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A CASE STUDY IN ADVANCED MATERIALS

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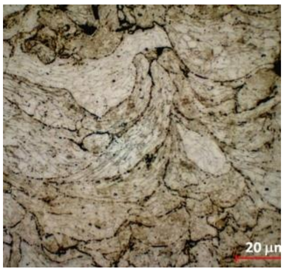

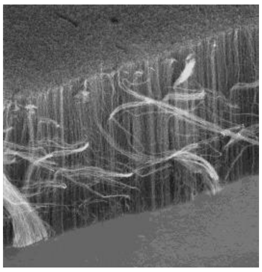

A report for the Government Office of Science & the Department for Business, Innovation & Skills

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A review of international public sector strategies and roadmaps: a case study in advanced materials

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Small pictures on cover (from left to right)
Picture a: *SpayLaze of 316L Stainless Steel*, Centre for Industrial Photonics, Department of Engineering, University of Cambridge
Picture b: Education Consulting Services, University of Cambridge
Picture c: *Castrejon-Pita: Drying patterns of AKD on Glass*, Dr. Ronan Daly and Dr. Alfonso, Department of Engineering, University of Cambridge
Picture d: *Carbon nanotube forest*, Christopher Williamson, Photonics & Sensors Group, Department of Engineering, University of Cambridge

Preface

This report reviews recently published international public sector strategies, roadmaps and initiatives related to *advanced materials* research and innovation. In particular, this study explores strategies developed by, or commissioned for, international government agencies. This report focuses on the approaches governments use to develop strategies, roadmaps and initiatives and what those aim to do, rather than focusing on specific advanced materials priorities (i.e. development needs, development goals and investments).

This report is intended to support the work of the UK Government Office of Science and the Department of Business, Innovation & Skills. Benchmarking international advanced materials priorities was beyond the scope of this study. In particular, this study has been designed in the context of the opportunities and challenges related to advanced materials, as identified in the '*Eight Great Technologies*' initiative of the UK Science Minister, the Rt Hon David Willetts, MP.

This review has been carried out within the context of ongoing research at the *Centre for Science, Technology and Innovation Policy* (CSTI) related to frameworks and effective practices for public sector roadmapping of key emerging technologies. CSTI is an applied policy research unit based at the *Institute for Manufacturing*, University of Cambridge, dedicated to exploring what makes national innovation systems effective at translating new science and engineering ideas into new technologies and industrial growth. As part of CSTI's ongoing research in this area – and in order to provide assistance to key government stakeholders – 'advanced materials' was selected as a case study for analysis of international roadmapping practices.

Advanced materials 'roadmaps' and strategies

In exploring international 'roadmaps' and related strategy documents, this review focused on governmental analyses addressing some or all of the following strategic issues: the advanced materials-related innovation needs of key technologies and industries; associated opportunities and challenges to exploitation; research and innovation priorities; critical development milestones; the role of R&D agencies and other stakeholders in supporting the emergence of novel advanced material-based products and processes; and their major implementation initiatives.

It is important to note that public sector roadmaps may not be developed in all areas of materials, covering all functions and applications. This does not necessarily mean that these materials are not key strengths or are not receiving high levels of investment in that country. In general, it appears that public sector roadmaps and strategies are typically developed in areas where there is an appropriate role for government: setting out a vision, coordinating stakeholders or addressing other key strategic imperatives (e.g. national security).

In the context of this report, a ‘roadmap’ is taken to mean a visual representation of strategic options to achieve stated goals, including potential ‘pathways’ to those goals mapped out against a timeline. Such ‘roadmaps’ are typically developed using a workshop approach designed to increase awareness and alignment among key stakeholders. Roadmaps are, of course, not the only source of important strategic information. Details of advanced materials R&D priorities, perceived opportunities and challenges, etc., can also be found in a range of ‘action plans’ and other documents developed by (or for) government agencies. Some high profile policy-oriented studies and workshop reports of national academies, learned societies and professional bodies are also summarised within this report.

Variation in ‘advanced materials’ definitions and terminology

In looking for and reviewing international strategy documents and roadmaps, we have taken a broad definition of ‘advanced materials’, while also attempting to more clearly distinguish different definitions and identifying the correspondence and overlaps between terms. There is significant variation in terminology, categories and themes addressed in different strategies. Materials types are labelled in variety of ways, often overlapping. Different types of materials can be defined or qualified in terms of traditional categories (e.g. ceramics, polymers, alloys), material properties (e.g. optical, electronic, magnetic), application (e.g. materials for low energy technologies), the nature or scale of engineering (e.g. nano-materials, micro-materials) and sector (e.g. aerospace materials). These categories are not intrinsically distinct. Some advanced materials could correspond to some or all of these labels. Furthermore, there a variety of labels used to qualify categories of materials. In addition to ‘advanced materials’, other common categories include ‘high value materials’, ‘modern materials’, ‘future materials’.

Scope of the review

Because of the huge diversity of advanced materials, their variety of properties, the diversity and range of application domains across a range of sectors, it was beyond the scope of this review to explore all strategic documents, action plans and ‘roadmaps’ associated with all individually promising materials and all possible pathways to economic and societal impact. This report focuses, instead, on the principal strategic documents and analyses of the key materials-related research and innovation agencies in important knowledge economies.

Particular attention is paid to strategies developed by key research and innovation agencies of the United States, Germany, Japan and the European Union, but this report also summarises analyses (where publically available and in English) from other countries with strong or emerging expertise in materials science and engineering, such as China and the Netherlands.

As part of this analysis, we also explored international approaches to convening national stakeholders to: support advanced materials strategy development; promote awareness and communication; and enhance coordination and alignment of national innovation efforts related to advanced materials. It is hoped that insights into some of these international practices may be of value, not only in the context of advanced materials strategy development, but for key emerging technologies more generally.

Finally, it was beyond the scope of this study to carry out an exhaustive review of international strategic interest in all promising novel materials (and all possible pathways to economic and societal impact). Some observations regarding new materials receiving particular international attention in domains of potential strategic relevance to UK science and innovation did occur during this study and has been presented separately, but is not released as part of this report.

Executive summary

Introduction

Advanced materials are an important strategic priority within all major knowledge economies considered in this report. Not only are advanced materials considered to be critical drivers of innovation across a range of important technologies and industrial sectors, but they are also seen as essential for underpinning key areas of high value manufacturing, as well as addressing a range of important societal 'grand challenges' in areas such as mobility, healthcare and energy.

This report explores published international strategies for supporting advanced materials research and innovation. In particular, this study analysed recent advanced materials-related 'roadmaps' (and other strategy-related documents) developed by or for governmental agencies in leading economies. Different approaches and practices for developing such strategies are also considered. Important differences in national innovation systems and industrial contexts, within which these strategies have been developed, are also highlighted.

Key themes identified during the course of this review are summarised below, and are discussed in more detail throughout the remainder of this report, in particular:

1. The importance of materials innovation to a range of technologies, applications and sectors
2. The role of advanced materials in underpinning other key emerging, enabling and 'Great' technologies
3. The role of advanced materials in addressing key socio-economic 'grand challenges'
4. The role of advanced materials in enabling advanced high value manufacturing
5. National and stakeholder variations in 'advanced materials' definitions, terminology and strategic focus
6. The national innovation system contexts of advanced materials strategies/roadmaps in different countries
7. The importance of enabling technologies and innovation infrastructure in underpinning advanced materials innovation
8. Government-supported coordination of advanced materials development communities
9. The strategic importance of 'security of access' to critical raw materials (underpinning key technologies and industries)
10. The role of advanced materials in addressing innovation needs and competitiveness challenges of key industrial sectors

1. The importance of materials innovation to a wide range of key technologies and sectors

Most of the strategies reviewed in this study highlight the critical cross-cutting nature of advanced materials, in particular their role in underpinning many of the most important modern technologies and high value products. Not only are advanced materials important in almost every manufacturing-based industry, but materials R&D is an important added-value source of innovation and competitiveness in many key sectors.

The large number of promising advanced materials, however, together with their variety of properties and range of potential applications across almost all industrial sectors, makes it challenging to develop an all-encompassing 'roadmap' for advanced materials. Instead, most of the strategies reviewed address particular categories of advanced materials in the context of the materials innovation needs of specific technology domains, societal grand challenges, or industrial value chains.

2. The role of advanced materials in underpinning key emerging and enabling technologies

A repeated theme in many international advanced materials-related strategies is their underpinning role for a range of key enabling technologies (e.g. micro/ nanoelectronics, photonics, nanotechnology), novel production technologies (e.g. additive manufacturing), as well as important technology-based application domains (e.g. energy technologies). Indeed, many international strategies highlight the role of advanced materials for technological domains highlighted within the 'Eight Great Technologies', including space technologies, robotics, energy technologies, regenerative medicine and synthetic biology. (Other key emerging technologies, such as big data-based technologies, are important in supporting materials innovation and development itself).

3. Advanced materials and socio-economic 'grand challenges'

Many of the international strategies and governmental analyses reviewed in this study highlight the potential role that materials science and engineering may play in addressing many societal grand challenges. Advanced materials innovations have the potential to enable new technology solutions for addressing challenges and opportunities in areas such as: renewable energy production and low-carbon energy technologies; transport; health applications; environmental protection.

4. Advanced materials and advanced manufacturing

Several international advanced materials-related strategies highlight the importance of advanced materials in underpinning advanced manufacturing. For example, the recent US Advanced Manufacturing Strategy identifies advanced materials as one of the four main categories of the Federal Manufacturing R&D portfolio, with related documents highlighting *Advanced Materials Design, Synthesis, and Processing* as a critical 'cross-cutting technology' R&D priority underpinning advanced manufacturing competitiveness.

Many promising emerging production technologies – including high-profile techniques such as additive manufacturing – will require critical materials innovations to reach their potential. Indeed, many international roadmaps highlight a range of R&D domains of common interest to both manufacturing and materials development (e.g. process simulation, in-situ characterisation and monitoring, autonomous processes, hybrid functional materials). A number of international strategies also highlight the potential for advanced materials (and related manufacturing processes) to increase manufacturing resource efficiency and reduce production costs. Similarly, advanced materials innovation also contributes to societal goals related to sustainability and 'green' manufacturing.

5. Variations in 'advanced materials' definitions and terminology

There are significant variations in categorisation and terminology across international strategies, with little consensus on how 'advanced materials' are defined. The scope and emphasis of particular definitions reflect, in part, the interests and priorities of different stakeholders (research councils, mission agencies, etc.) and care should be taken in interpreting the goals and priorities of international roadmaps. In addition to 'advanced' materials, another commonly used category is 'high value materials'; where 'advanced materials' typically implies materials with significantly novel or enhanced properties, 'high value materials' also includes materials types which may be more established but continue to require knowledge-intensive manufacturing or underpin key markets.

Materials are also categorised in more detail with a range of labels, including: traditional materials categories (e.g. alloys, ceramics, etc.), material properties (e.g. optical, magnetic, etc.), application/ sector within which materials are deployed (e.g. aerospace materials), and the *scale* at which materials are engineered (e.g. nano-, micro-materials). A schematic identifying these commonly used categories of materials research priorities is illustrated in Figure 1. It should be noted that *scale of engineering* refers to the level at which tools and processes are used to specifically control the structure of materials, thus defining nanomaterials as materials that have been engineered at the nanoscale.

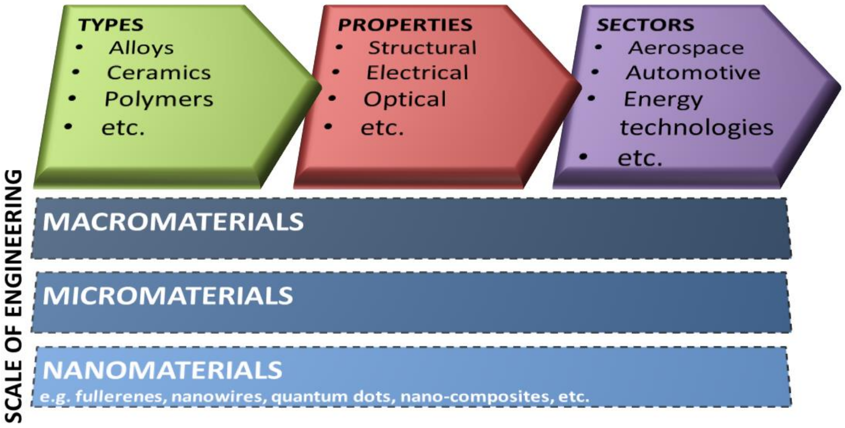

Figure 1: Schematic illustrating some commonly used materials categories

6. National innovation system context of advanced materials strategies

There are significant variations in the focus areas and emphases of international *advanced materials* roadmaps, reflecting, in part, differences between the *advanced materials* innovation 'ecosystems' of different countries. Not only do different nations have different industrial and scientific strengths, opportunities and challenges, but the innovation systems actors in each country – universities, research and technology organisations (RTOs), research and development (R&D) agencies, leading R&D-intensive firms, etc. – can vary significantly in configuration, mission, and levels of interconnectedness. Furthermore, the different missions, priorities and structures of organisations developing advanced materials-related roadmaps (funding agencies, national laboratories, intermediate institutes, etc.) also vary by country, influencing the focus and content of advanced materials strategies. Care should be taken in attempting to 'benchmark' the outputs of such exercises against UK priorities and interests.

7. Advanced materials innovation and 'public good' supporting technologies

A key theme in many international materials-related strategies – and a key feature of many roadmaps – is the importance of a range of supporting technologies required to translate advanced materials into emerging technologies and industries. By contrast with firm-level roadmaps, many international governmental roadmaps appear to pay more attention to enabling technologies with a strong 'public good' element, for example: measurement instruments and in situ characterisation technologies, pilot production facilities, modelling and simulation tools, etc. A diagram highlighting important categories of technology development activity is illustrated in Figure 2.

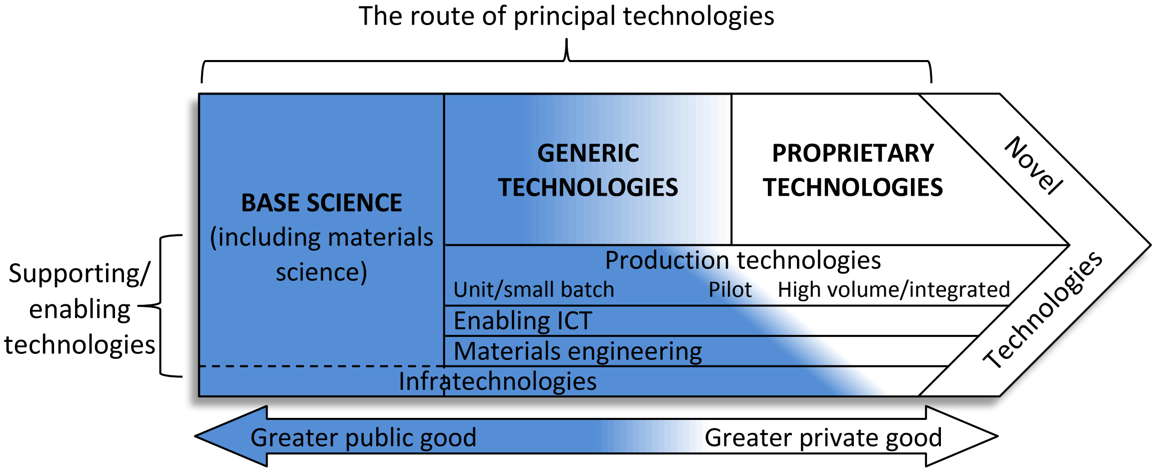

Figure 2: Schematic highlighting important categories of technology development activity
NB: The shading implies the level of public good in that activity

Several countries have major initiatives (and related strategies) addressing the need for key supporting technologies and related 'innovation infrastructure' for advanced materials. One of the most high profile of these initiatives is the US *Materials Genome Initiative* designed to build a national infrastructure for multi-scale modelling of advanced materials, including enhanced computational, data-management, and data- sharing capabilities, to accelerate the pace of discovery and deployment of advanced materials (and advanced materials-based systems).

8. The coordination and alignment of advanced materials research and innovation

Several strategies highlight the fragmented nature of materials R&D, pointing to the intrinsically multi-disciplinary nature of the domain (with contributions from physics, chemistry, biology and manufacturing engineering, etc.) as well as the variety of materials types, properties, applications, etc. Consequently many strategies identify coordination efforts as key activities, as well as using the strategy development exercise itself as an opportunity for increasing awareness, communication and coordination among key stakeholders. In this context roadmaps are often identified as important 'coordinating instruments' to support effective advanced materials innovation within key technology domains, in particular those where research and innovation goals span multiple developmental phases (and partners) or address system applications challenges which involve many interdependent development activities.

9. The strategic importance of 'security of access' to critical raw materials

An important theme in a number of international advanced materials-related strategies is access to certain critical materials than underpin promising emerging technologies. These critical raw materials include rare earth elements and materials that have a high level of supply chain risks, for example restrictions introduced by China on trade in selected rare earth elements. Consequently, R&D agencies in a number of countries are developing strategies for mitigating these risks and identifying potential approaches that could be adopted by key national stakeholders, including materials research into design-for-recycling and the development of novel substitute materials and technologies. Some application domains, for example low-carbon energy, are particularly affected, with a number of rare earth metals likely to prove crucial for several important technologies.

10. Advanced materials, industrial innovation needs and sector strategies

Many reviewed advanced materials roadmaps address the materials innovation needs of key sectors. Indeed some strategies suggest that, given the difficulty in anticipating which novel materials will have greater applicability and appeal to industry, the prioritisation of materials R&D can only be carried out within the relevant industrial context. Many sector-focused materials strategies take a 'value chain' approach to structuring their analysis – i.e. addressing potential materials innovation needs along the extended value chain of specific sectors from the processing of raw materials, through component manufacture, application system integration and scale-up challenges. It is worth noting that many of the sectors most commonly cited in the context of advanced materials correspond to key sectors highlighted in the Government's 'industrial strategy', including aerospace, automotive, energy, and construction.

