair or remanufacture

Digital revolution

Innovate UK will work with manufacturing and digital industries to help the UK gain maximum advantage from the digital revolution.

Digitalisation will improve manufacturing efficiencies and be crucial to achieving desired outcomes. Rapid developments in high-fidelity simulation, artificial intelligence and business models will enable whole-system design and hyper-customised products. This will also enable supply chain visibility across all tiers and all sectors, through-life design with circularity in mind, and an emerging remanufacturing sector.

The UK as a global green shoring destination

Innovate UK will work with government and industry to help make the UK a destination of choice for advanced low carbon manufacturing.

Looking at emissions reduction, technological advancement and resilience of supply in a holistic way reveals areas of critical importance. New economically appealing business models are needed, and they require connectivity and visibility through supply chains and across sector value chains.

The UK is well positioned to take advantage of these future trends and the areas of opportunity they bring. We foresee the UK as a green financing hub and a global green shoring destination, founded on a networked ecosystem with:

- a regulatory framework that is proactive and that sets carbon accounting standards globally
- an energy system that is reliable, clean and affordable
- future skills that are foresighted to ensure that demand for them is met
- machines and software that are made locally.

Working together

Innovate UK will work with partners to build networks and communities, and provide the ecosystem to support companies to innovate.

We must invest collaboratively across the UK industrial ecosystem, and in close partnership with our UKRI colleagues to achieve our aims. UK Industry, government and others must have a shared vision and shared understanding of key opportunities.

UK manufacturing is part of a global system, and we must work with international partners to develop global solutions. We will take the systems-wide approach needed to ensure that changes are well considered and deliver on our ambitions. We will use this vision alongside our international benchmarking and other inputs to inform our decisions, including on where to invest, and offer it to others to help inform their investments.

A view of the future cannot be exact, and our insights are based on information available today. We will update this vision as new information becomes available. We will provide ways for you to feedback and look forward to working with you as we further develop thinking on the future for UK materials and manufacturing.

Autonomous and adaptable production enables manufacturing as a service

Appendix SWOT analysis

Strengths

The following four pages show a structured SWOT analysis with points superimposed onto the activity model described in the body of the document.

More than 1000 salient points have been extracted from over 170 recent references. Each SWOT quadrant shows the most relevant 55 points. A force-directed algorithm was used to spread these points out evenly across a 9-column grid whilst maintaining proximity to their corresponding focus areas. This analysis helped to join the dots and to recognise common themes and innovation strands.

Weaknesses


Limited high-volume propulsion tech mfg
Medium to high-tech industry <5% of domestic value add
Productivity lags internationally, incl for leading industries
EV adoption needs more charging infrastructure
Leadership of industrial digitalisation is fragmented
Limited Tier 1 power electronics supply capability
UK has one of OECD's smallest foundation industry sectors
UK support for electrolytic H_2 is not ambitious
Low adoption of digital tech to address resource efficiency
AI is well-adopted, but less so in mfg
Slow policy and infrastructure progress in low-carbon heating, CCS, H_2
Insufficient mechanisms to support servitisation
Despite large investments, robotics not widely deployed
Lack of long-term strategic vision for UK mfg
World-class digital start-ups, mainly non-mfg
No concerted effort to grasp opportunities from emerging technologies
Much of component supply for propulsion tech moved off-shore
Skills shortage of hardware, software, data science, digital
Comparatively slow uptake of automation
Business barriers to adopting energy efficiency
Insufficient skills for digital and brain drain to fintech
Bio, optical, electronic, magnetic materials sectors are small
Mfg supply chain depends on non-UK supplies
Low digital readiness score in an EU ranking
Business R&D spending is below int'l competitors
Resource efficiency and resilience not yet prioritised
IDT for resource efficiency or resilience poorly adopted
Less automation in UK compared to int'l peers
Comparatively low-tech adoption levels
Insufficient support for systems and design thinking
Lack of facilities and skills to commercialise material-based innovations
Hardware is frequently imported
Skills shortage in digital, AM, AI
Investments are inhibited by legacy infrastructure
Limited visibility of supply chain gaps
Not all sectors can reduce emissions at the same pace
Ageing factories compared to int'l competition
Regulations are not incentivising net zero mfg
Limited production capability for some new materials
Waste management is still low-tech
Disconnect between digital start-ups and the industrial workd
Decarbonisation challenges for low-productivity SMEs
Regulatory system favours incumbent businesses over innovative new ones
Biomass is used for energy, rather than chemicals
Business barriers to adopting decarbonisation
Business want regulations to evolve for disruptive change
Many 'renewable' technologies designed as a linear system
Significant emission beyond own 'factory gate'
AI hype with a lack of understanding of its best application
Materials funding is seen as single sector solutions
No common standards for cyber-security
Businesses believe current regulations don't help innovation
Business investment in R&D has fallen relative to our int'l peers
Standards lagging behind fast-moving tech e.g. digital
Engineering design not sufficiently supported