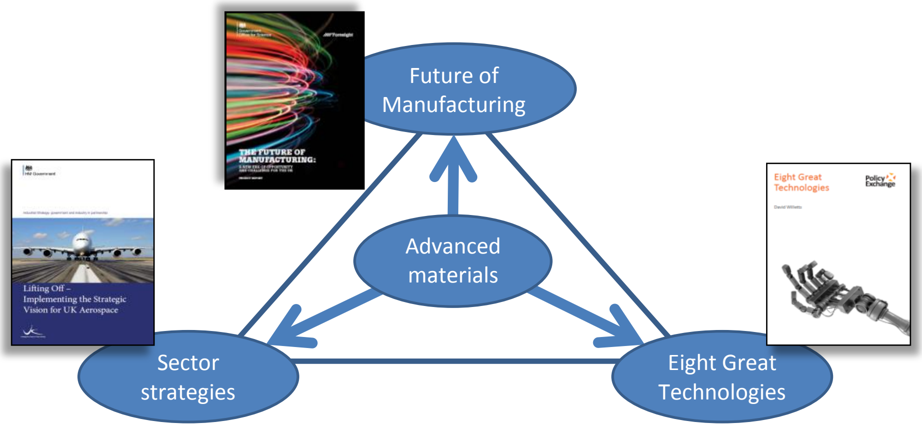

Figure 3: Schematic highlighting the importance of advanced materials to key technologies, sectors and production

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Introduction

Products, services, and processes can create value and are results of economic activity. Materials form the foundation of all products and are integral to many services and processes. Their selection, development, integration, and performance are often critical in the innovation process. Materials are also often at the centre of disruptive technologies (NRC, 2008). With its integral role in technology development, it is important that the processes by which they are developed is understood and where necessary and appropriate, supported by government.

The processes and stages of innovation and what influences them are not fully understood, and this is no less the case with materials. To understand how materials are developed and deployed, both the activities that develop materials and their support activities need to be identified and their roles understood (Tassey, 2004). These activities need to be characterised and their dynamics of interaction understood for governments to know where they can invest to support materials development and maximise their return on investment for their constituents.

Research and development is not a completely private enterprise. The Science base is often developed in universities and publically supported research endeavours. The work done in the Science base often creates the foundation of technological innovations. Examples can be seen with the development and subsequent commercialisation of many technologies with roots in the Science base, such as computers. Understanding how this science base interacts with industry can assist work done in it to have an impact on our lives and quality of life. Furthermore, the science base can be leveraged to support economic growth, particularly in high wage economies (Sainsbury, 2007). The positive, impact that the Science base can have in a number of different areas in society means that it has a high level of public good, which confirms the support is receives centrally from governments (Tassey, 2004).

Materials form the foundation of products and often have significant involvement in processes and services. Development in materials provides underpinning and enabling capabilities in many different areas, including information and communication technologies (ICT), energy and aerospace and more broadly in engineering and manufacturing (EPSRC, 2013). Novel materials, novel properties and novel applications can help develop competitive advantages in these areas, increasing the competitiveness of UK manufacturing and industry and helping to rebalance its economy.

Materials are pertinent for industry because recent developments in the field have given rise to a number of new materials that have the potential to significantly impact products, processes and services. Developments in materials science, particularly around 2005-2008, established a number of new fields where a significant amount of research is being done (Adams & Pendlebury, 2011). Given the time to market of new materials, which is often around 20 years (NSTC, 2011a), timely investment and the exploration of required standards at this early stage of these material's development is important.

In the wake of recent policy developments in the UK, it is important to understand how these policies affect one-another. As one of the Eight Great Technologies, it is important the UK understands the role of advanced materials in the context of the other Eight Great Technologies. Furthermore, advanced materials has a role in a number of the sector strategies that have been developed by the UK government. Understanding how materials influence innovation in these industries and how other countries support this process can be used to support these strategies.

This report reviews how other countries plan for and support materials R&D in their particular innovation contexts. In particular, it explores the major published, public materials related roadmaps and strategies and reveals how countries view materials in their economy and how they contribute to economic activity and social and environmental issues.

This report

Innovation systems have different contexts (organisational, legal, economic, historical, cultural and social structures) which influence how science research and technology innovation occurs (Sainsbury, 2013). The next chapter gives a brief introduction to advanced materials, innovation systems and technology roadmaps for public policy development. The next four chapters outline the key strategies, roadmaps and initiatives in materials for the United States of America (US), Germany, Japan and the European Union EU. Each chapter begins with the key points outlining the major strategies, roadmaps and initiatives and a description of the key points that makes each country's innovation system different to that of the UK. The rest of each chapter provides further detail for each of the key points.

The key points from these reviews are drawn together to highlight the common themes and their implications for policy practice. These themes are used to paint a more detailed picture of materials in the innovation, discuss the lesson learnt for materials roadmaps and relevant practices for developing them and the relevance of the review for UK industrial strategy. To do this strategies and initiatives from other countries reviewed but not discussed elsewhere in the report will be drawn upon, including China and the Netherlands. The final section gives some concluding observations from the review.

Materials and innovation systems

Advanced materials and advanced materials research

‘Advanced materials’ have been defined in a number of different ways and these variations place different emphases on why some materials are prioritised. The United States’ National Institute for Standards and Technology (NIST) define it as:

> *‘Materials that have been developed to the point that unique functionalities have been identified and these materials now need to be made available in quantities large enough for innovators and manufacturers to test and validate in order to develop new products.’*
>
> (NIST, 2011)

The Technology Strategy Board (TSB) defines advanced materials as:

> *‘materials designed for targeted properties. Both completely new materials such as graphene or high temperature superconductors and those that are developments on traditional materials such as alloys or composites may be described as an advanced material. Such materials show novel or improved structural (strength, hardness, flexibility) and/or functional properties (electronic, magnetic, optical).’*
>
> TSB

For the purpose of this report, these definitions will be adopted; they help highlight why advanced material is particularly unique and assists the comparison of different means of prioritisation internationally. It is important to note that as suggested by the TSB, advanced materials are not only novel materials, but materials that have been put together in novel ways to give new structural and functional properties. This definition is consistent with the definitions of advanced materials used by Oxford Research AS (2012) and Rensselaer (2004). Oxford Research AS (2012) suggest that Value Added Materials (VAMs[1]) are a subset of advanced materials, which is a subset of new materials. Caution must be used when using such a definition, because Oxford Research AS’s (2012) ‘new materials’ do not exclude novel developments to ‘traditional’ materials.

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[1] *‘Value Added Materials are a group of advanced materials that have strategic importance for economic growth, industrial competitiveness or for addressing the Grand Challenges of our time’ (Oxford Research AS, 2012, p. 9)*

Smart materials is another term used to group materials. Smart materials are ‘materials that receive, transmit, or process a stimulus and respond by producing a useful effect that may include a signal that the materials are acting upon it’ (Harvey, 2002, p. 401). For the purpose of this report, they will be considered a subset of advanced materials, because they are materials that are developed with unique functionalities.

Materials research is conducted in a number of different fields, including materials science, chemistry, physics and engineering and by a number of organisations including universities industry and public and private research organisations. This means that the field of materials science is particularly fragmented when compared to other fields of research.

Innovation systems

The role of materials in economic and social life and how they come to have this impact cannot be understood without understanding the system in which they are developed. This system – the innovation system – is the assets, actors and processes involve in developing new technologies or new combinations of technologies to a point where they can be sold as a component or product. This definition of innovation system includes the science base, applied engineering, entrepreneurial activity and the various value chain activities. It also includes the unique characteristic that components and products developed in the system can be used in the system for R&D and innovation. An example of this is measuring equipment, which might be used in experimentation and development processes for less developed technologies.

Innovation system functions: Different types of activities

An innovation system is the system generating knowledge and mobilising it to make that knowledge useful. It involves – particularly from a materials perspective – the generation of knowledge (through, for example, science) and its employment in a technology. There are a number of different functions that occur in the innovation system. Liu and White (2001) identify five such functions:

1. Education
2. Research and development (R&D)
3. Implementation (manufacturing)
4. End-use
5. Linkage (bringing together complementary knowledge)

This study focus found itself focussing mostly on the R&D and linkage functions involved in developing materials, a consequence of the review process that was taken. However, as with many systems, these functions cannot be isolated from the rest of the system. Throughout the study relationships with the other functions in the innovation system was omnipresent and of constant consideration.

Economic models of innovation systems: Different types of technology

Tassey (1991, 1997, 2004) offers an (evolving) model for distinguishing between different R&D elements that reflect their 'private and quasi-public nature' and their linkages. A depiction of this model can be seen in Figure 4. The model divides the R&D into different types of R&D based on different types of technology and their stages of development. These 'technology types' are shaded based upon their 'private and quasi-public nature': the greater the degree of public good an element has the darker its shading (Tassey, 2004).

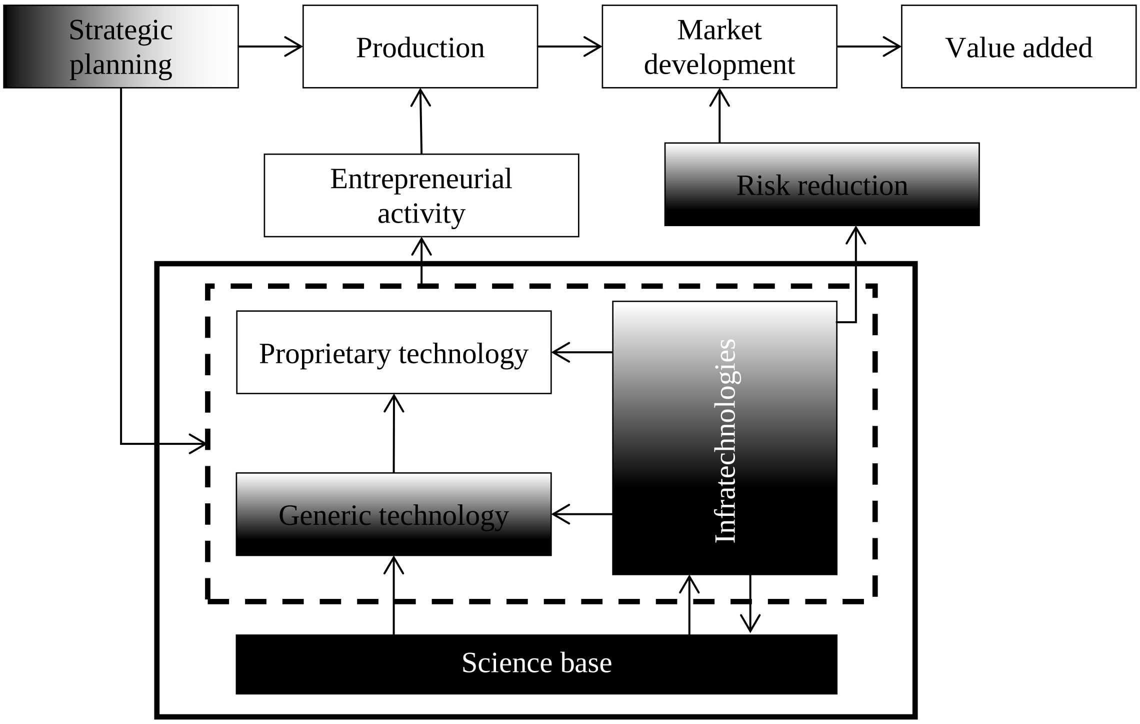

Figure 4: Tassey's (2004, p. 92) Economic model of a technology-based industry

Tassey's (2004, p. 92) *Economic model of a technology-based industry* describes how a principle, deployable technology is developed. Whether the theory and knowledge on which the technology is built was developed privately or publicly, it is still considered part of the science base and has a high level of public good. Once the science theory has been developed and demonstrated it becomes a generic technology. Examples or generic technologies include reciprocating engines (piston engines) and magnetic sensors. When these are developed into a specific product with detailed specifications – and maybe patented/patentable – they become proprietary technology.

According to Tassey (1991, 1997, 2004) infratechnologies are technical tools that assist the development of a principle technology, whether it be in the Science base, a Generic technology or a Proprietary technology. Infratechnologies include such tools as measurement and characterisation equipment (Tassey, 1997, 2004). Infratechnologies are important to conduct R&D at any stage of a technology's development because they provide the infrastructure necessary to execute R&D (Tassey, 1997, 2004). Advanced instrumentation, for example, is a group of technologies that provide R&D infrastructure that the Mathematical and Physical Sciences Advisory Committee see as 'a principal driver of progress in materials science' (MPSAC, 2012a, p. 3).

The blocks outside the solid black outline that has been inserted into Tassey's (1991, 1997, 2004) *Economic model of a technology-based industry* model do not directly influence technology development and are not R&D specific activities. Out of these, the blocks that are relevant are the Strategic Planning block and the Production block. Production is relevant because it is closely related to what technology is developed and if and how value is derived from it and Strategic Planning is relevant because it has an impact on how and what R&D is conducted.

Tassey's (1991, 1997, 2004) *Economic model of a technology-based industry* model can be used to characterise the stages various technologies are at and the functions other technologies, other assets and actors has in the development of those technologies. However, the model is static and only breaks the notion of technology into four –all-be-them useful – categories. There could be other types of technology, such as manufacturing, that might need to be included in the model.

Innovation system make-up: Different actors

The actors in a national innovation system are important for understanding how innovation in a country occurs. Drawing on Liu and White's (2001) classification of actors, system actors are any facet of the system, real or conceptual, whose state, changes in state or both have an impact on the system. System actors are responsible for conducting the activities, define how they occur and can coordinating them. Liu and White (2001) classify actors into three groups:

- Primary actors – those individuals and organisation that perform an activity;
- Secondary actors – actors that affect the behaviour of primary actors and their interactions;
- Institutions – which 'are the set of practices, rules and other disembodied organizations that guide or constrain an actor's behavior'[2] (p.1096).

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[2] Liu and White (2001) acknowledge that this definition of institutions is aligned with North's (1990).

Private, public, non-government organisations (NGO's) and non-profit organisations can be primary or secondary actors. Both types of actors (primary and secondary) are relevant to the review. Institutions play a considerable role in defining how and why these organisations interact and are also prevalent throughout the review.

Social value, public good and materials needs

Tassey (1997) also outlined another relevant theory that argues for government intervention in only particular instances and aspects of the R&D function of an innovation system. Tassey (1997) outlined a distinctions between two rates of return on R&D investment: social rate of return (SRR) and private rate of return (PRR). The argument is then made that when the PRR is high, then firms will make the investment, but when the SRR is high and the PRR is too low to attract private investment, only then government should invest in that R&D themselves[3] (Tassey, 1997). The difficulty for government is to assess if PRR is high enough to attract private investment fund and, if it is likely not to, to assess its SRR to establish if government investment is worthwhile (Tassey, 1997). This picture is further complicated when spillover is considered and firms do not wish to invest because there are benefits to other firms, and possibly competitors, who may not have helped to make the investment (Tassey, 1997). The role of government, then, is to help overcome such market failures.

Technology roadmaps and using technology roadmapping for developing strategies

Technology roadmaps are frameworks that help to inform strategies. Roadmaps often have a number of dimensions, including what the end points or vision is (usually a product or service to be delivered), why it is necessary, what needs to be achieved to reach the vision (often arranged in a hierarchy), how it is to be achieved (often referred to as a path or route) and the actors involved in achieving it all against a time dimension. Technology roadmaps also often have visualisations to organisation and communicate this strategy to other stakeholders and even competitors.

Technology Roadmapping is a framework that can be used to develop strategies and plans for their implementation. When this framework is functionalised (implemented?) it becomes a means of gathering and structuring information about a topic: it identifies the major technical and organisational barriers and enablers for developing and delivering a new product or service. This information can then be used to identify the most efficient route for developing and delivering the product or service: a strategy. In effect, this strategy is mediating between the

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[3] 'High' and 'low' rates of return are used here to indicate a 'high enough' or over what Tassey (1997) calls 'hurdle rate' or 'lower than'.

capacity to deliver a product or service and the need for it (how and why value can be derived from it). The information gathered can then be used to identify the major goals and milestones along the way to developing the product or service and to coordinate and commit resources: a plan.

When implemented as Phaal and his colleagues expound (2010), Technology Roadmapping uses a consensus driven structure to gather the appropriate information, develop common language, align views, increase awareness and develop feasible goals for the different stakeholders required. This multi-stakeholder approach uses both a bottom up and top down approach to identify the technical limitations to delivery and a detailed picture of how and why there might be market acceptance (need).

Technology Roadmaps originate in private enterprises, but they can also be used to coordinate public action, particularly in the field of innovation policy. Yasunaga and her colleagues (2009) describe how technology roadmapping was used to inform innovation policy development in Japan. Technology roadmaps have also been used in other public sectors, including the International Space Exploration Coordination Group's (ISECG, 2013) roadmap for exploring extra-terrestrial objects, including the Moon, asteroids and Mars.

Technology roadmapping is only one framework and dynamic process for developing a strategy. This study reviewed strategies more broadly to explore how materials were being viewed and supported by other governments. Many of these strategies had similar dimensions to Technology Roadmapping, but were not structured in that particular format. However, they still provided valuable input into the review and led to pertinent findings that may have been overlooked otherwise.

The United States of America

This chapter summarises the key advanced materials related strategies, roadmaps and initiatives recently published in the US. The following are the key observations from these official documents and are discussed in more detail in the rest of the chapter.

- **The context for materials in the US is different to the UK** – the US Departments, such as the Department of Defense (DoD) and the Department of Energy (DoE) and mission agencies and themselves drive research. The National Institute of Science and Technology (NIST) also carries out a significant amount of research and with the National Science Foundation (NSF) and the National Academies plays a role in materials planning and development in the US.
- **There are few materials specific roadmaps in the US** – mostly driven by the US' mission agencies and NIST, roadmaps and strategies that include materials focus on the development of new technologies specifically for an application and include considerations of the materials needed for that technology, rather than focus specifically on materials.
- **The US pays close attention to the development of enabling technologies** – for example, the National Genome Initiative aims to develop infratechnologies that support materials R&D **(NSTC, 2011a, 2012)**. This is not a new trend; attention, for example, is also paid to the US' measurement system (NIST, 2006). Infrastructure needs, much of which are infratechnologies themselves, are also addressed by NSF (see MPSAC, 2012a).
- **The US departments are mission agencies, which has implications on materials R&D** –as mission agencies, US department invest heavily in developing the materials needed to achieve their missions and constitute a large investment in materials R&D.
- **The US considers materials innovation important for manufacturing leadership** – despite not having a single organisation responsible for manufacturing technologies, the US highlights an important link between materials and manufacturing. For example, materials is one of the pillars of the US' Advanced Manufacturing Strategy (PCAST, 2011). The US aims to develop materials for manufacturing through its Technology Innovation Program (TIP) (NIST, 2009).
- **The US Government actively coordinates materials R&D activities across its different agencies** – national level workshops often coordinated by high level groups, such as the White House, are often convened to coordinate activities, such as materials research. For example, workshops were convened to coordinate activities related to nanotechnology as part of the *National Nanotechnology Initiative* (NSTC, 2011b).
- **The US is concerned with critical materials** – it aims to reduce the risk to its production system posed by critical materials by reducing its dependence upon them. The US is supports research into replacing critical materials – rare materials or those with high levels of supply uncertainty – through alternative materials or substitute technologies (DoE, 2010).

Innovation system context

The US innovation system is characterised by a hierarchy of federal organisations and a strong, vibrant private sector. Rhetoric in the US is mainly about the government allowing private industry to drive R&D, but the US government, through its Federal Departments who each have their own mission, engages in several initiatives that are design to facilitate some of the short-comings of the innovation system. The Federal 'mission agencies', through these initiatives, help drive basic scientific research through tertiary education and federally funded R&D. They also facilitate privately funded R&D by supporting developments in a number of assets with high levels of public good, such as infratechnology development, in areas such as measuring equipment and standards, and skills.

The US is the dominant country in R&D funding in absolute terms, but spends a smaller amount as a portion of GDP than some other countries. According to the OECD (2012), the gross US domestic expenditure on R&D was USD874 billion in 2009. According to UNESCO IS (2013) this was 2.90% of GDP, putting the US expenditure on R&D as a portion of GDP below Israel (4.46%), Finland (3.93%), Sweden (3.60%), South Korea (3.56%), Japan (3.36%) and Denmark (3.06%) and above Germany (2.82%).

The US Federal Government plays a significant role in the country's R&D expenditure. Particularly through its mission agencies, it contributed USD140 billion to the total expenditure on R&D in 2009 (OMB, 2013). In 2012 this had marginally decreased (all in 2013 USD) to USD139 billion (OMB, 2013; Sargent *et al.*, 2013). In 2012, National defence (56%) and Health (22%) received the majority of this R&D funding, as shown in Figure 5 (Boroush, 2013).

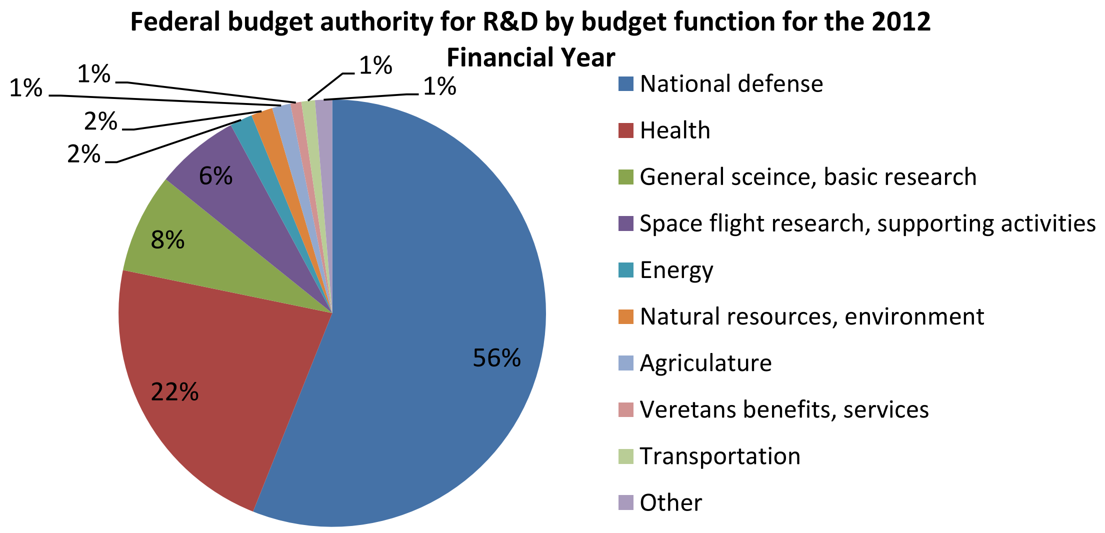

Figure 5: Federal budget authority for R&D by budget function (Boroush, 2013).

The US recognises that materials are an important part of its R&D activities. Materials are seen as an asset that cuts across a number of different research fields (Sargent *et al.*, 2013). Its importance is also emphasised by that fact that more than half of the DoD's R&D expenditure was in base sciences, including materials, in universities and other research institutes (Sargent *et al.*, 2013).

Materials specific R&D expenditure by the US Government is less clear because almost all of these organisations conduct materials R&D through a number of programs and in parallel to other non-materials R&D. In their discussion of materials research in the US' FY2014 (financial year 2014) budget, Kelley and Goldblatt (2013) identify the key publicly funded organisations that conduct materials research as the National Science Foundations (NSF), Department of Energy (DoE), Department of Defense (DoD) and the Department of Commerce's National Institute of Standards and Technology (NIST), many of whose FY2014 budgets have increased on their FY2012 budgets faster than inflation[4] has increased in recent years (Kelley & Goldblatt, 2013). Other agencies Kelley and Goldblatt (2013) identify as key publicly finding organisations that conduct materials R&D include the National Aeronautics and Space Administration (NASA), the National Institutes of Health and the Department of Homeland Security (DHS). Kelley and Goldblatt (2013) also make special mention of the Federal Government's National Nanotechnology Initiative (NNI), which is cross-departmental.

Observations from the review

There has been considerable policy activity in the US regarding materials and materials innovation. A number of policy documents highlight the importance and the needs, opportunities and challenges of materials development. These policy documents range from specific developments in particular classes of materials, such as nanotechnology (NSTC, 2011b) to broader considerations of the role of materials in manufacturing (for example see IAM NSTC, 2012).

There are few materials specific roadmaps in the US

The review of US documentation revealed that the US places significant emphasis on R&D that supports the development of materials, rather than on R&D in materials itself. With the exception of a select few studies from specific government departments (such as the DoE and DoD, see for example AISI, 2013; Brindle *et al.*, 2001), the surveyed documentation avoids identifying specific materials R&D priorities that correspond with material types (for example metal and alloys, polymers, etc.) or with relevant properties (structural and functional). Instead, they focus on specific R&D priorities that develop tools, techniques and technologies that support materials R&D. An example of this is the Materials Genome Initiative (NSTC, 2011a, 2012), which focuses on developing characterisation and simulation techniques to assist the design and testing of materials.

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[4] When compared to inflation estimates were compared to the Consumer Price Index issued by the U.S. Department of Labour's Bureau of Labor Statistics (2013)

The US pays close attention to the development of enabling technologies

Perhaps ones of the more unique observations to come from the United States is to see the explicit attention they have paid to infratechnologies, particularly to measurement, characterisation and modelling technologies. This appears to have emerged over a number of years. NIST's (2006) *Assessment of the US Measurement System* for example discusses the need for these types of equipment and their importance in innovation. This theme continues through the Mathematical and Physical Sciences Advisory Committee's (MPSAC) documents at the National Science Foundation (NSF) (MPSAC, n.d., 2012b, 2012a) and has so far culminated in the development of NSTC's Materials Genome Initiative (2011a, 2012). This initiative is, as far as the review has gone, unique in its attempt to develop the aforementioned infratechnologies.

Such attention is evident in a number of US policy documents. NASA's space technologies roadmaps also focuses on test tools and methods in materials and the structures they are integrated into (Piascik *et al.*, 2012) and on modelling and simulation (Shafto *et al.*, 2012). NIST's Technology Innovation Program (TIP) also aims to support process scale-up predictive modelling, the manufacturability of materials and manufacturing processes of products more generally (NIST, 2011). These technologies are seen as crucial to supporting technology innovation. Furthermore, MPSAC (2012a, p. 4) see 'access and continued innovation in instrumentation drives scientific output and is essential for … leadership in materials science'. Furthering the call for infratechnology development for materials, MPSAC (2012a, p. 5) believe that 'characterization equipment and facilities are paramount to advancing the state-of-the-art in materials research'.

The US departments as mission agencies

The aforementioned observation that the US focuses on supporting technology and on particular applications of materials demonstrates a distinguishing characteristic of the structure of the US innovation system. The US departments are mission agencies – agencies that have specific goals and targets linked to their budgetary appropriations. To meet these goals and targets, these agencies play a key role in planning and developing a technology through to its implementation. As part of this process, rather than creating materials specific plans, materials developments form part of a larger project. For example, materials play a key part NASA's targets for in-space propulsion system; materials are themselves in this instance listed as an important supporting technologies (Meyer *et al.*, 2012).

In these mission agency documents materials development is discussed in terms of the functions they need to perform, rather than by materials type. Materials functions, as opposed to materials types (i.e. metals and alloys, polymers, composites, etc.), are the focus for these documents because the goal was to develop and deploy a core technology rather than only to develop materials. For example, NASA's fourteen[5] roadmaps exploring the 'critical enabling technologies' for NASA 'to maintain its research and development base in space technology' identified 295 specific technologies required (NRC, 2012, pp. 13–14). Even at this level of detail, materials were generally referred to by their required properties, rather than their composition. Furthermore, the *Materials, Structures, Mechanical Systems, and Manufacturing Roadmap* (Piascik *et al.*, 2012), referred little to specific material types, and more to the properties new materials need to demonstrate.

By not referring to material types, but rather to their properties, roadmaps such as the NASA Space Technology Roadmaps (NRC, 2012) define their own class of materials on which to focus. By defining the relevant materials based on particular applications, these documents call for materials to be developed to fulfil a need. For example, the *Roadmap for US Robotics* (Computing Community Consortium, 2009, p. 75) identifies the materials needs for robotics as being 'lightweight, safe, low cost, compliant, and durable structures' for robotics. By viewing materials from this perspective they are narrowing the scope of materials that could be used for a particular application, but also removing tunnelled vision by looking across the types of materials for possible solutions.

Some documents can be quite property specific in the identification of their materials needs. The *Roadmap for US Robotics* (Computing Community Consortium, 2009) also calls for miniaturisation down to the meso, micro and nano scales. Such specificity stipulates the scale of engineering needed to meet such requirements. This, in itself creates subclasses of materials, for example those that need manipulation at the nanoscale.

Materials innovation and manufacturing leadership

The US also pays significant attention to materials as part of its manufacturing strategy. The collection of manufacturing policy documents[6] to come out of the over the past few years emphasise the importance of a strong manufacturing sector to the US economy. Materials play a specific role in this strategy, being identified as one of the four core pillars of this strategy (IAM NSTC, 2012).

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[5] (Hill *et al.*, 2012; Hurlbert *et al.*, 2012; Lyons *et al.*, 2012; McConnaughey *et al.*, 2012; Meador *et al.*, 2012; Meyer *et al.*, 2012; Piascik *et al.*, 2012; Adler *et al.*, 2012; Ambrose *et al.*, 2012; Barney *et al.*, 2012; Clements *et al.*, 2012; Rush *et al.*, 2012; Shafto *et al.*, 2012; Kennedy *et al.*, 2010)

[6] This collection of papers and policy documents include *A Framework for Revitalizing American Manufacturing* (EOP, 2009), *Report to the President on Ensuring American Leadership in Advanced Manufacturing* (PCAST, 2011), *A National Strategic Plan For Advanced Manufacturing* (IAM NSTC, 2012), *Report to the President on Capturing Domestic Competitive Advantage in Advanced Manufacturing* (PCAST, 2012) and the *National Network for Manufacturing Innovation* (AMNPO NSTC, 2013).

Despite the US' interest in manufacturing, it is important to note that 'NIST is the only agency with a broad mandate to support manufacturing' (VCAT, 2012, p. 3). Other federal departments and agencies are involved in the development of manufacturing by proxy of their mandates, including DOE, DOD and NSF, but the US recognises that this is not suitably coordinated or supported. To correct this, the US government has recently deployed fifteen Institutes for Manufacturing Innovation (IMIs), as part of its National Network for Manufacturing Innovation (AMNPO NSTC, 2013). These institutes will not only help to coordinate manufacturing research in particular fields (for example additive manufacturing) but also directly support manufacturing R&D.

Manufacturing and materials: The case of additive manufacturing

The dominance of US companies in the global additive manufacturing equipment industry has been helped in no small way by innovation in materials. In many cases, new additive manufacturing equipment has been launched simultaneously with novel fabrication materials (in many cases the new equipment was designed to use this new material). The new equipment combined with the new materials offer extra-functionality (for the equipment and the parts it produces) and a distinct competitive advantage.

Nanotechnology was a frequent research priority observed during the international review of materials strategies. The US is a leader in nanotechnology. In September 2013, *The Project on Emerging Nanotechnologies* had catalogued 1317 products that used nanotechnology in some form, 587 of which originated in the United States. The US National Nanotechnology Initiative (NNI) was designed and implemented to support the development of nanotechnology in the US. The program attempts to 'establish… shared goals, priorities, and strategies complementing agency-specific missions and activities and providing avenues for individual agencies to leverage the resources of all participating agencies' (NSTC, 2011b, p. 1). Key to nanotechnology is its related set of tools that supports the manipulation of nanomaterials at the nanoscale. These tools blur the distinction between material manipulation and device fabrication, making materials R&D and manufacturing R&D inseparable.

The role of government in R&D coordination

The final significant observation arising from the review of US strategies for materials development is in the role government plays in the coordination of materials R&D. The field of materials draws on a number of disciplines, including engineering, physics, chemistry and more and more on the biological sciences. This often means that materials R&D community is not cohesive and aware of research occurring in other disciplines. Compounding the problem in the US is that the different agencies have their own materials agendas, which can lead to the duplication of R&D (NSTC, 2011b). To manage these, the US government, often through the President's Office, but also through NSF and NIST coordinate activity by convening workshops to discuss the current R&D activities occurring in the different agencies. These workshops often occur as part of a cross-cutting program, such as the NNI, which is a fitting example as it explicitly aims to make the agencies aware of the R&D that each of the other agencies are conducting (see NSTC, 2011b, p. 7).

Critical materials in the US

The US aims to reduce the risk to its production system posed by critical materials by reducing its dependence upon them. The US is doing this by supporting research into replacing critical materials – rare materials or those with supply chains subject to high levels of uncertainty – either through alternative materials or substitute technologies (DoE, 2010, 2011). The US is even involved in a series of trilateral conferences with the EU and Japan concerning critical materials and aiming to 'improve extraction, find substitutes, improve use efficiency and encourage recycling' (European Commission, 2013a, p. 1).

Key references for materials related strategies and initiatives in the United States of America

- NIST, 2006: An Assessment of the United States Measurement System: Addressing Measurement Barriers to Accelerate Innovation
- Computing Community Consortium, 2009: A Roadmap for US Robotics: From Internet to Robotics
- EOP, 2009: A Framework for Revitalizing American Manufacturing
- Glotzer *et al.*, 2009: International assessment of research and development in simulation-based engineering and science
- NIST, 2009: Accelerating the incorporation of materials advances into manufacturing processes
- DoE, 2010: U.S. Department of Energy Critical Materials Strategy
- NIST, 2011: Manufacturing and Biomanufacturing: Materials Advances and Critical Processes
- NSTC, 2011: Materials Genome Initiative for Global Competitiveness
- NSTC, 2011: National Nanotechnology Initiative: Strategic Plan
- PCAST, 2011: Report to the President on Ensuring American Leadership in Advanced Manufacturing
- IAM NSTC, 2012: A National Strategic Plan For Advanced Manufacturing
- MPSAC, 2012: Developing a vision for the infrastructure and facility needs of the materials community: Report of NSF Materials 2022
- MPSAC, 2012: MPS Advisory Committee Meeting August 16, 2012
- NSTC, 2012: Charter of the Subcommittee on the Materials Genome Initiative (SMGI)
- NSTC, 2012: oneNSF Investments: Cyber-enabled Materials, Manufacturing, and Smart Systems (CEMMSS)

- PCAST, 2012: Report to the President on Capturing Domestic Competitive Advantage in Advanced Manufacturing
- VCAT, 2012: 2011 Annual Report (NIST)
- AMNPO NSTC, 2013: National Network for Manufacturing Innovation: A Preliminary Design

Germany

Key points

This chapter summarises the key advanced materials related strategies, roadmaps and initiatives recently published in the Germany. The following are the key observations from these official documents and are discussed in more detail in the rest of the chapter.

- **Germany's innovation system includes a number of distinguishing organisations** – including:
  - The Fraunhofer Society[7] – a group of industry orientated research institutes
  - Industrial Research Associations[8] (AiF) – a small organisation that allows over 50,000 SME's to access public funds for R&D (AiF, 2013).
  - The Max Plank Society for the Advancement of Science[9] (MPG), which is an independent collection of base science research institutes.
- **Germany's innovation system is acutely aware of industry needs and applications** – Germany is particularly aware and actively conducts R&D to address industry's materials needs. This is particularly the case with the Fraunhofer Society because of its mixed source of funding, where a significant portion of its funding comes from industry engagements.
- **Germany pay attention to coordinating materials R&D at a high level and considers complex maters such as value capture from materials** – as with the US, Germany aims to coordinate materials research at a high level across its departments and across industry (acatech, 2008; Lust *et al.*, 2008; BMBF, 2004). Germany's flagship initiative WING[10] ('Materials Innovations for Industry and Society') is one such example (BMBF, 2004). Germany is also actively addressing value capture in high wage economies. By recognising that materials are often an enabler of new products, Germany highlights the importance of materials research, despite materials production often only capturing a small fraction of the final product's monetary value (acatech, 2008; BMBF, 2004).
- **The academies play an active role in coordinating research in Germany** – The German Academy of Science and Engineering (acatech[11]) convenes a variety of stakeholders from materials' fragmented community to help coordinate materials R&D (e.g. see acatech, 2008).
- **Germany pays close attention to the manufacturability of materials** – Through organisations like the Fraunhofer Society, Germany ensures manufacturing is considered in materials R&D.

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[7] Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V. (Fraunhofer Society)

[8] Allianz Industrie Forschung e.V. (AiF)

[9] Max-Planck-Gesellschaft zur Förderung der Wissenschaften e.V. (MPG)

[10] Werkstoffinnovationen für Industrie Gesellschaft (WING)

[11] Deutsche Akademie Der Technikwissenschaften (acatech)

- **Particular attention to supporting/ enabling technologies** – similar to the US, Germany also pays particular attention to technologies that support R&D, for example simulation technologies (acatech, 2008; Lust *et al.*, 2008; BMBF, 2004).
- **Germany also considers 'conventional materials' and R&D into conventional important** – Germany is not only paying attention to novel materials, but also 'conventional' (i.e. non-novel) materials that potentially have high value themselves or are particularly important for other established industries.

Innovation System Context

Germany is one of the major manufacturing countries in the world. According the World Bank (2013) Germany is the fourth largest manufacturing country in the world (see Figure 6), behind China, the US and Japan. Manufacturing, by value added, constitutes 21% of Germany's economy (see Figure 6), making the country more dependent on manufacturing than the US (for which manufacturing makes up 13% of GDP) and Japan (for which manufacturing makes up 19% of GDP) (World Bank, 2013). The value of manufacturing for Germany makes R&D and innovation important, particularly as it is an advanced, high wage economy and which finds it difficult to compete against low wage economies in some manufacturing areas. As a result, Germany pays particular attention to technology developments that could make its manufacturing base more competitive. To do this, Germany has created an R&D base that is responsive to and focused on the needs of industry.