Opportunities

Threats


Lack of trust in 'cloud' infrastructure for critical systems
Insufficient attention to automation of foundation industries
Intense global competition in aerospace
UK falls behind in H_2 tech if bold actions are not taken
Remanufacturing is hampered by a lack of reverse logistics network design
Resistance to sharing manufacturing data externally
Complexity of digitalisation hampering its adoption
10% of all industrial power is used for compressed air
The world is rapidly shifting to a 'service' economy
Low value add sectors are out-growing high value add
Lack of data 'highways' for real-time connected factories
Many net zero models ignore equipment reliability
UK deployment of robot-based mfg is lagging
A brain drain with UK being a net exporter of talent
Automation puts 30% of jobs at risk (US: 38%, JP: 21%)
Underutilised knowledge due to slow technology adoption
Continued outsourcing and global fragmentation of value chains
Gap in higher technical education below degree level
Reliance on imported tooling and processes due to expertise gap
UK risks losing leadership in servitisation
Insufficient changes of mindset and practices for circularity
Other countries have more comprehensive digital mfg strategy
Growing skills gaps in some key areas
Uncertainty in the global political environment and markets
Industrial and product designers are 95% male
Overseas acquisition of UK companies
Pressure on limited raw material resources
Perceived high costs of digital adoption
GDP alone no longer a sufficient performance metric
Absence of a national Materials Strategy
EV plants move abroad if battery factories are built there
Barriers to (int'l) certification of critical skills
Fierce int'l competition moving up the value chain
Poor understanding of the value of circular business models
Rising freight and shipping cost and increasing delays
The industry needs end-to-end supply chain visibility
Insufficient time or skills to migrate to the 'cloud'
No WTO resolution for carbon border adjustments
Half of 'bioplastics' are not biodegradable
Lack of investments putting the supply of critical raw materials at risk
Business culture inertia hindering servitisation
Manufactured goods drive UK's trade deficit
Unbalanced industrial regulations and investment support
Limited business cases for CCU-based feedstocks
C19 has exposed the reliance on a just-in-time system
Growth is increasingly due to consumption, not investment
Unstable carbon pricing and emissions policy may deter investments
Scarcity of natural resources
Embedded carbon in the supply chain is often not accounted for
CO_2e emissions due to inadequate market monitoring
Insufficient compelling business case to adopt digital
The multitude of approaches makes it hard for SMEs to engage in circularity
Other countries certify circular economy processes faster
Risk of losing supply chain design authority of OEMs
Electronics companies go to US or Asia to find early adopters

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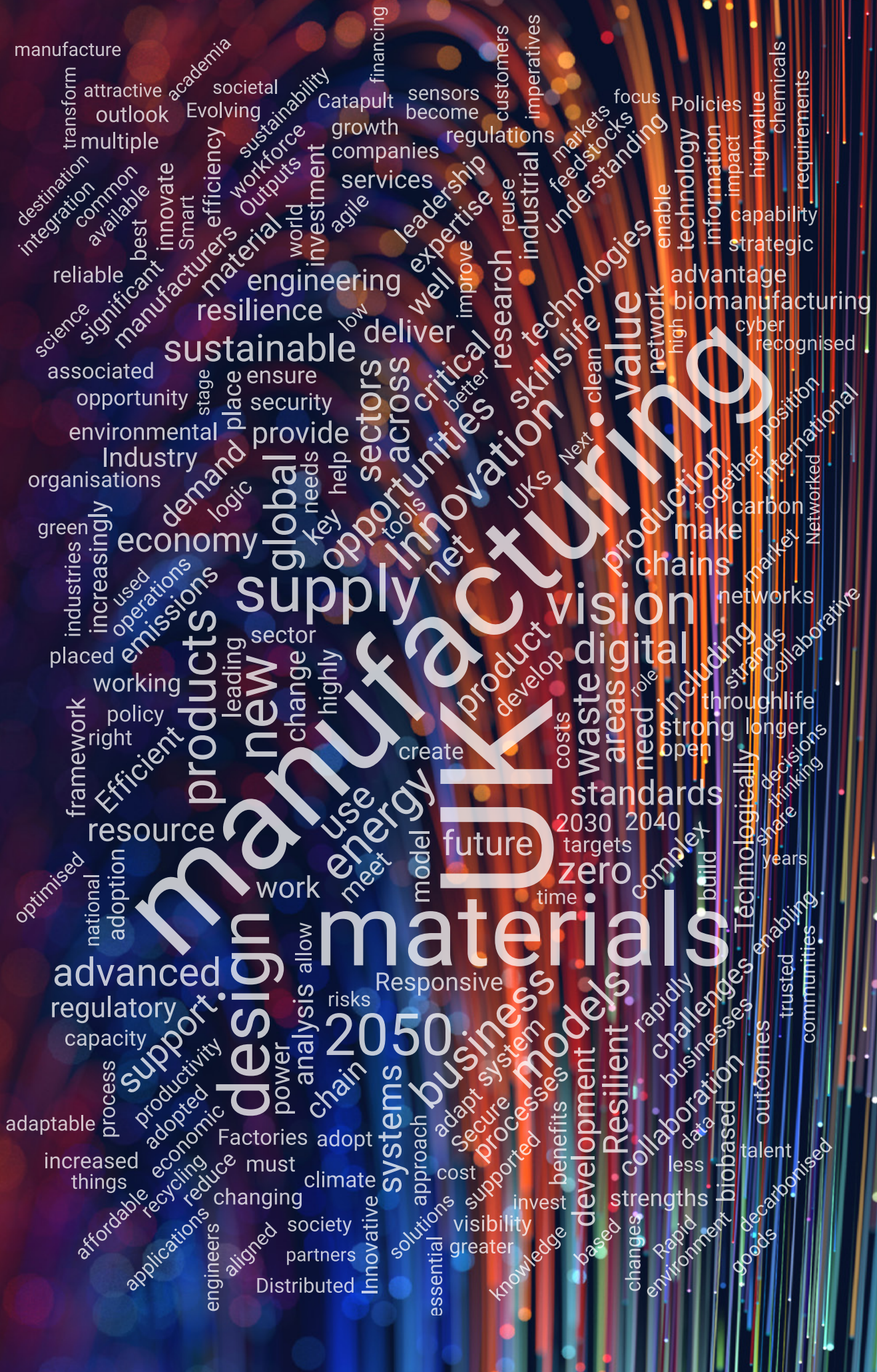

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