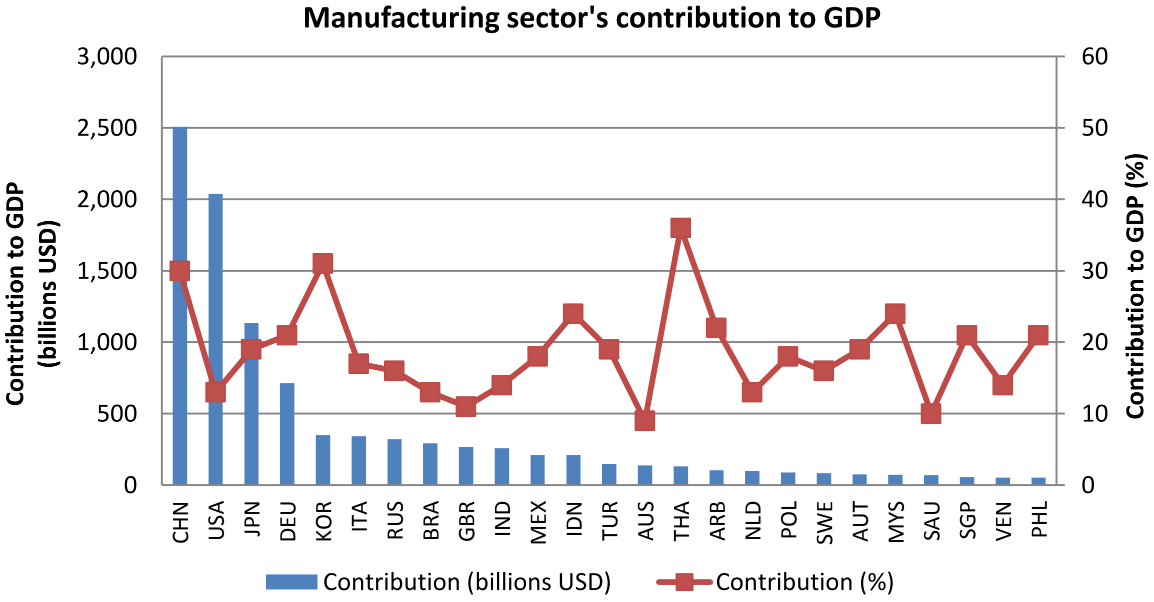

Figure 6: Manufacturing sector's contribution to GDP in 2012, billions of US dollars (World Bank, 2013)

Germany's innovation system's structure of organisations has a number of unique organisations which help it to address industry needs. Dominating the materials discussion on science and technology is the Fraunhofer Society (Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e. V.), which is a group of industry orientated research institutes who are funded by the German Federal Government, the Länder (state) governments and industry. Also important is the German Federation of Industrial Research Associations (Allianz Industrie Forschung e.V., AiF), which distributed almost 485 million euros of public funding (mostly from the BMWi[12]) in 2012 to research associations that comprise solely of SME members. Finally, there is the Max Plank Society for the Advancement of Science (Max-Planck-Gesellschaft zur Förderung der Wissenschaften e. V., MPG), which is an independent collection of non-government, not-for-profit research institutes. Funding for the MPG comes from Germany's Federal and Länder governments. While the MPG mostly focuses on basic research, it research still often finds its way to industrial applications.

These organisations constitute some of the greatest differences between Germany's innovation system and that of other countries. The large industry orientated nature of the Fraunhofer Society, combined with the emergent nature of the SMEs' research societies (which become members of AiF) and the strong, large base science research institutes, including the MPG and universities, create a unique innovation system. This partly designed and partly emergent structure ensures that a number of innovation system needs are met, including research priority elicitation – with input from a number of sources and reduced role of the central government in selecting research priorities – and ensures that much of the country's R&D is driven from industry needs. Other organisations, such as the German Academy of Science and Engineering (acatech), take leading roles in coordination – through communication of R&D activities rather than government led research agendas – and by building networks of researchers and industry. These organisations create a responsive innovation system, coordinated and aligned in such a way that allows research priorities to be predominantly defined bottom-up to support industry needs.

To support its manufacturing sector, Germany prioritises materials R&D. Materials are seen as particularly important as it is a key input to the country's manufacturing sector and is a major creator of employment in the country, with over five million jobs in Germany being in materials related sectors (acatech, 2008, p. 7). Germany aims to leverage its materials R&D to keep its manufacturing sector competitive. Furthermore, it uses its industry orientated research organisations, in particular Fraunhofer Institute for Manufacturing Technology and Advanced Materials (Fraunhofer IFAM) to tackle materials related constraints and possible future advances being explored by industry. Germany's emphasis on manufacturing, its unique organisational structure and its strong science and engineering base and culture make Germany a key player in materials innovation.

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[12] The Federal Ministry of Economy and Technology (Bundesministerium für Wirtschaft und Technologie)

Observations from the review

Paying particular attention to industrial needs and applications

In the materials roadmaps and strategies reviewed, Germany's emphasis is on pull as the major mechanism for materials innovation. Acatech (2008) and BMBF (2006) define two mechanisms for materials innovation: the push principle – where new materials from science search for applications – and the pull principle – where researchers develop new specific materials in response to industry needs. In their research, acatech (2008) identified that the pull principle was the dominant form of materials-driven innovation in Germany.

The Fraunhofer Society is perhaps the most significant organisation in industry orientated materials research in Germany. The Fraunhofer Institute for Manufacturing Technology and Advanced Materials (Fraunhofer IFAM) and the Fraunhofer Institute for Mechanics of Materials (Fraunhofer IWM) are the society's key materials research institutes, but a number of the society's other members, such as the Institute for Environment, Safety, and Energy Technology (Fraunhofer UMSICHT) also participate in materials research. These organisations operate under the Fraunhofer model, where much of their research is commissioned and predominantly paid for by industry. In 2011, just under 50% of Fraunhofer IFAM's budget came from industry projects, with the remainder coming from Federal and State sources (Fraunhofer IFAM, 2012, p. 11). This mixed funding model, where money is drawn from both government and industry sources, means that the Fraunhofer develops new materials and searches for applications (technology *push*), but also has a significant remit to respond to the needs of industry (technology *pull*).

High level planning and coordination and a focus on value capture

The fact that acatech (2008) explores materials R&D innovation in such detail demonstrates another observation made during the review: that a number of high level government and non-government organisations in Germany take an interest in and explores the challenges to, and the barriers and enablers for, materials innovation. This high level involvement has led to some of the nation's major initiatives, such as BMBF's (2004) materials innovation program, WING (Werkstoffinnovationen für Industrie Gesellschaft – 'Materials Innovations for Industry and Society').

The WING program is Germany's major, central materials initiative. WING is run by the DFG (Deutsche Forschungsgemeinshaft – 'German Research Foundation') and the DGM (Deutsche Gesellschaft für Materialkunds – 'German Materials Society'), under the oversight of BMBF (Bundesministeriums für Bildung und Forschung – the 'Federal Ministry of Education and Research'). WING's on-going aim is to increase materials innovation for industry by enhancing the industry orientation of materials research, use materials to address social and economic needs or 'grand challenges' (including mobility, infrastructure, health and the environment) and use materials for sustainable development (BMBF, 2004). WING aims to achieve these by investing in supporting technologies (e.g. computational capabilities to support 'computational materials science'), supporting materials development in SMEs (particularly young research intensive start-ups), aims to speed up the innovation process by accelerating technology transfer and develop an education program that promotes both technical and research materials skills (BMBF, 2004).

The review also revealed that Germany's major materials programs and projects are contributing to an understanding of how developed nations can retain and growth their strong industrial sectors. Both the WING program (BMBF, 2004) and the acatech (2008) project explore how Germany can capture value from materials research through manufacturing. They acknowledge that materials research is essential for major industrial companies, but is made difficult by the combination of the high cost of materials R&D and by the fact that materials only capture a fraction of the final value of a product (BMBF, 2004). These have a significant impact on the motivation for materials research, for both major industrial companies and SMEs (BMBF, 2004). Acatech (2008; Höcker, 2007) explores this issue through what it calls the material-to-product chain – a concept that covers the stages from materials development through to its integration in the final product. According to acatech (2008) this is a knowledge transfer driven process and inhibited by barriers to knowledge transfer including the heterogeneity of the people involved, the complexity of the task and the low levels of integration along the material-to-product chain. Acatech (2008) also acknowledge other 'hurdles' that inhibit 'flows' in the material-to-product chain. These include:

- Issues with intellectual property
- Organisational hurdles
- Communication and technology issues
- Technical issues, such as incompatible forms of data
- Lack of funds for supporting prototyping
- Length of time required for materials R&D
- A lack of supporting technologies
- A lack of communication of customer and product requirements upstream to R&D

The attempt of high-level government and non-government organisations to address such issues in the context of materials to such a degree was unique to Germany in the review.

These reports demonstrate the planning role played by higher level government and non-government organisations in Germany. BMBF (2004), for example, lists ten specific fields of action in which its funding will be distributed by the WING program. Acatech also supports planning for materials development. In its 2008 report, acatech provides specific recommendations regarding what Germany needs to do to increase its competitive capabilities in materials R&D and (acatech, 2008). Fraunhofer Institutes also participate in planning at this level, with reports such as *Zukunftsfeld Werkstofftechnologien* (The Future of Materials Science) (see Lust *et al.*, 2008). These reports demonstrate the planning role played by government departments and the advisory role played by the academies and major research organisations in Germany.

Non-government coordination organisations, particularly the academies

The academies in Germany also appear to have a coordinating role in German industry; similar to NSTC's observed role in the US. For example, acatech (2008) convened a workshop with people from a range of materials related sectors in order to elicit their views on what they thought materials innovation in Germany needed. This not only brought together the fractured and decentralised materials community, but also informed the discussion around Germany's materials R&D needs and industry's materials needs.

Paying attention to the manufacturability of materials

The review revealed that in Germany there is an emphasis on considering the manufacturability of material concurrently with a materials development. The structuring of advanced materials with manufacturing technology in a Fraunhofer institute, Fraunhofer IFAM, is one example of this. Driving this appears to be not only the structure of this centre, but its funding model: the fact that a large portion of its income comes from industry. By focusing on developing materials through centre-industry commissions and collaborations, manufacturability is an important consideration for such a partnership to be successful and for industry to benefit from this engagement. This is also reflected by the WING program (BMBF, 2004) and by acatech (acatech, 2008) and their acknowledgement that to get value out of materials, its production, however-a small part of the final value of the product – may be the only route to realising any value at all.

Paying attention to supporting/ enabling technologies

Germany's focus on supporting technologies was somewhat different to that of the US. As discussed, manufacturability was an integral part of the Fraunhofer Society's industrial engagement. Germany also placed great emphasis on simulation and computational support in the design of materials (acatech, 2008; Lust *et al.*, 2008; BMBF, 2004). However, the remaining advocacy for supporting technologies appears to be mainly driven by the Alliance of Industry and Science, an advisory group for Germany's high-tech strategy, rather than by the academies or by government agencies. Lust and his colleagues (2008), in a report for the Alliance, lists a number of Tassey's (2004) infratechnologies as important to the development of materials. Aside from this mention in passing however, the German documentation reviewed did not generally discuss the importance of or advocate support for infratechnologies or other information and communication technologies.

Not neglecting 'conventional' materials

A final observation from the review is that Germany retained a balanced view of the potential of both new and established 'conventional' materials. A number of materials strategy documents explicitly outline the conventional materials that will be important to industry alongside the new materials classes. Cuhls and her colleagues (2009), for example, explicitly list both conventional and new materials classes and their potential applications in their industrial foresight exercise for BMBF. Perhaps this is in response to the warnings from acatech (2008, p. 9), which claims that there is too much focus on new materials with 'catchwords such as "nano" and "bio materials"' that 'are frequently given priority by public research funding over traditional materials that are far more significant for industrial use'. Either way, Germany's government documents considered conventional materials, which are potentially high value and industrially strategic, to a greater extent than the US and Japan.

Key references for materials related strategies and initiatives in Germany[13]

- BMBF, 2004: Materials Innovations for Industry and Society – WING
- acatech, 2008: Materials Science and Engineering in Germany
- BDA, unknown: BDA: Doing Business Together
- Lust *et al.*, 2008: Zukunftsfeld Werkstofftechnologien (The Future of Materials Science)
- Cuhls *et al.*, 2009: Foresight Process – On behalf of the German Federal Ministry of Education and Research (BMBF)
- AiF, 2013: Research for SMEs - AiF at a glance

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[13] This reference list mostly includes and is mostly limited to reports written in English

Japan

Key points

This chapter summarises the key advanced materials related strategies, roadmaps and initiatives recently published in Japan. The following are the key observations from these official documents and are discussed in more detail in the rest of the chapter.

- **Japan's R&D base has a few, strong non-university public organisations conducting materials research** – while Japan's R&D base in materials is dominated by universities, there is a significant amount of work being done by three independent public organisations, namely the National Institute of Advanced Science and Technology (AIST), the Japan Science and Technology Agency (JST) and the National Institute for Materials Science (NIMS).
- **The structure of Japan's key public research organisations suggest:**
  - **Materials focus reflects its industrial strengths** – much of the research conducted by AIST, JST and NIMS is orientated towards industry needs.
  - **Japan's materials R&D focus also reflects its desire to use innovation to address social and environmental needs** – AIST also targets social and environmental challenges with its materials research, such as health and population issues.
  - **There are benefits to grouping materials, manufacturing and nanotechnology** – the grouping of materials, manufacturing and nanotechnology by AIST suggests there are research benefits
- **Nanotechnology is a particular focus in Japan** – a string of reports from Japan evidence the importance and emphasis it is placing on nanotechnology (see CRDS, 2013a; AIST, 2008a, 2003). Nano-related materials research is explicitly a focus in a number of NIMS' key research fields and the emphasis on Nanosystem Modelling highlights the perceived importance of both infratechnologies and nanotechnology for Japan and their interconnected nature[14].
- **Japan pays particularly close attention to supporting/ enabling technologies relevant to materials research** – AIST, NIMS and the Centre for Research and Development Strategy (CRDS) all promote supporting/enabling technology development, including simulation, measurement and characterisation technologies as well as developing and maintaining common databases. AIST also pays particular attention to manufacturing and materials and the links between the two fields (AIST, 2005, p. 6).

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[14] The previous structure of NIMS also reflected this with centres such as the Advanced Nano Characterisation Center and Computational Materials Science Center (both under the Key Nanotechnologies Field) (NIMS, 2010).

- **The interdependence of advances in materials, manufacturing, infratechnologies and ICT is emphasised in Japan in the case of nanotechnology** – a number of challenges and priorities identified in Japan evidence the recognition of the interdependent nature and importance of co-developing materials, manufacturing, infratechnologies and ICT (see AIST, 2005, p. 6). Such priorities include nanotechnology/ materials being the one of the Council for Science and Technology Policy four key priority areas (Council for Science and Technology Policy, 2010), CRDS' notion that nanotechnology is 'inseparable from the field of materials science and engineering' (CRDS, 2013a, p. vi) and AIST's (2013) acknowledgement that ICT and materials/ systems production are two of the key challenges to advanced technology. This is again supported by AIST's grouping of nanotechnology, materials and manufacturing into one research field (AIST, 2013). Finally, AIST (2008a, p. 2) believes that simulation technology (an infratechnology) has played a central role in supporting development and promoting innovation in nanotechnology.
- **Japan coordinates activity differently to other countries**
  - **Japan conducts international reviews** – this review revealed the level of attention Japan paid to how other countries deal with materials research was unique, as evidence by a number of published international reviews (see, for example, CRDS, 2013a).
  - **Japan routinely develops a Strategic Technology Roadmap (STR)** – the STR is a three layered approach to planning for technology development and includes detailed roadmaps on particular technologies, which are aggregated into Technology Overviews, which themselves are aggregated into sets of scenarios (METI, 2010; Yasunaga *et al.*, 2007, 2009).
  - **Japan also conducts a large scale Delphi study to get insight into what policies will be needed in science, technology and innovation policy** – the process is focused on major national and global challenges and aims to identify how important specific technologies are, when they are likely to be developed and who should be responsible for its development (NISTEP, 2010).
- **Japan, like the US, is concerned about critical materials** – by participating in the Trilateral EU-US-JP Conference on Advanced Materials and the Japan-EU Workshop on Substitution of Critical Raw Materials Japan is showing particular concern for critical materials.

Innovation System Context

Japan's production system is characterised by the keiretsu organisational structure and strong buyer-supplier ties. The keiretsu are networks of companies that are either horizontally organised – where firms in different industries share ownership and are often clustered around a bank – or vertically organised – where up- and down-stream firms are linked by a single large corporation by long-term buyer-supplier relationships (Blackford, 1998; Liu *et al.*, 1998). However, strong buyer-supplier relationships are not uncommon in Japan. Large, vertically organised keiretsu, such as Toyota, epitomise these characteristics of Japanese industry. In such a structure, SMEs are protected and nurtured by the central organisation, who maintains the SME's through extensive long-term sub-contracting (Liu *et al.*, 1998). Through these arrangements organisations cooperate closely on design, reduce transaction costs and up- and down-stream SMEs fend of competition by being quasi-permanent partners with the large coordinating firm (Liu *et al.*, 1998). Such links promote spillover (Branstetter, 2000) and encourage long term investment, including in R&D (Liu *et al.*, 1998).

Japanese industry also benefits from a culture that supports manufacturing and value creation. The Japanese combine their industrial structure with their cultural emphasis on harmony to cooperate when assisting each other, such as contractors sharing reduced profit margins with their keiretsu partners during economic downturns (Liu *et al.*, 1998). Japanese manufactures also benefit from monozukuri – an admiration of skill involved with value creation, realised in manufacturing as skill in design and production (Fujimoto, 1999). Both of these cultural aspects help to support manufacturing and manufacturing companies in Japan and has flow-on consequences for materials production and R&D.

Through their planning activities and the institutes they oversee the Ministry of Economy, Trade and Industry (METI) and the Ministry of Education, Science, Sport and Culture (MEXT) dominate public science and technology research in Japan. These government departments conduct large scale planning and coordination exercises that collect input for a large number of stakeholders from academia, the public service and industry. These detailed, multi-layered plans are designed to stimulate discussion and guide research. METI and MEXT also play a significant role in materials research through their Independent Administrative Institutions (IAIs).

Materials research in Japan is dominated by universities and IAIs. Figure 7 shows the top twenty Japanese research organisations by number of materials related publications from a bibliometric exercise carried out on the Web of Science (Thomas Reuters)[15]. The exercise suggests that, by publications in English, the major materials research universities are the University of Tokyo, Tohoku University, Kyoto University and Osaka University and that the major IAI's include the National Institute of Advanced Science and Technology (AIST), Japan Science and Technology Agency (JST) and the National Institute for Materials Science (NIMS), the first of which is overseen by METI and the latter two of which are overseen by MEXT.

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[15] On publications published in 2013 until the 12th of November, 2013

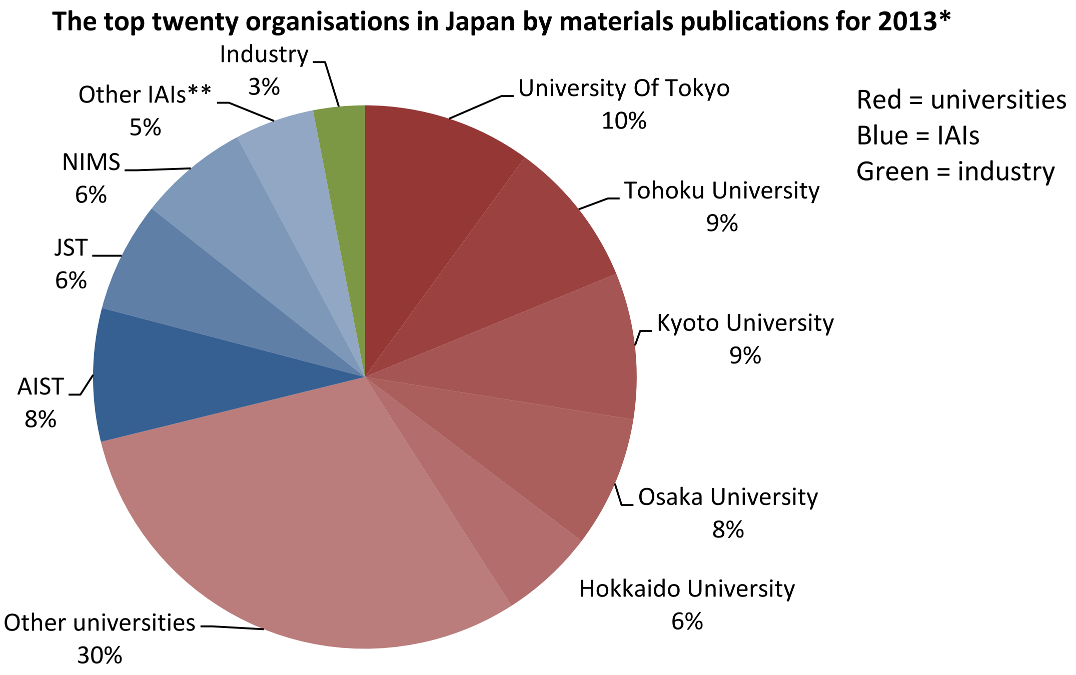

Figure 7: The top twenty organisations by materials related publications on the Web of Science
* Of the publications reported in the Web of Science (Thomas Reuters) as of the 12th of November, 2013
** Independent Administrative Institutions (AIST, JST & NIMS are also IAIs)

The bibliometric exercise, with its language and publication bounding parameters, suggests that only a handful of universities and IAI's dominate materials research in Japan and industry's contribution is small. The Toyota Motor Corporation was the only industrial organisation in the top 20, coming 13th and contributing 3% of the publications to the top 20 organisations' cumulative publications). However, caution should be taken when interpreting this result, since industry does not necessarily focus on producing publications from their R&D.

Observations from the review

Observations from public research organisations: industrial strengths and its needs, social and environmental needs, benefits in grouping Materials, manufacturing and nanotechnology

The review revealed that Japan's interest in materials development reflects its industrial strengths and its desire to address critical social and environmental challenges. Japan's industry targeted materials research is predominantly driven by the aforementioned three major IAIs in materials research: AIST, JST and NIMS. AIST, for example, structures its six research units so that some of them directly address specific sectorial needs and applications. The research units within AIST's Information Technology and Electronics field, for example, is working on a flexible printed pressure sensor for Songle – a technology that identifies music through vibration recognition, database searching and results feedback – for its electronics industry (AIST, 2013). AIST's research fields include:

- Information Technology and Electronics
- Nanotechnology, Materials and Manufacturing
- Life Science and Biotechnology
- Environment and Energy
- Metrology and measurement
- Geological Survey and Applied Geoscience

Critical social and environmental challenges also top the agenda for Japan. AIST has aligned its structure to directly develop technology to addresses these challenges. Its Life Science and Biotechnology field of research (with 8 research units) and its Environment and Energy field of research (with 12 research units) focus on some of Japan's socioeconomic challenges such as its aging population and the environment (AIST, 2013). However, AISTs research fields are not isolated since some of these needs are expected to drive demand for future products. A number of AIST's other research laboratories, such as the Research Center for Ubiquitous MEMS and Micro Engineering[16] (which is in the Nanotechnology, Materials and Manufacturing field of research) focuses on applications to the environment, health and security, which have direct industrial applications.

AIST also suggests that there are benefits to grouping materials, manufacturing and nanotechnology together in the one research group. This is particularly pertinent as the five centres within this research group[17] are kept together despite their strong links and overlapping interests with AIST's other research fields and their application domains.

Japan pays particular attention to nanotechnology

AIST's emphasis on nanotechnology reflects the emphasis Japan has placed on nanotechnology more broadly. AIST and CRDS have developed a string of reports discussing the needs of nanotechnology (see CRDS, 2013a; AIST, 2008a, 2003), which explore the potential applications, opportunities and needs of nanotechnology. Nanotechnology is also one of NIMS' three core

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[16] MEMS is microelectromechanical systems

[17] These research centres include: the Materials Research Institute for Sustainable Development, the Advanced Manufacturing Research Institute, the Nanosystem Research Institute, the Nanotube Research Center and the Research Center for Ubiquitous MEMS and Micro Engineering.

streams of research, reflected in the fact that six of NIMS' ten research fields have some focus on materials manipulation at the nanoscale (NIMS, 2010).

Japan & infratechnologies

Japan's rhetoric around nanotechnology also highlights another trend in Japan: the country's tendency to pay particularly close attention to the development of infratechnologies. AIST (2008a), for example, outlines the need to develop simulation technology to support nanotechnology development. This emphasis is not isolated to nanotechnology. Furthermore, NIMS' Department of Materials Infrastructure also supports infratechnology development by focusing on the development of measurement, characterisation and analytical technologies and supporting the construction and maintenance of databases (see NIMS, 2010). Equipment such as these constitute a large portion of the assets which are seen as important 'intellectual infrastructure' in Japans 4th Science and Technology Basic Plan (Council for Science and Technology Policy, 2010).

Japan's backing of supporting/ enabling technologies for materials is endeavouring to change the way materials research is conducted. CRDS's (2013b) *Materials Informatics* report describes a change in the materials development process that is similar to that promoted and supported by the US' National Genome Initiative (see NSTC, 2011a). The CRDS (2013b) is conducting research and aims to develop new technology so that instead of 'discovering' materials properties, materials are designed with the properties that are required, using modelling and characterisation tools and techniques. Computer-based simulation is key to un-locking this shift; AIST (2008a, p. 2) believes that simulation technology has already played a central role in supporting the development of, and promoting innovation in, nanotechnology. This shift alters the role of Tassey's (2004) infratechnologies from supporting exploration to enabling the explicit identification and testing of novel materials in the design stages before they are physically realised, with the goal of reducing resources for materials development and potentially further compressing R&D and innovation timeframes.

A more complete view of the innovation system: Materials, manufacturing, infratechnologies, nanotechnology and skills

A detailed understanding of how Japan views supporting/ enabling technologies is developed when the views of a number of its public research and policy organisations are considered. The 4th Science and Technology Basic Plan in Japan places nanotechnology/materials as one of its four key priority areas (Council for Science and Technology Policy, 2010). CRDS (CRDS, 2013a, p. vi) similarly believes that nanotechnology is 'inseparable from the field of materials science and engineering'. CRDS (2013a, p. vii) also acknowledges the importance of common user facilities and 'Science and technology infrastructure', which is the intersection of fundamental science and infratechnologies, in nanotechnology developments. Finally, AIST (AIST, 2013) acknowledges that

ICT and materials/ systems production are two of the key challenges to advanced technology development. These views strengthen the links between materials, manufacturing and information and communication technologies (ICT) – demonstrated through the research field of nanotechnology.

Japan is considering even more of the innovation system with its concern for skills shortages. For example, Japan developed the *Fusion of MT [manufacturing technology] and IT to Enhance Manufacturing Capability* to address a fall in the availability of skilled workers in manufacturing and IT (AIST, 2005). Combined these views suggest that Japan is considering a range of technologies that it believe can be used to support technology development. Through this collection of organisations and perspectives, Japan has increasingly broadened its view of the innovation system and what is can do to support R&D innovation.

Coordinating activity

Of the literature covered in this review Japan had three distinct characteristics when it came to the planning of materials R&D. First, Japan was the only country to have published an international review of advanced materials. CRDS' (2013a, p. vi) *Panoramic View of the Nanotechnology/ Materials Field* (mostly in Japanese) includes a review of countries in Asia and Europe and America and gives an 'overview of the nanotechnology/materials field including national R&D projects, [and report the] relevant investment strategy, research potential, technological evolution and commercialization trends of each country in the world'. AIST's (2006) Nanotechnology also does a brief review of the nanotechnology R&D around the world. Such reviews indicates that these organisations at least, if not Japan, sees it as important to understand how other countries are thinking about and support materials related R&D.

Secondly, Japan engages in large scale, multi-sectorial technology planning that identifies explicit technologies on which R&D organisations can focus and hence has implications on the materials used the make them. Orchestrated by METI and NEDO (The New Energy and Industrial Technology Development Organization), the Strategic Technology Roadmap (STR) has three layers: a series of detailed technology roadmaps, technology overviews that aggregate their information and a set of scenarios. STR 2010 considered 31 fields of research and involved 974 experts from private and public research and manufacturing organisations (METI, 2010). The STR included a 'materials' field that was structured to reflected what is needed from materials (the *why* element of TRMs) and the core technologies that will be developed to meet those needs (the *what* element), but the scope of this study was narrowed by grounding the materials in particular applications (METI, 2010). The STR also acts as an information and knowledge mobiliser and coordinator, by gathering researchers and manufacturers from both private and public organisations and generating a vision based on their perspectives (METI, 2010). Finally it communicates (in Japanese only) this view to other Japanese organisations not involved in the process, including other R&D organisation and manufacturers (METI, 2010).

The third difference is that the National Institute of Science and Technology Policy (NISTEP) – which is overseen by MEXT – engages in a large scale Delphi study to understand what types of technologies might be developed and when these developments might occur. The study was structured to understand what was needed to address national and global challenges, and as such had panels set up along these lines, rather than along the science and technology streams (NISTEP, 2010). The survey then outlined detailed technical developments and asked questions about how important those developments were, which R&D organisations should address such problems and the years in which these developments are likely to occur. This very detailed process was intended to be used to 'clarify the policies to be taken in the fields of science, technology and innovation' (NISTEP, 2010, p. 1).

Critical materials

Like the US, Japan also considers critical materials to be a topic that contributes to the countries materials research priorities. Kishi (2011) provides an overview of a range of projects exploring rare earth materials and substitution, which have be carried out by a range of Japanese organisations, including NIMS, NEDO, METI and the MEXT[18]. These programs focus mainly on the substitution of rare earth materials and harmful elements in technology (Kishi, 2011). AIST (2008b) has also given the topic of rare metals serious consideration. Finally, Japan is also involved with the EU-US-JP Trilateral Conferences on critical materials (European Commission, 2013a) and workshops and symposiums have been held with the EU exploring the substitution of materials that have supply risk and materials and elements that are toxic or have negative environmental impacts (European Commission, 2011a). The outcome of one particular engagement, the Japan-EU Workshop on Substitution of Critical Raw Materials, was a call for more closely linked theory and experimental materials development, greater materials characterisation and the development of nanomaterials and nanotechnologies with unique functionalities to replace critical materials (European Commission, 2011a). Through engagements like this, Japan demonstrates a multi-faceted view of materials research and what it can do for it economically and socially and what it can do for the environment.

Key references for materials related strategies and initiatives in Japan[19]

- AIST, 2005: Materials & Manufacturing Technology in AIST: Get Maximum Output with Minimal Input
- AIST, 2008: Nanoworld Simulation: Opening Keys to Developments of Industrial Technology

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[18] The Ministry of Education, Culture, Sports, Science and Technology

[19] This reference list limited to reports at least partially written in English

- Yasunaga, 2009: Application of technology roadmaps to governmental innovation policy for promoting technology convergence
- Council for Science and Technology Policy, 2010: Japan's Science and Technology Basic Policy Report (The 4th Basic Plan)
- METI, 2010: Strategic Technology Roadmap 2010: Roadmap for Strategic Planning and Implementation of R&D Investment
- NIMS, 2010: NIMS Pamphlet
- NISTEP, 2010: The 9th Delphi Survey (NISTEP Report No. 140)
- Kishi, 2011: Overview of Japanese Research Activity on Critical Raw Materials: Elemental Strategy Project
- AIST, 2013: AIST: Integration for Innovation
- CRDS, 2013a: Materials Informatics: Materials Design by Digital Data Driven Method
- CRDS, 2013b: Panoramic View of the Nanotechnology/ Materials Field
- AIST, n.d.: Nanotechnology: For New Industry Creation and Life-Style Innovation

The European Union

Key points

This chapter summarises the key advanced materials related strategies, roadmaps and initiatives recently published by the EU and programs the EU funds. The following are the key observations from these official documents and are discussed in more detail in the rest of the chapter.

As a union of sovereign states, each with their own innovation system, the EU is a funding provider and promotes supranational coordination. It is these goals that make its activity pertinent to the study.

- **The has two large scale roadmaps that attempt to address a broad range of materials: the Materials Roadmap Enabling Low Carbon Technologies and the *Research Road Mapping in Materials*** – these two roadmaps (see European Commission, 2011b; DG-R, 2010 respectively) were the most detailed materials roadmap found during the review. However, their scopes were narrowed by selecting particular applications; in the first it was materials related to low carbon technologies and in the second a limited number of sectors were chosen to reduce the number of materials properties and hence materials that needed investigation. Despite this activity, these are the closest attempts to cover materials in a single roadmap or strategy.
- **The EU's programs highlight the importance of supporting/enabling technologies** – the *Research Road Mapping in Materials* (see DG-R, 2010) and the *Materials Roadmap Enabling Low Carbon Technologies* (see European Commission, 2011b) advocate the development needed in technologies that support materials R&D and enable their deployment.
- The EU has a very strong focus on material with a number of programs investigating them:
  - **KET** – Materials are one of the EU's Key Enabling Technologies (KETs) and features strongly in Horizon 2020 (E-MRS & MatSEEC, 2011; KET AMT, 2010)
  - **EuMaT** – The European Technology Platform (ETP) for Advanced Engineering Materials (EuMaT) has a roadmaps that details a number of materials and their research goals based on particular applications – EuMaT aims to support the EU's decision making, planning and investment decisions regarding materials with roadmaps such as its *Materials for Life Cycle* roadmap (EuMaT, 2006).
  - **MatVal** – launched in February 2013, MatVal (Materials Value Initiative) aims to coordinate the activities of the ETPs who have materials related agendas and for future Horizon 2020 materials related initiatives and specifically focuses on the role of materials in generating value.
  - **There are other materials related events in the EU** – of particular interest is the Future Materials Conference in 2011 (FUMAT2011) which convened representatives from industry, the civil service and academia to discuss research progress in materials, in

particular how materials might be used to address society's 'grand issues' (IPPT/KPK *et al.*, 2012).

- **The EU suggests strong links between materials, nanotechnology and manufacturing** – The EU's 7th Framework Program's (FP7) *Theme 4: Nanosciences, nanotechnologies, materials and new production technologies (NMP)* suggests there are strong links between and possibly even benefits in keeping materials, nanotechnology and manufacturing together in research programs. The Directorate-General of Research (2010, p. 4) believes NMP underpins FP7's other themes.
- **The EU is paying considerable attention to critical materials** – the EU is not only involved in the aforementioned conferences and workshops with other countries, but also has its own Critical Materials Initiative, which focuses on issues relating to materials with supply shortages.

Innovation System Context

The EU's innovation system is different because it is a union of sovereign states, each of whom have their own research organisations and agendas. The EU therefore takes a role as funding provider, creating a common platform for R&D funding in the EU and promoting supranational research coordination. The EU's funding for R&D supplements that of the nations that make it up.

The primary source of funding for R&D in the EU is the Framework Programmes for Research and Technological Development. The large number of research organisations within the EU can apply and be granted funding from these programs through a number of instruments. Framework Programme 7 (FP7) is the current program, which has run from 2007 and finishes at the end of 2013. It is open to any country in the world, but access and rights regarding the funding program vary and EU member states have the greatest access and right regarding the money. The next program, FP8 or Horizon 2020, is due to begin next year and run until 2020. When it was commenced, FP7 was given a budget of over €50 billion (European Communities, 2007). Horizon 2020 brings together even more of the EU's R&D funding programs, including the Framework Programme for Research, the European Institute of Innovation and Technology (EIT) and the Competitiveness and Innovation Framework Programme (European Commission, 2011c).

Three major R&D and innovation related organisations operate at the EU level: the European Research Council (ERC), the Joint Research Centre (JRC) and the Directorate-General of Research and Innovation (DG-R). The ERC distributes funding to applicants within the EU and the European Economic Area, performing a similar function to research councils in other countries. The JRC is a Directorate-General of the European Commission and its central role is to provide based evidence and advice to the European Commission. As part of this role it carries out a number of activities, including accreditation, testing and commission testing, and evidence collection and analysis for policy development. Finally, the DG-R is responsible for coordinating and promoting research at the EU level (known as the European Research Area, ERA) and to support EU policy development in research and innovation. One of the main instruments through which the DG-R carries these aims out is the Framework Programs.[20]

Observations from the review

Large scale roadmaps for materials

Perhaps the most extensive example of a materials roadmap uncovered in the review comes from the DG-R's *Research Road Mapping in Materials* (see DG-R, 2010). This roadmap was unique because its maps were based on materials grouped by material type as well as groupings based on properties and scales of engineering and was the most extensive mapping of materials type found during the review. However, the only way that such an extensive list of materials types could be mapped, was for each type's focus to be narrowed by identifying key application sectors and then key structural and functional properties for each materials type. The Metallic Alloys group, for example, were to be explored for their application to the Energy and Transport sectors (see DG-R, 2010). The materials were further narrowed by the systems in those sectors to which they applied. Based on this description, the functional properties of the materials could then be explored and the challenges relating to those materials, for those properties in those applications identified.

Another serious attempt by the EU to produce a roadmap on materials is represented by the *Materials Roadmap Enabling Low Carbon Technologies* (see European Commission, 2011b). This roadmap identifies key applications for materials that will help to realise lower carbon energy production. It outlines key specifications for these materials, their current level (if there is one) and their main performance targets. This roadmap is another extensive roadmap and covers a number of different materials and a number of different structural and functional properties. However, as with the previous, its scope was limited by the application on which it focused: low carbon technologies. Despite this narrow focus, a considerable amount of work still went into informing this work, including the following 'sub'-roadmaps and reports:

- *Technology Nuclear Energy* (Buckthorpe *et al.*, 2011)
- *Fossil Fuels Energies Sector, including Carbon Capture and Storage* (Gomez-Briceño *et al.*, 2011)

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[20] Other R&D stats can be found in the European Commission's (2012) report *Enhancing and focusing EU international cooperation in research and innovation*. For example, the report outlines that the EU 'is a world leader in research and innovation, responsible for 24% of world expenditure on research, 32% of high impact publications and 32% of patent applications, while representing only 7% of the population' (European Commission, 2012, p. 2).

- *Concentrating Solar Power* (Heller *et al.*, 2011)
- *Photovoltaic Technology* (Rigby *et al.*, 2011)
- *Bioenergy* (Schwarz *et al.*, 2011)
- *Energy efficient materials for buildings* (Van Holm *et al.*, 2011)
- *Hydrogen Fuel Cells* (Cerri *et al.*, 2012)
- *Wind Energy* (Janssen *et al.*, 2012)

Despite these two large scale attempts to map materials, they were still bound to their applications and there has not been an attempt to comprehensively map materials. These two roadmaps demonstrate the detail involved in exploring individual materials and the number of properties they have. The DG-R's *Research Road Mapping in Materials* (see DG-R, 2010) in particular only identified specific material research needs and challenges because it makes reference to a small selection of applications (DG-R, 2010). The *Materials Roadmap Enabling Low Carbon Technologies* (see European Commission, 2011b) is also restricted in its scope by its application domain. The publications found during the review suggest that more detailed and spanning roadmaps of materials have not been done by an EU organisation.

The EU and supporting/ enabling technologies

The EU's materials planning and strategy exercises also touch on a number of supporting technologies needed for materials development. The *Materials Roadmap Enabling Low Carbon Technologies*, for example, dedicates a section to the research infrastructures, including , simulation and modelling and materials characterisation, that are required to support materials development (see European Commission, 2011b). Furthermore, modelling and characterisation needs in particular were made reference to throughout the *Research Road Mapping in Materials* report (DG-R, 2010). The NANOfutures report also had a number of supporting technology requirements such as database development, data integration techniques, and testing tools (NANOfutures, 2012).

Also prominent in these reports are the benefits recognised with developing manufacturing processes alongside materials development. For example, processing techniques were one of the research needs in the *Tissue engineering* section of the *Research Road Mapping in Materials* report (see DG-R, 2010). This is not an isolated example: the DG-R (2010) identify a number of other materials related manufacturing research needs, including self-assembling processes for magnetic materials (p.17), low temperature processes for piezoelectric materials (p.19), nanostructuring processes in polymers (p.20) and scale-up processes for organic multifunctional materials (p.22).

The EU's emphasis on materials: Programs and events

Reflecting the importance of materials to a number of different sectors and technology applications, materials were identified by the European Commission (European Commission, 2009a, 2009a) as one of the six Key Enabling Technologies (KET)[21]. Materials were chosen because they play a key role in a number of different technologies, including those that might be used to address key 'societal challenges' (KET AMT, 2010). Furthermore, materials are seen as important because they form the foundation of equipment and underpin components, which collectively form product systems, and therefore a part of an entire industry's value chain (KET AMT, 2010). This underpinning role of materials has been exemplified (see Figure 8) by the Key Enabling Technology working group on Advanced Materials Technologies (KET AMT, 2010). Materials will continue to play a key role in Horizon 2020, the EU's next Framework Program (European Commission, 2011b).

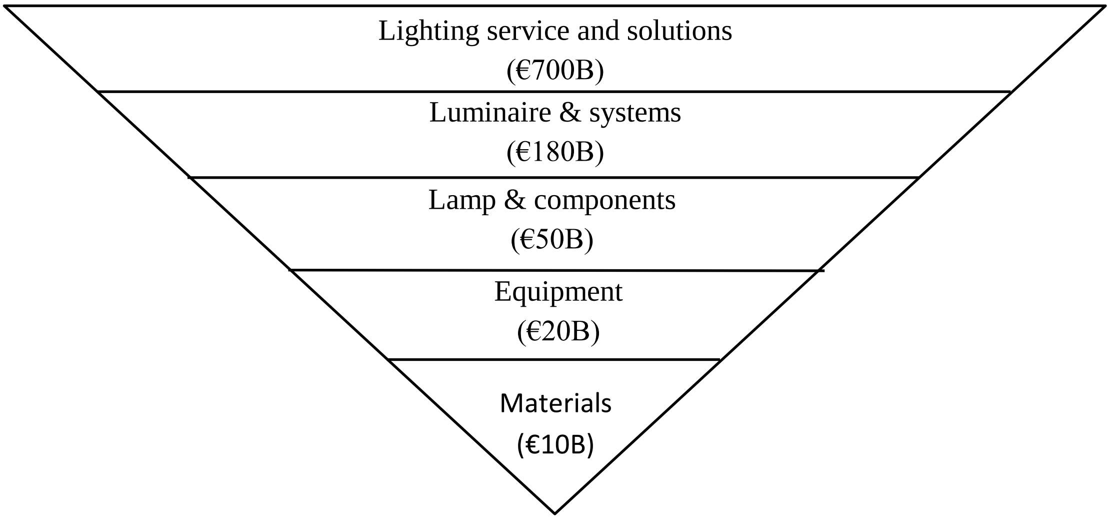

Figure 8: An depiction of how materials underpin broader industries, an example from micro-/nano-electronics and photonics (HLG KET, 2011, p. 11; KET AMT, 2010, p. 3)

Materials are also being addressed an FP7 funded European Technology Platform (ETP), entitled the European Technology Platform for Advanced Engineering Materials (EuMaT). ETPs are an 'industry-led stakeholder for a that develop short- to long-term research and innovation agendas and roadmaps for action at EU and national level to be supported by both private and public funding' (European Commission, 2013b, p. 2). EuMaT 'supports [EU] planning, decision making and investments in advanced materials technology' (EuMaT, 2012, p. 23). It aims to promote materials development as a means of addressing society's 'grand challenges' and is particularly concerned with materials' life-cycle for environmental sustainability and EU competitiveness (EuMaT, 2006, 2012). In a roadmap for EuMaT (2006), five key topics were identified:

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[21] The other five Key Enabling Technologies (KETs) are nanotechnology, micro-nanoelectronics, industrial biotechnology, photonics and advanced manufacturing systems.

1. multi-functional materials with gradient properties
2. engineering materials for application in extreme conditions
3. hybrid and multi-materials
4. relevant materials production and other related technologies
5. multi-scale modelling

The roadmap outlines in great detail the hybrid materials that can be used to address specific extreme conditions and the development goals needed (EuMaT, 2006). It also outlines the fields of base science research and supporting technologies that are required to meet these goals, including ICT (e.g. databases), simulation systems and development in the materials' production technologies (EuMaT, 2006). The roadmap outlines in detail the research priorities of EuMaT. The ETP program is set to continue under Horizon 2020 after being reviewed (European Commission, 2013b). The results of this review were unpublished at the time of writing.

MatVal (Materials Value Initiative) is another EU initiative that aims to support materials R&D and innovation. The Alliance for Materials (A4M) is an alliance of ETP's with strong materials agendas (e.g. EuMaT). MatVal is an A4M initiative is funded by FP7 and aims to coordinate these ETP's for future Horizon 2020 materials related initiatives. No published information on MatVal could be found, but presentations at its launch[22] emphasise its focus on taking a value chain perspective to support and coordinate materials research.

There are yet further materials activities in the EU that are separate to the KET program, the ETPs and MatVal. Fumat 2011, for example, was a conference that focused on the development of materials to address society's grand challenges (IPPT/KPK *et al.*, 2012). The conference brought together representatives from industry, the civil service and academia to discuss research progress in materials and how the EU can support its development (IPPT/KPK *et al.*, 2012). The position paper stemming from the conference (IPPT/KPK *et al.*, 2012) also gives considerable attention to the Manufuture 2011 conference – a conference for the Future Manufacturing Technologies ETP (Manufuture) that explored the future of manufacturing in Europe and its affiliated countries – and discusses their outcomes in tandem.

The EU's 7th Framework Program: Materials, manufacturing and nanoscience

A number of the themes in FP7 relate to other observations made in other countries. For example, FP7 groups materials with nanoscience/ nanotechnology and manufacturing/production processes (Theme 4: Nanosciences, nanotechnologies, materials and new production technologies) suggesting prominent links between materials, nanotechnology and manufacturing in research (DG-R, 2010, p. 4). The Directorate-General of Research goes further and says this theme 'underpins progress in virtually all' of the 7th Framework Program's other themes, including ICT, health, energy and transport (DG-R, 2010, p. 4).

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[22] http://www.youtube.com/user/A4MMatval?feature=watch

Critical materials

As with the US and Japan, the EU is taking concerns regarding the supply of critical materials seriously. The EU is involved in the aforementioned Trilateral Conference on Critical Materials with the US and Japan (European Commission, 2013a) and in bilateral critical materials workshops with Japan (European Commission, 2011a; Kishi, 2011). The European Commission also has a Raw Materials Initiative (European Commission, 2013c), which stemmed from a detailed report identifying the EU's critical materials (European Commission, 2010a) and for which an implementation strategy was developed (see European Commission, 2010b). These have been supported by the Polinares[23] project, an EU's 7th Framework Program project on the EU's Policy on Natural Resources (see Polinares, 2013; Sievers *et al.*, 2012) and by the European Round Table of Industrialists (see ERT, 2013). These are examples of the serious action taken by the EU to address issues related to rare earth materials and materials with high levels of risk and uncertainty in their supply chains.

Key references for materials related strategies and initiatives from the EU

- DG-R (2010): Research Road Mapping in Materials
- IPPT/KPK *et al.*, 2012: FuMat2011 Position Paper: Future Materials for Grand Challenges of our time
- European Commission, 2011: Commission Staff Working Paper: Materials Roadmap Enabling Low Carbon Technologies
- KET AMT, 2010: Working Group on Advanced Materials Technologies (working document)
- E-MRS & MatSEEC, 2011: Materials for Key Enabling Technologies
- EuMaT, 2006: Materials for Life Cycle: Roadmap of the European Technology Platform for Advanced Engineering Materials and Technologies
- EMIRI *et al.* (2013), The Implementation of the SET Plan Roadmap "Materials for Low Carbon Technologies"
- Nanofutures (2012), Integrated Research and Industrial Roadmap for European Nanotechnology
- European Commission, 2010: Critical raw materials for the EU: Report of the Ad-hoc Working Group on defining critical raw materials
- Sievers *et al.*, 2012: Critical minerals for the EU (POLINARES working paper n. 31)

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[23] Policy on Natural Resources project

Common themes and implications for policy practice

This section discusses the common themes identified in the review, particularly those relevant for policy practice. It builds on the observations outlined in the previous chapters to develop an understanding of materials in the innovation system. It also draws on the reviewed documents to develop a taxonomy for materials priorities and to discuss some of the observed practices for public policy development. Finally, it relates these themes to UK public sector strategies and industrial policy and discusses the implications. The sections in this chapter discuss the following the key themes and their implications:

- **Few materials specific roadmaps**
- **The underpinning and cross-cutting nature of materials**
- **Materials as an answer to society's 'grand challenges'**
- **A taxonomy for materials research priorities**
- **Materials as part of the different types of technology in the innovation system**
- **A common focus on the intersection of advanced materials, manufacturing and nanotechnology**
- **Lessons for developing materials roadmaps**
- **Observed practices used to support roadmapping and strategy and initiative development**
- **Availability and access to critical materials**
- **Countries coordinate advanced materials and sector needs (strategies)**
- **Relevance of the review and its findings for UK industrial strategies**

Few materials specific roadmaps

The review of international materials strategies, roadmaps and initiatives revealed that few materials specific roadmaps have been developed and published. Where they have been developed, their scope has been narrowed substantially, as in the case of the *Research Road Mapping in Materials* (DG-R, 2010). Even where the foci of these roadmaps' had been reduced, some roadmaps needed to be quite lengthy to cover their materials needs and targets in any detail. This is emphasised by acatech (2008, p. 16), who stated that, 'a prioritisation of the innovation potential on individual materials or materials classes appears to be neither feasible or purposeful'.

The underpinning and cross-cutting nature of material

The review also revealed the cross-cutting nature of materials and how relevant materials are to a number of different sectors. Materials are important to a wide range of technologies and through those to an even wider range of products (KET AMT, 2010). The Directorate-General of Research and Innovation in the EU stated that:

> *'New materials can make crucial differences in many products. Multi-application materials form a generic, horizontal, cross-cutting field with actors in many different industrial sectors'*
>
> (DG-R, 2010 preface)

However, materials underpin more than just technologies and products, they also underpin the ability to provide complementary products and services in a much broader industry than just materials constitute on their own (HLG KET, 2011, p. 11; KET AMT, 2010, p. 3). This is key to Germany's thinking about the strategic role of materials in the supply chain (acatech, 2008). It is also the motivation for materials being one of the EU's six Key Enabling Technologies (KETs) (HLG KET, 2011; European Commission, 2009b, 2009a)[24]. To exemplify its broad impact, BMBF (2004, p. 5) reported that more than 15 of Germany's ' 20 largest industrial companies classify materials research as significant to very significant for their future corporate development'. In addition, BMBF (2004, p. 5) reported that materials innovation can realise completely new products through the availability of new combinations of properties, making products with greater economic efficiency, reducing production expenses, reduced environmental impact and increasing component lifetime.

Advanced materials and society's 'grand challenges'

Materials are considered a possible route to addressing some of society's 'grand challenges' (CRDS, 2013a; European Commission, 2011b; DoE, 2010). The term grand challenges refers to the global, often interrelated, challenges relating to climate change, population, health, transport and the environment[25]. Materials R&D is seen as a route to addressing these challenges because it is

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[24] The other five KETs are nanotechnology, micro-nanoelectronics, industrial biotechnology, photonics and advanced manufacturing systems.

[25] Horizon 2020 define the grand challenges as:

1. Health, demographic change and wellbeing;
2. Food security, sustainable agriculture, marine and maritime research, and the bio-economy;
3. Secure, clean and efficient energy;
4. Smart, green and integrated transport;
5. Inclusive, innovative and secure societies;
6. Climate action, resource efficiency and raw materials.

http://ec.europa.eu/research/horizon2020/index_en.cfm?pg=better-society fundamental to the developments of a number of new technologies and because the implications of materials research cuts across a number of these different domains (CRDS, 2013a; European Commission, 2011b; DoE, 2010). For example, a number of organisations have investigated and assessed their materials R&D needs in low carbon technologies because developments here may help them to address issues relating to climate change and energy. Such organisations include the DoE (2010, 2011), the EU through EMIRI[26] (EMIRI *et al.*, 2013; European Commission, 2011d, 2011b), CRDS (CRDS, 2013a) and AIST[27] (see AIST, 2013).

Materials taxonomy

A number of different methods of grouping materials were observed in the course of this review. These methods include grouping by (i) type, as defined by the elements and the chemical bonds that make up the material, (ii) the properties the intended research is aiming to develop, and (iii) the target industries in which the outputs will be deployed.

Nanomaterials is a prominent category of materials not included in the above groupings. Nanomaterials (and nanotechnology) has been defined as the understanding and control (including design and production) of materials typically at scales of less than 100nm (NSTC, 2011b; Elsner *et al.*, 2009; BSI, 2005; AIST, 2003). This definition would suggest that any material with a deliberately controlled structure is a nanomaterial. For example, steel, which can have a deliberate emergent structure resulting from specific smelting processes, would be classified as a nanomaterial using this definition.

However, different *degrees of control* can be achieved through different methods of engineering. For example, in synthetic biology, materials can be specifically controlled to make predetermined, designed DNA structures. The bulk processes of steel, however, while dictating composition, allows the material to assemble at the nano-scale in a relatively random manner. These different *scales of engineering* – the *specific* control of material structure using tools and processes at the macro-/ micro-/ nano-scale – are what make materials with specific, novel emergent properties arising from the way they are processed nanomaterials/ micromaterials/ macromaterials) in the common way the term is used to refer to materials research priorities. Essentially, nanomaterials are material engineered at the nanoscale.

Nanomaterials
Nanomaterials are materials that have been engineered at the nanoscale

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[26] The Energy Materials Industrial Research Initiative
[27] The National Institute of Advanced Industrial Science and Technology

Figure 9 is a visualisation of how these different groups of materials research priorities can be arranged. The different groups are:

1. materials types – related to their chemical compositions, materials types include categories such as metals and alloys, polymers, ceramics, biological materials, composites or any breakdown of these
2. properties – emergent from their base structure, properties include both structural properties , for example mass, tensile strength, etc.; and functional properties, for example, conductivity, absorptivity, etc.
3. sector – defined by their industrial application, for example aerospace, automotive, chemicals, etc.
4. scale of engineering – materials can also be manipulated at varying scales, for example macro, micro and nano, and possibly even at different scales for the one material

Figure 9 is a means of grouping the materials research priorities identified in the review. It does not describe the flow of materials through to a sector. Rather it allows the separation and identification of different groups of research priorities. Different fields that work with materials can be identified, for example, by the scales on which they manipulate materials to give rise to particular properties. Figure 9 demonstrates this with synthetic biology. By extension, it also shows the different categories by which a material could be classified if it had been designed, fabricated, and deployed in industry. For example, a material in an aircraft could be a composite, with specific strength and mass properties, produced using more macro-level processes, and deployed in the aerospace industry.

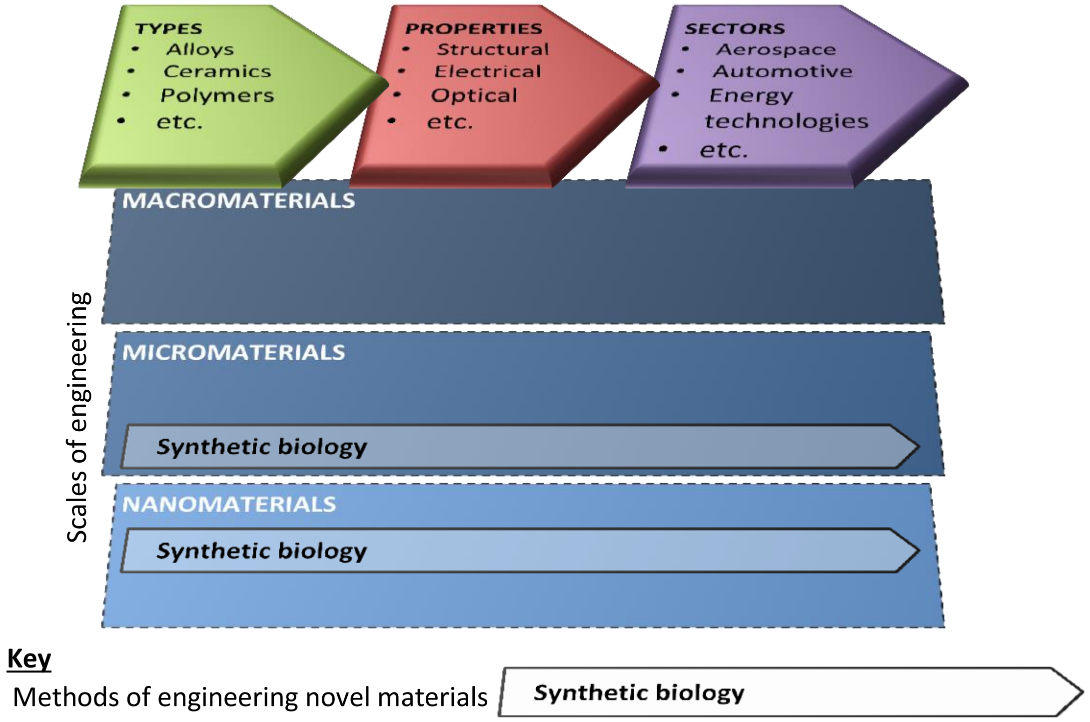

Figure 9: A framework for mapping the terms used for different materials research priorities

The lists of published research priorities found during the review categorised materials in different ways. The KET working group on Advance Materials Technologies (KET AMT, 2010) categorised their materials by a mix of materials types and applications. Whereas NSF's Division of Materials Research (NSF DMR, 2011) grouped their research priorities almost entirely by materials types (except for one category, which focused on materials properties: electronics and photonic materials).

Figure 9 has two consequences for the classification of materials. First, it considers a number of different materials terms, including terms for 'conventional' materials and for popular terms, such as 'bio' and 'nano'. Popular terms are 'frequently given priority by public research funding over traditional materials' (acatech, 2008, p. 9) and draw the focus away from other materials types which could satisfy priority areas such as sustainability and 'high value' or that support other high value industries. This framework can help demonstrate the full expanse of materials R&D that could take place and be useful for industry.

Second, it incorporates the notions of processing and patterning. Often the lines between material and component or product are blurred or at least different depending on the point of view taken (e.g. a mining company versus a car company). The term *scale of engineering* helps bridge this by considering the tools and techniques used to manipulate materials and produce the desired properties required, making the framework adaptable to and compatible with the different perspectives.

The framework depicted in Figure 9 highlights some of the consequences of the terminology used in the prioritisation of different R&D needs. First, it shows that the terms given to material research priorities often do not describe the implications of that priority on the other categories outlined in Figure 9. This was the case in many of the lists of materials research priorities observed in this review. For example, EuMaT's (2006) research priority of 'lightweight materials' (*property*) does not define the materials *types* which could be used to make them and nor does it define the *sectors* in which such materials might be deployed. However, the composite material, used for particular properties, processes using mostly macro-processes, and deployed in aerospace is much more specific

Second, and related to the first, it shows that particular materials research can be defined under different priority categories (as shown in Figure 9). If the priorities of a research or research funding organisation are non-mutually exclusive, a particular research project can fall under multiple priorities. For example, composites could fall under a 'composites' specific or a 'lightweight' research priority[28]. While this is not necessarily detrimental to a set of materials research priorities (indeed, it can be far from it), organisations setting these priorities should be conscious of their possible overlapping nature.

Materials as part of the different types of technology in the innovation system

A number of materials roadmaps and strategies focus on much more than just materials development. Many of the strategies, roadmaps and initiatives explore supporting or enabling technologies. Some of these include the US' National Genome Initiative (NSTC, 2011a, 2012), NASA's space technologies roadmap (for example see Piascik *et al.*, 2012; Shafto *et al.*, 2012), Germany's WING project (BMBF, 2004), acatech's *Materials Science and Engineering in Germany* (acatech, 2008), Japan's 4th Science and Technology Basic Plan (Council for Science and Technology Policy, 2010), CRDS' *Materials Informatics* (CRDS, 2013b) and the EU's *Materials Roadmap Enabling Low Carbon Technologies* (European Commission, 2011b) and *Research Roadmapping in Materials* (DG-R, 2010). Some of these strategies do not list research priorities at all, but instead focus solely on these supporting/ enabling technologies, such as the National Genome Initiative (NSTC, 2011a, 2012) and acatech's (2008) *Materials Science and Engineering in Germany* report.

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[28] The review only the explored publicly available roadmaps and strategies, which are published for communication purposes and might omit the detail description of research priorities (which could be left to particular research groups, panels of experts or even individual research projects).

The technologies mentioned in these reports can be roughly clustered into three categories of supporting technology: Tassey's (2004) infratechnologies, production technologies and information and communication technologies (ICT). However, materials can also be seen as a supporting technology, because it is an enabler of new technologies. Developments in materials enable new products to be developed (e.g. the development of concrete), new technologies often require new materials for them to be realised (e.g. new materials were needed to improve jet engines) and often even the supporting/ enabling technologies need new materials to be developed to be realised (e.g. tool bits). These four types of technologies support or enable new principle technologies, which can be combined with other materials, technologies, components, products and systems to create value.

Figure 10 depicts this 'flow' of technology R&D. It uses the evolution of a new principle technology as outlined by Tassey (2004), from Base science through 'proof of concept' to an application (see p. 5). The technologies that take this route in Figure 10 are called principle technologies – these can be any technology from novel materials themselves (as highlighted by the review) to new technologies for generating power. Supporting their progress are the aforementioned supporting or enabling technologies, which are called upon and sometimes themselves developed as needed during this process. Figure 10 is structured to capture the co-dependencies that often, but not always, exist between these different types of technologies.

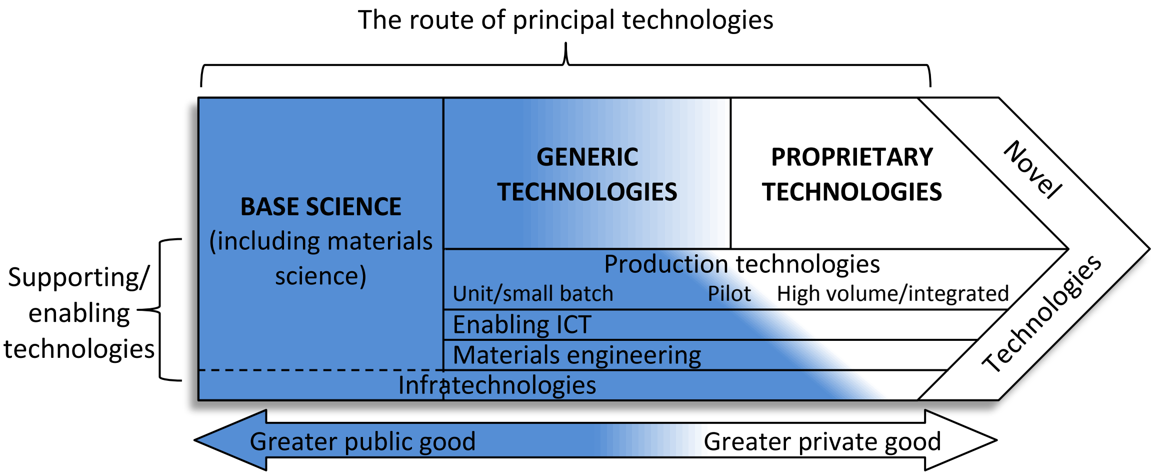

Figure 10: The principle technology route and the supporting/enabling technologies in the technology development process

Implications of the Technology Development Process framework on perspectives of and approaches to support the Eight Great Technologies

Figure 10 can be used to depict two different perspectives of the technology development process. The first perspective is its depiction of the progression of an individual technology (somewhat in line with technology readiness levels) and the categories of supporting/ enabling technologies that might be needed to for it to realise value or to enhance the value realised from it. The second perspective is as a portfolio of technologies within a country's innovation system, against which private activity and government support can be mapped. For example, it can be used to ask questions such as, 'are infratechnologies a major barrier to technology development and if they are, what can we do about it?' Such questions can help inform an organisation, public or private, about their materials development strategy or even their technology management strategy more generally.

Figure 10 also captures the two drivers that are often used to typify how technologies emerge: push and pull. From the push perspective it depicts the development of a single or a set of discoveries/ theories/ etc. from the science base through to its application in a value creating product. From the pull perspective, it depicts the stages that an individual technology progresses through (however rapidly or slowly) and the categories of supporting/ enabling technologies that might be needed for that progression to occur (and it is applied in a sector). From this perspective it appears that governments and industry (through their participation in government reviews) are concerned with the dynamics of the flow of the principle technology and with supporting the technologies that are needed to support this process.

The framework outlined in Figure 10 supplements the categories of materials research priorities identified in the previous section (see Figure 9). A number of the reviewed reports identified materials priorities by the categories in Figure 9 (materials type, properties, application and scale of engineering), but also included materials research priorities relating to the supporting/ enabling technologies in Figure 10. For example, Fraunhofer IFAM's[29] (2012) materials research priorities can be grouped into four of these categories: materials types, properties, infratechnologies and manufacturing technologies.

This framework can also be used to map the functions of organisations involved in each country's innovation system. For example, the NSF[30], DFG[31] and NIMS[32] all perform R&D closer to the Base science end of the technology development process, whereas the Fraunhofer Society, AIST[33] and TNO[34], while also contributing to Base science, also work closely with industry to pull technologies out of the science base for deployment in industry. Initiatives are also used in areas were particular efforts are needed to support the innovation process and supplement the work of these organisations, such as the National Genome Initiative. The organisations and initiatives in the UK's innovation system can also be mapped onto the technology development process in a similar way.

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[29] The Fraunhofer Institute of Manufacturing Engineering and Applied Materials Research (Das Fraunhofer-Institut für Fertigungstechnik und Angewandte Materialforschung)

[30] National Science Foundation, USA

[31] The German Research Foundation (Deutsche Forschungsgemeinshaft, DGF)

[32] National Institute for Materials Science, Japan (NIMS)

[33] National Institute of Advanced Industrial Science and Technology, Japan (AIST)

[34] The Dutch Organization for Applied Scientific Research (Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek, TNO)

Organisations' specific materials research priorities reflect their goals and their role in the innovation system. The Fraunhofer IFAM, for example, helps to pull technology through by conducting close-to-market research and contributes to the development of the supporting/ enabling technologies that assist realising and enhancing value creation, such as developing the necessary manufacturing technologies. A number of the US government departments, such as the DoD[35] and DoE[36], are mission agencies and pull technologies through to meet their specific goals. To support this activity they ensure the supporting/ enabling technologies are developed in parallel to help overcome barriers related to these technologies. This was an important observed characteristic of mission agencies in the review. Furthermore, such priorities demonstrate their specific role in the innovation system and can be used to contrast their role with other organisations, both domestically and internationally.

A focus on the intersection of advanced materials, manufacturing and nanotechnology

The review revealed that a number of countries group materials research done in public organisations with manufacturing and nanotechnology. In Germany, for example, among the many Fraunhofer Institutes with responsibility for materials, the specific category of applied materials is the responsibility of the institute centrally responsibility for manufacturing: Fraunhofer IFAM[37]. The Japanese research IAI[38] AIST also groups these research fields together in their Nanotechnology, Materials and Manufacturing research unit, one of its six core research groups.

There is a compelling argument for grouping these fields together. Both materials and manufacturing can be seen as enabling technologies (see Figure 10) and the development of materials for an application and their development for manufacturing (essentially their manipulation and integration) has benefits when considered in parallel, particularly when production is likely to be large scale. Nanotechnology is also relevant to both these fields because it explores the manipulation and patterning of materials at the nanoscale to produce a technology that can be incorporated with other manufactured components and systems to create a product. These three fields of research are closely linked and as reflected by their structures, a number of organisations such as the Fraunhofer IFAM and AIST recognise the potential benefits of grouping these fields together.

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[35] Department of Defense

[36] Department of Energy

[37] Other Fraunhofer Society institutes that are involved in materials research include Fraunhofer IWM (Mechanics of Materials), Fraunhofer IMS (Microelectronic Circuits and Systems) and Fraunhofer UMSICHT (Environment, Safety, and Energy Technology) to name a few.

[38] IAI (independent administrative institution) is a government funded but independent public organisation with specific operational responsibilities.

Lessons for developing materials roadmaps

As stated, few materials specific roadmaps were found. The review of published national roadmaps and strategies revealed that the *Research Road Mapping in Materials* report (DG-R, 2010) and the *Materials Roadmap Enabling Low Carbon Technologies* report (European Commission, 2011b) were two that specifically mapped only materials and did so the most comprehensively. Even these, however, only qualify when roadmaps are defined in a particular way. These are roadmaps according to Sandia Labs (Garcia & Bray, 1997), who claim that TRMs are needs driven because they identify critical issues and technical challenges to reaching a visions or sets of goals. However, others, including Phaal and his colleagues (for example, Phaal *et al.*, 2010), advocate the benefits of visual roadmaps. If this is adopted as a requirement, then the *Research Road Mapping in Materials* report (DG-R, 2010) and the *Materials Roadmap Enabling Low Carbon Technologies* report (European Commission, 2011b) do not qualify as roadmaps. These conflicting taxonomies highlight the mixed definitions and terminology applied to roadmaps (and hence the broadening of this study to include strategies – arguably a type of roadmap or a roadmap in particular form – and initiatives).

These roadmaps are also only manageable because their focus was narrowed in some way. The above roadmaps were made feasible by restricting the materials research to which they applied. In the case of the *Research Road Mapping in Materials* (DG-R, 2010), for example, the scope was reduced by selecting a number of specific materials applications on which to focus. The scope used for the *Materials Roadmap Enabling Low Carbon Technologies* (European Commission, 2011b) is self-evident. By restricting their scope and defining potential applications, they are linking these applications with particular materials properties, which define Sandia Lab's (Garcia & Bray, 1997) 'needs' or the vision for the roadmap by linking these to potential industry applications. The DoE sums this linking up:

> *'it is often difficult to determine in advance which materials are more likely to have greater applicability and appeal to industry. The selection of materials for further RD&D can only be judged in terms of the industrial environments in which they apply. In fact, the only sound basis for materials development and selection is to match the requirements of the industrial environment with the physical properties of the candidate materials.'*
>
> (DoE, 2000, p. 3)[39]

The review revealed that there are a number of characteristics of roadmaps that priority-setting organisations include in their roadmapping exercises (best practices). Such characteristics include whether it identifies key challenges, key targets (a collection of which might be called a 'vision'), a hierarchy of activities and actions that are executed to meet those targets, a time dimension for

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[39] RD&D is used by DOE to refer to Research, development and demonstration

those activities, the reasons why that target needs to be met and whether it identified multiple 'paths' or 'routes' to reaching that target. These characteristics are advocated by the roadmapping literature (see, for example, Phaal *et al.*, 2010, 2011; Phaal & Muller, 2009). A critical eye is needed when developing, using and reviewing roadmaps. When developing a roadmap, a criterion of what makes a good roadmap should be established and the roadmaps reviewed before the project is started (which should be good practice) and judged against this criterion. Furthermore, when using a roadmap to inform, guide or communicate material research priorities, which of these characteristics it includes and omits are important considerations.

Observed practices for roadmapping and strategy and initiative development

The review also highlighted a number of different practices that can be used to support the development of roadmaps, strategies and initiatives. NISTEP (2010), for example, used a Delphi survey which iterates the same survey a number of times with the same applicants until their responses converge. It was used in this case to collect information such as how important participants thought particular developments in technology were, the timeframes over which these developments might be achieved and the sectors that will be involved in these developments (NISTEP, 2010).

Another example is the process NIST (2011) used to develop a list of materials challenges related to manufacturing. This process combined a search of industry based roadmaps maps with a white paper submission process (NIST, 2011). This not only ensured that previous efforts to develop R&D strategies were considered, but also allows for new industry input and for recent R&D efforts to be considered.

The review also highlighted a number of methods of coordinating research efforts. The US uses cross-departmental workshops, often convened by NSTC (but also convened by NSF), to coordinate R&D activity. Examples of this include the NNI (NSTC, 2011b). Germany's method of engaging with SME's also helps coordinate research activity. Many SME's in Germany are part of research organisations who are members of the AiF[40], Germany's organisation for assigning research funding to SME's. This funding is then given to the intermediary research organisations who conduct industrial based research with their constituents. Germany's national academies, for example acatech, also play a major role in coordinating the countries R&D in materials (see acatech, 2008). The EU also puts effort into coordinating action through its various programs, including the EuMaT, the ETP that aims to coordinate and support materials research efforts in the EU and advise the EU on materials related matters (European Commission, 2013b). The EU is

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[40] The German Federation of Industrial Research Associations (Allianz Industrie Forschung e.V., AiF)

also aiming for greater levels of international cooperation for research, particularly through Horizon 2020 (see European Commission, 2012). Finally, China's Academy of Science also coordinates the development of considerable R&D roadmaps (for example, see CAS, 2010)

Finally, the review identified a unique example of how different tools can be integrated across different levels of coordination to help identify materials R&D and innovation needs and targets: Japan's Strategic Technology Roadmap (STR). Coordinated by METI and NEDO, the STR integrates something like a roadmap, a technology overview and scenarios to coordinate and communicate Japan's R&D needs and targets (Yasunaga *et al.*, 2007, 2009). The STR has three layers: a set of dissemination scenarios, technology overviews and technology roadmaps (Yasunaga *et al.*, 2007, 2009). The order that these were produced in STR 2006 varied, some were top down (from market value, to function, to technology and where the market value was defined either by economic or social needs) and others were developed using a mix of top-down and bottom-up (Yasunaga *et al.*, 2009). STR 2006 involved people from private firms, civil servants and academics and often involved iterating through these three different tools. The STR is a unique integration of tools that aim to link technical targets to social and economic needs, identify market opportunities and communicate these to a broad audience (Yasunaga *et al.*, 2007, 2009).

Availability and access to critical materials

The review also revealed that there is significant activity in the field of critical materials. Critical materials are materials that are of strategic significance, materials where their supply is exposed to a significant level of risks or materials with rare earth elements in them. Reduced availability of materials can jeopardise national security, limit a country's production quantities (and reduce the value realised from technology development) or both. The US has developed strategies in this area (DoE, 2010, see 2011), which has triggered a significant amount of activity. The US now has a critical materials research plan, has new funding for priority critical materials and has increased efforts to coordinate work among US federal agencies (DoE, 2011). Where the DoE looks at critical materials for the energy industry and power generation (DoE, 2010, 2011), the DoD monitors critical materials from a national security perspective (see DoD, 2013). In particular the focus has been on diversifying supply, identifying substitutes and improving recycling capabilities and capacity (DoE, 2011).

Japan and the EU also demonstrate concern for critical materials. With the US they hold the EU-US-JP Trilateral Conference on Critical Materials[41], which has been held each year for the last three years and has technical workshops on recycling, geological research and the efficient use of materials (European Commission, 2010a). Japan and the EU also have bilateral meetings regarding the substitution of critical materials (European Commission, 2011a). The EU's Raw Materials Initiative (see Nowakawska, 2012; European Commission, 2011e, 2010a, 2010b) and

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[41] Run by the European Commission, DoE, METI and NEDO

related programs, for example Polinares[42] (see Polinares, 2013; Sievers *et al.*, 2012), also demonstrate the EU's activity in addressing critical materials.

Critical materials play an important role in the technology development process. If materials are a supporting/enabling technology, then their supply can hinder development. More importantly, however, if critical materials are functionally required for a principle technology, materials research can help to identify substitute materials and potential substitute technologies. R&D at this level requires infratechnologies that help to characterise materials and assist understanding how the atomic structures of a material lead to their functional properties (DoE, 2010). However, R&D of this kind only influences the demand for, and consumption of, a material. Specific R&D can also target the supply and recyclability of critical materials, which may itself have significant materials R&D requirements.

The DoE (DoE, 2010, 2011) explores its critical material substitution activities on a scale of technology readiness level (TRL) and risks and on a scale of rewards. High risk, but high reward R&D is tackled mainly in the science base with large investments of public funds and low risk, incremental R&D that occurs in later TRL phases, is mostly funded by private firms and supported through financial loans and other short-term schemes. These notions maps well onto the role of government and its support of public good technologies and the development of technologies themselves, as shown in Figure 10.

Coordination and national sector strategies

The fractured nature of the materials community means that public organisations can play a key role in coordinating R&D, particularly in the later stages of technology readiness. The review revealed that Germany and Japan are going to particular lengths to design an innovation system that feeds into industry and coordinate R&D for particular applications. Furthermore, and perhaps more importantly, the review revealed that a number of government and other organisations (for example not-for-profit and non-government organisations, including National Academies) see it as important to coordinate R&D activities in some particular areas between government organisations, within industry or both. This indicates that they believe there is a market inefficiency (or even failure) in R&D coordination[43].

This coordination helps governments to assess R&D investments that have low private rate of return (see page 7). Furthermore, it helps them to solve problems of asymmetric information: governments not knowing industry needs, but willing to invest in technologies with healthy social rates of return. These coordination issues are addressed in a number of ways, including industry

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[42] A FP7 project on EU Policy on Natural Resources (Polinares)

[43] And not only in R&D investment (because governments are investing in it anyway), which is well established

reports being developed and submitted to governments, the civil service employing people with industry experience, governments using expert panels to inform policy development and assess applications to calls and competitions. This review highlights an exclusion from this list: explicit industry involved R&D strategy development. The study revealed an evident belief that there is great value in explicit R&D coordination, even to the point where other organisations (especially National Academies) see it as part of their remit to help coordinate these planning exercises and connect industry and government. This is a key potential role that the UK's sector strategies can play in their respective sectors.

The review also found that particular attention is also being paid to the development of infratechnologies, materials, manufacturing technologies and information and communication technologies that support technology development. Sectors can benefit from having these enabling technologies available and at the fore of scientific progress. A novel material can be an enabler for new technology, which can allow new products to emerge and directly benefit related sectors. Countries are taking steps to ensure these technologies, which can have high levels of public good (and have a lower private rate of return than social rate of return) are being developed and are available for both private and public firms alike.

Supporting these technologies and research on technologies with a low TRL does not mean that research at the science base should be sacrificed. The science base produces research that has a high level of public good (Tassey, 2004). However, it appears from the review that public organisations, to varying degrees, play a lesser role in coordinating this research directly (and rather leave that to the workings of their funding organisations, such as research councils).

As mentioned in the previous section, critical materials can be a production constraint. The US, Japan and the EU have a number of R&D programs and initiatives in place to address these concerns. The organisations that cluster around the sector strategies could be used to gather information about critical materials research needs and targets to complement work already being done in those areas (including, for example, BIS & DEFRA, 2012; DEFRA, 2012).

Relevance of the review and its findings for UK industrial strategies

Drawing on these observations and common themes a number of comments can be made about the UK's industrial strategy. In particular, the focus will be on the UK's Sector Strategies (BIS, 2013c, 2013b, for example, see 2013a) and Eight Great Technologies (Willetts, 2013), with reference to the recent report *The Future of Manufacturing* (Foresight, 2013).

From the pull perspective of the different technologies involved in technology development (Figure 10) it is apparent that the Eight Great Technologies are different as they offer support at different levels of development. For example, Robotics can be considered a Generic technology, but is also present in Proprietary and Pilot and production technologies. Advanced materials, because of its prolific nature, plays a role in all of the different technology types. These technologies were selected on the basis that they are areas of important scientific advancements, Britain has a 'distinctive capability' in them and that these field 'have reached the stage where… new technologies are emerging with identifiable commercial opportunities' (Willetts, 2013, p. 9). Understanding the role each of these technologies has in the technology development process can help to develop an understanding of how they can be leveraged to improve the UK's industrial competitiveness.

The aforementioned framework (Figure 10) demonstrates how the UK's Sector Strategies, Eight Great Technologies and the Future of Manufacturing are linked and how materials play a vital role in all of them. The Sector Strategies pull new technologies through the technology development process, something that materials helps support. The Eight Great Technologies, being different types of technologies, either help materials underpin principle technologies or are themselves underpinned by materials. Finally, manufacturing not only supports and enables new technologies, but is often also underpinned by materials developments. With the relationship that materials has on each of the other technologies, both depending on them for their development and also assisting the development of other technologies, materials is intrinsically related to key technologies, sectors and manufacturing.

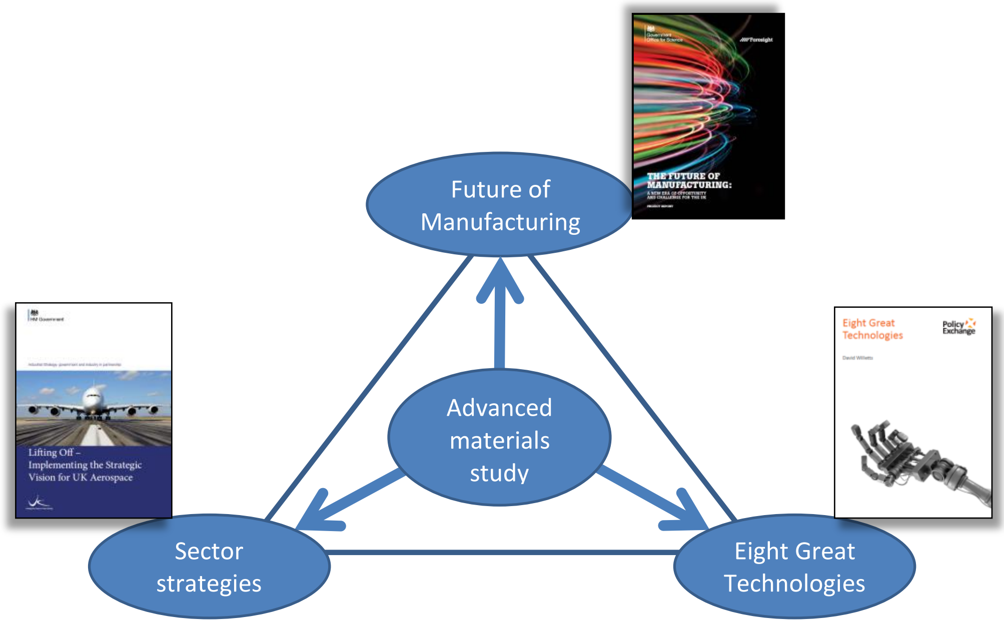

Figure 11: Schematic highlighting the importance of advanced materials to key technologies, sectors and manufacturing

Concluding observations

This report explored published international public strategies for supporting advanced materials research, development, and innovation. In particular, this study reviewed recent advanced materials-related roadmaps (and other strategy-related documents) developed by or for governmental agencies in the US, Germany, Japan and the EU. The chapter outlines a number of concluding observations from the review.

1. Materials innovation is relevant and important for a range of technologies, applications and sectors

The review highlighted the importance of advanced materials R&D to a range of technologies, applications and sectors. This cross-cutting nature means that materials, as a category of research, has a huge impact on industry and on our lives. The roadmaps and strategies covered in this review highlighted the importance of advanced materials to technology R&D and innovation. The large number of materials, with their variety of properties and even greater number of applications makes it extremely difficult to develop an all-encompassing materials roadmap and is perhaps the reason why no-others few materials specific roadmaps were uncovered in the review.

2. Advanced materials have underpin other key emerging, enabling and 'Great' technologies

A repeated theme in many international advanced materials-related strategies is their underpinning role for a range of key enabling technologies (e.g. micro-/nanoelectronics, photonics, nanotechnology), novel production technologies (e.g. additive manufacturing), as well as important technology-based application domains (e.g. energy technologies). These observations suggest that advanced materials are a key enabling technology for a number of other technologies, which supports the UK Government's prioritisation of advanced materials as one of the Eight Great Technologies. Materials are often important in the technology development process because they enable new products to be developed through radically different and unique functionality, from novel materials like graphene, through to more complex composite structures for aerospace. Materials R&D even enables the development of other supporting/ enabling technologies, including infratechnologies, production technologies and ICT. The interrelated nature of technology development means that these technologies also support the development of novel advanced materials.

3. Advanced materials have a key role in addressing key socio-economic grand challenges

A number of the strategies and roadmaps highlighted the potential role of materials in addressing society's grand challenges. These challenges include climate change and issues relating to population, health and transport. Advanced materials potentially play a role because they support and enable the development of new products that can help address these challenges, including low carbon technologies, novel treatments of illness and disease and technologies that coordinate and integrate transport modes.

4. Advanced materials has a key role in enabling advanced/ high value manufacturing

Several international advanced materials-related strategies also highlight the importance of advanced materials in underpinning advanced manufacturing. Realising new advanced materials can accelerate or even enable novel high value manufacturing technology developments. However, manufacturing technology is also pertinent in materials research and development when considering its application, in particular when scaling up the making and manipulation of a material. Many countries believe there are benefits to conducting materials and manufacturing related research and development in tandem, perhaps as a consequence of their interdependence.

5. Supporting/ enabling technologies and innovation infrastructure underpin advanced materials innovation

The review also revealed that international strategies and roadmaps highlight the need to develop supporting/ enabling technologies, in particular infratechnologies, materials, manufacturing and ICT. These technologies are heavily interdependent: developments in one are supported by the others (and even by technologies in its own technology class). This was highlighted by advanced materials, in which the roadmaps and strategies emphasised the need for developments in infratechnologies and ICT (for example in the US' National Genome Initiative) and for which the manufacturability of was also important. However, these technologies support and enable the development of a considerable number of other technologies, further emphasising their importance. The interdependent and important nature of infratechnologies, materials, manufacturing and ICT was captured, for example, by NASA in its Space Technology Roadmaps[44].

6. There are considerable differences in advanced materials terminology adopted by different national and stakeholder bodies

There are significant variations in the categorisation and terminology relating to advanced materials across international strategies. This reflects the different national contexts, their industrial strengths, and the agenda of individual organisations; not least the organisations involved in constructing a strategy or roadmap. Despite these variations, materials priorities can be defined by the following categories: materials types (e.g. metals and alloys, polymers, ceramics, etc.), properties (tensile strength, permeability, conductivity, etc.), applications (e.g. aerospace, chemical, oil and gas, etc.) and scales of engineering (e.g. nano, micro, etc.). These categories allow the comparison of particular priorities. Furthermore, they demonstrate how priorities can be vague when they refer to only one category (perhaps deliberate). For example, a research priority classified by property does not specify the material type or its specific application (although in some cases this could be clear). An extension to this is that the research priorities might overlap, allowing particular research to fall under multiple priorities. For example, carbon-fibre composites can fall into both a call for composites and into a number of different

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[44] See Piascik *et al.* (2012), Meador *et al.* (2012), Shafto *et al.* (2012) and Barney *et al.* (2012) to name a few.

property, sector and scales of engineering priorities. Finally, these categories of materials classifications can be used to identify the related fields on which the research might draw and where it might have an impact.

7. A country's advanced materials strategies and roadmaps are driven by the context of its innovation system

The different national innovation systems have a considerable impact on the materials related strategies and roadmaps that emerge from particular countries and who generates them. In Japan, the government departments METI and MEXT, and NEDO take leading roles in planning and promoting R&D and the independent administrative institutions AIST and JST undertake significant work to identify and address specific materials related challenges. In the US, many federal departments, as mission agencies, fund specific materials R&D that support their respective remits (e.g. DoE and DoD) and other bodies, such as the NSTC, NSF, and the national academies coordinate these activities across-departments. These different methods of coordination reflect countries' different innovation systems and the approach they take to developing materials considered to be of national public importance.

8. Advanced materials R&D coordination is an important function performed often by government

A number of strategies and roadmaps in the review highlight the fragmented nature of the materials science and technology community and point to the multi-disciplinary nature of materials R&D an explanation. Consequently, a number of strategies and roadmaps aim to coordinate materials R&D and provide visibility for the community. Other national strategic documents even point to these as key functions national innovation systems need to have. There are particular benefits in coordinating these activities when research and innovation involves a number of interdependent development activities, it is carried out across development phases (a range of TRLs) or because its spans a number of applications. Furthermore, the number of government strategies and roadmaps that aim to perform this function suggests that there are markets inefficiencies related to R&D coordination. National academies were also found to play a considerable role in coordinating activity in Germany and the US.

9. A strategic role of materials R&D is to address the supply of critical raw materials that underpin key technologies and industries and their 'security of access'

National organisations involved in materials research are also paying considerable attention to critical materials. These materials have either scarce reserves or their supply chains are exposed to a high level of risk. If their supplied quantities fall, production levels and the benefits that can be gained from technologies could fall – particularly as they are increasingly important for advanced energy technologies[45] – possibly compromising national security and safety. Countries are developing strategies to address the risks posed by critical materials. In particular, from an

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[45] See Achzet and his colleagues (2011)

R&D perspective, they are targeting the development of substitutes, new increased efficiency in processing, more efficient deployment in technologies, new recycling techniques and technologies, and new technologies to search for untapped reserves.

10. Developments in advanced materials helps address innovation needs and competitiveness challenges of key industrial sectors

Many of the advanced materials 'roadmaps' reviewed in this report are built around the innovation needs and challenges of key sectors. The roadmaps and strategies aimed to coordinate action to more efficiently conduct R&D to meet these sector specific needs and overcome their challenges. Some strategies even suggest that, given the difficulty in anticipating which novel materials will have greater applicability and appeal to industry, the prioritisation of materials R&D can only be carried out by bounding the analysis to a particular application or applications. It is worth noting that the sectors most commonly cited in the context of advanced materials correspond to key sectors highlighted in the UK Government's 'industrial strategy' (e.g. aerospace, automotive, energy, and construction).

There is much to be learnt from existing published public documents regarding strategies and roadmaps supporting advanced materials research. Countries can use this information to understand the mechanisms other countries use to coordinate and support materials research. Furthermore, such documents outline the materials research focus and strategy other countries have adopted, which contributes to a broader industrial strategy (explicit or otherwise) and supports R&D, innovation, industrial competitiveness and future key challenges.

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Appendix A List of abbreviations and acronyms

A4M – Alliance for Materials, AU
AAAS – American Association for the Advancement of Science, USA
acatech – Deutsche Akademie Der Technikwissenschaften (German Academy of Science and Engineering)
AiF – German Federation of Industrial Research Associations (Allianz Industrie Forschung e.V., AiF)
AiS – The Alliance of Industry and Science (Die Forschungsunion Wirtschaft – Wissenschaft), Germany
AIST – National Institute of Advanced Industrial Science and Technology, Japan
CAS – Chinese Academy of Science
DFG – German Research Foundation (Deutsche Forschungsgemeinschaft), Germany
DoC – Department of Commerce (DoC), USA
DoE – Department of Energy (DoE), USA
DoD – Department of Defense (DoD), USA
DHS – Department of Homeland Security (DHS), USA
DG-R – Directorate-General for Research and Innovation, EU
ETP – European Technology Platform, EU
ERC – European Research Council, EU
EU – European Union
EuMaT – European Technology Platform for Advanced Engineering Materials and Technologies, EU
FP – Framework program (e.g. FP7 or FP8, also Horizon 2020)
Fraunhofer Society – Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e. V., Germany
Fumat – Future materials conference, EU
FY – Financial year
IAI – Independent Administrative Institute, Japan
JST – Japan Science and Technology Agency
KET –Key Enabling Technologies (KETs), EU
Manufuture – Future Manufacturing Technologies ETP, EU
NEDO – The New Energy and Industrial Technology Development Organization, Japan
METI – Ministry of Economy, Trade and Industry (formerly the Ministry of International Trade and Industry, MITI), Japan
MEXT – Ministry of Education, Science, Sport and Culture, Japan
MPG – Max Plank Society for the Advancement of Science (MPG, Max-Planck-Gesellschaft zur Förderung der Wissenschaften e. V.), Germany
MatVal – Materials Value - an A4M initiative involving the materials related ETPs, EU
MPS – Directorate for Mathematical and Physical Science, NIST, USA
NIMS – National Institute for Materials Science, Japan
NIST – National Institute of Standards and Technology, USA
NISTEP - National Institute of Science and Technology Policy, Japan
NSF – National Science Foundation, USA

NSTC – President's National Science and Technology Council, USA
OSTP – Office of Science and Technology Policy, USA
PCAST – President’s Committee of Advisors on Science and Technology, USA
Polinares – Policy on Natural Resources project (Polinares), an FP7 project, EU
TSB – Technology Strategy Board, UK
TNO – The Dutch Organization for Applied Scientific Research (Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek)
UK – United Kingdom
USA – United States of America (also US)

Appendix B Reviewed roadmaps and initiatives

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